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Remote monitoring and diagnosis solutions for relay interlockings

PhD thesis
Extended abstract

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Preface

It would not be a mistake to equate railways with modernity. This invention, which emerged in the midst of the industrial revolution, was fundamental to economic and social development worldwide. Looking at transport in general, railways have a history of almost two centuries. The opening of the first railway line between Liverpool and Manchester (1830) predates by more than half a century the invention of the first motor car (1885) and by seven decades that of the first aeroplane (1903).

The issue of the safe routing of rail traffic has been a priority since the early decades of the industry. The solutions developed have evolved with technological progress from rudimentary mechanical systems to advanced electrical systems to today's state-of-the-art electronic systems.

Safety of movement has been and continues to be the rail industry's top priority. By attaching a high level of importance to this aspect, the railway sector is characterised by technical conservatism. In particular, the pace of adoption of new technologies is much slower than in other branches of engineering. This slower pace is driven by the need to use mature technologies whose weaknesses could be detected and remedied in time.

At present, the percentage of older generation interlockings still predominates in Europe. In the case of mechanical installations, there are numerous examples of systems that have been in operation for over a century.

It is expected that mechanical installations will be replaced by electronic systems within a time horizon of up to 20 years, with a few systems maintained for historic preservation. The replacement of relay installations is expected to be less straightforward and a time horizon for full replacement cannot be estimated. The reasons for this are explained at length in this paper.

A weakness of the old interlocking technologies is the need for more staff to operate and maintain railway installations and equipment than in modern electronic systems. This translates into an absolute minimum number of staff required to keep the railway system in working order.

A problem which is not specific to the railway sector, but which has the potential to affect traffic safety, is the staffing needs which can no longer be met. Another weakness is the growing shortage of qualified staff for older generation installations.

This paper proposes a solution to compensate for the staff shortage by implementing a support system for CED relay interlockings. The solution is intended to help detect and remedy faults in interlockings much faster. The advantages of the proposed solution include the low cost of implementation, the non-invasive technique of interacting with existing installations, and the possibility of being used even by personnel with a basic technical background in the operation of DDC installations.

At the same time, the paper proposes a structure for virtualising the hardware logic of CED installations into software logic for electronic centralisation systems using the Ladder language for PLCs. By directly translating the schematics of CED installations it is possible to reduce the design time of new electronic systems as well as their development cost.

This paper is structured in five chapters summarised below.

Chapter 1 contains an overview of the main elements and systems specific to the railway system. It details the design principles for railway interlockings and the technical features of the main generations of such interlockings (mechanical, relay and electronic). The chapter also contains an analysis of the current situation at European level with regard to the distribution of types of interlockings, as well as forecasts of developments in the field.

Chapter 2 includes an analysis of the main automation technologies currently in use, highlighting railway applications. PLC-type equipment, widely used in the industrial field, is presented and analysed, as well as wireless sensor networks (WSNs) which are becoming increasingly widespread in the context of developing IoT applications.

Chapter 3 contains the description of the proposed solution. The physical components used for the proof of concept are presented, as well as the platforms used for the development of the software components (Arduino IDE and Arduino PLC IDE). The central part of this chapter is dedicated to the translation of the hardware logic related to the test station into Ladder software logic. Software design principles are detailed by establishing standard rules for developing logic functions from traditional relay schematics.

Chapter 4 is dedicated to the exposition of the tests performed during the development of the solution. The first series of tests were carried out to determine the potential use of magnetometers for monitoring railway relays. The theoretical model developed to simulate the magnetic behaviour of the relays is presented, as well as the results of physical measurements in several operating scenarios.

The second set of tests is dedicated to the assessment of the accuracy of the proposed WSN network for monitoring the CED interlocking. The tests verify the real-time detection of the state of the monitored relays, the reproduction of the hardware logic through the software loaded on the PLC and the comparison of the two distinct data sources.

Chapter 5 is dedicated to presenting the conclusions of the scientific research, mentioning and highlighting own contributions, and proposing the main research directions for the future.

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Explanatory dictionary of terms and abbreviations

2002 – logic 2 of 2
2003 – logic 2 of 3
CE – Electronic interlocking
CED – Electrodynamic interlocking
CEL – Line electronic interlocking
CEM – Electromechanical interlocking
CF – Code plug
CFR – Căile Ferate Române
COTS – Commercial off-the-shelf
CR-2/3 – Relay interlocking
CRM – Underground relay interlocking
FBD – Function Block Diagram
HMI – Human Machine Interface
I2C – Inter-Integrated Circuit
ICB – Installation with keys and block
IDE – Integrated development environment
IDM – Signaller
IoT – Internet of Things
LD – Ladder Logic
LI – Instruction List
Open line - the line segments between the entry signals of two adjacent stations
NAND – Negated AND
NF – Neutral plug
NOR – Negated OR
OSI – Opens Systems Interconnection
Route - the path between two signals along which a train may travel
Compatible routes - routes that can run simultaneously
Incompatible routes - routes where simultaneous execution is not allowed
PLC – Programable Logic Controller
PMC – Portenta Machine Control
RCC - Rail Communications and Control
SBW – Südbahnwerke
SCADA – Supervisory control and data acquisition
DA Schematic - Schematic of artificial route cancelling relays
EF Schematic - Schematic of front exclusion relays
IP Schematic - Schematic of the starting relays
KS Schematic - Schematic of section control relays

P Schematic – Route relay schematic
Z Schematic – Locking Relay Schematic
Semaphore - equipment located along the track that provides indications in the form of positioning of mechanical arms, supplemented by light signals to the train driver
Signal - equipment located along the track giving indications in the form of light signals to the driver
SFC – Sequential Function Charts
ST – Structured Text
TCP – Transmission Control Protocol
UDP - User Datagram Protocol
VES – Vereinigte-Eisenbahn Signalwerke
WABCO - Westinghouse Air Brake Company
WSN – Wireless Sensor Network
WSSB – Werk für Signal- und Sicherungstechnik Berlin

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Chapter 1. Railway interlocking - an introduction

1.1 Fundamental Concepts

The development of rail systems has had a profound impact on global dynamics, enabling the rapid transport of goods and people. This sub-chapter details the basics of railways and the essential components for directing rail traffic, including switches and signals.

1.1.1 Basic elements of the railways

A railway line consists of two metal rails mounted perpendicularly on wooden, metal or reinforced concrete sleepers. The section of line between two stations is called open line. Lines between stations can be direct or branch lines, depending on how they branch from the current line. Train routing is impossible without switches, which allow trains to move from one line to another, and signals, which give directions to train drivers[1] [2].

A rail signal is a piece of equipment mounted on the track, used to issue and receive commands and indications to train drivers [2]. The first railway signals emerged as a necessity as rail networks expanded and traffic increased. At first, information was passed on to train drivers via flags by day and lanterns by night.[3]. These evolved into paddle-type signals whose state could be altered by a system of rods, levers and handles. Today, the term 'signal' generally refers to electrical signals, while for mechanical signals the term semaphore is used. Signals are classified according to the functions they serve[4] [5][6].

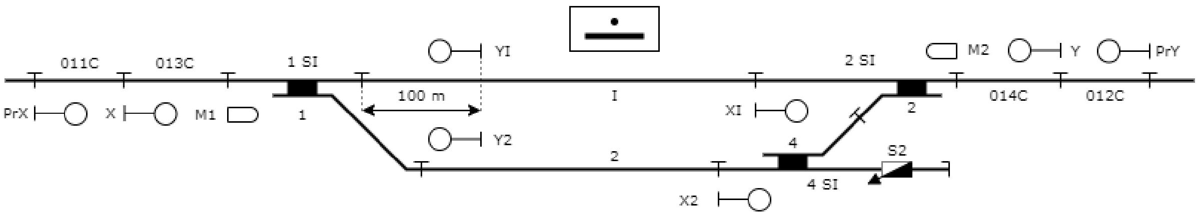


Figure 1. Main elements of a railway station

1.1.2 Routes

A route is a path delimited by two successive signals on which a train can travel within a station. Routes are classified into running and shunting paths, differentiated by running speed and operating area[1][5]. Routes can be compatible (simultaneously executable) or incompatible (degree 0, I or II)[7]. Incompatibilities are managed by slip roads and avoidance lines fitted with derailers.[8]. The lifecycle of a route involves the ordering, checking and partial or total locking of the included elements[6].

1.1.3 Design principles of railway interlockings

Railway interlocking involves the control of a station's objects (points, signals) from a single station. There are three design principles: chained, tabular and topological [9]. The chained principle, being restrictive, is no longer used. The tabular principle defines dependencies between routes and station elements through tables, which is efficient for small stations, but complicated for large stations [10]. The topological principle defines dependencies based on how elements are connected and is more efficient for complex stations [10] [11]. Differences in performance between the two principles are relevant for relay interlockings. For electronic installations both principles are used [11].

1.2 Mechanical Interlockings

The first interlockings were mechanical, using switch locks and pin boards or mechanical panels to control the position of the switches [12][13][14]. These methods have evolved to allow objects in the field to be manoeuvred from one place by levers and internal mechanisms similar to mechanical panels.

Complex mechanical installations led to the development of complete interlockings, with a central control device and two actuators. The control and operating devices are coordinated by block fields [12], allowing the implementation of mechanical and electrical dependency between station elements. This configuration was the basis for complete interlockings, allowing efficient and safe control of rail traffic.

1.3 Relay interlocking

1.3.1 Mechanical-electrical transition

The transition from mechanical to electrical actuation of switches and signals was driven by the limitations of mechanical interlockings, such as limited control distance and the need for physically capable personnel. Electric, pneumatic and hydraulic interlockings offered alternative solutions [9] but electrical interlockings have become the most widespread due to their efficiency.

1.3.2 Relays - general

Relays are passive electronic components consisting of a coil, armature and contacts. When the coil is energised, a magnetic field is generated which attracts the armature, moving the contacts. The contacts can be normally open (NO) or normally closed (NC), depending on their state at coil energisation [15].

Relays are used to switch high currents and voltages using a small current, providing an efficient solution for rail logic control. They have largely replaced mechanical components in railway switchgear, offering increased reliability and efficiency.

1.3.3 Railway relays

Railway relays are specially designed to withstand the operating conditions specific to the railway industry. They include robust contacts and protection against external influences, ensuring reliable and durable operation [9] [16]. The UIC classification includes the following types of relays [16]:

- Type N (uncontrolled) relays - These relays can be used in traffic safety applications without requiring a condition check. Their sizes are usually large, and the movable contacts always fall out when the internal mechanisms lose power by their own weight. As an additional protective measure, the tips of movable contacts and working contacts are made of materials that cannot be welded in the event of overcurrent, usually silver and carbon.
- Type C (controlled) relays - Can be used in traffic safety applications, but their position must be controlled. Advantages over N-type relays are smaller size and lower cost. Disadvantages include the need to check their condition, involving the use of a higher number of contacts (20-50%) compared to N-type relays.
- Relays that cannot be used in traffic safety applications.

1.3.4 Evolution of relay interlocking

Relay interlockings have evolved to include advanced control and diagnostic systems, allowing efficient monitoring and control of rail traffic. They have gradually replaced mechanical switches and have been widely implemented in modern railway networks. The majority type of relay interlocking in Romania was taken over from the Soviet Union [17][18], being a descendant of the relay interlockings developed by Westinghouse in the United States [19][20].

1.3.5 CR-3 interlocking

CR-3 interlockings are an advanced type of electrodynamic interlocking used in Romania for the automation and safety of rail traffic. The first installation of this type was implemented in the 1960s, marking an important transition from simple mechanical and relay systems to more complex and automated systems [21][22].

CR-3 interlockings use plug neutral (NF) and plug code (CF) relays for various control and monitoring functions. These relays are configured in standard schematics, each performing specific functions within the interlocking [1].

The establishment of a route requires the successive pressing of a start button (BI) and a route completion button (BF). The information processed at the level of the selection schematics is then passed on to the execution schematics and stored at the level of each scheme. Safety conditions are continuously monitored and a problem at any scheme will cause the other schematics to fail and the ordered route cannot be authorised.

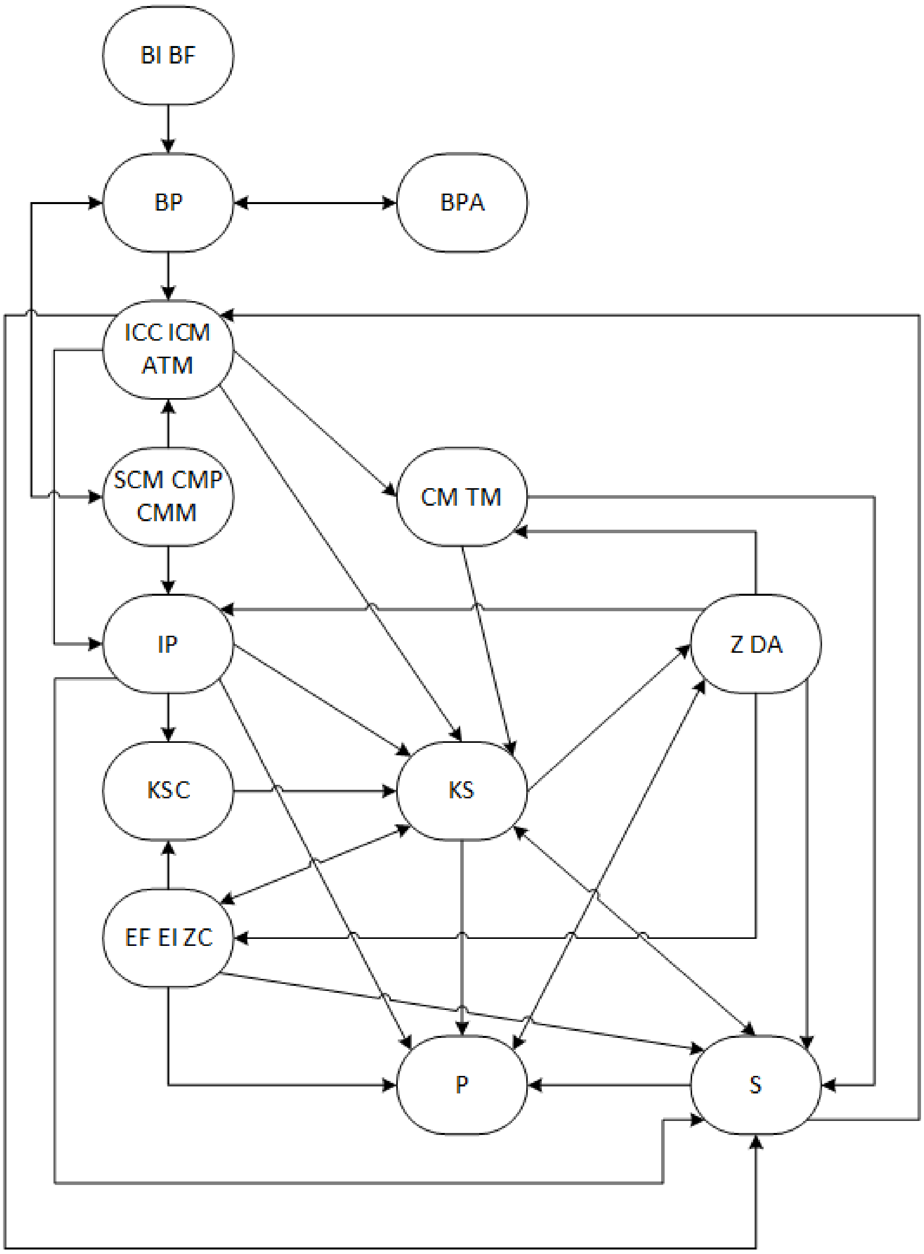


Figure 2. Dependencies of CR-3 schematics [23]

1.4 Electronic interlocking

1.4.1 General considerations

Electronic interlockings are the most advanced type of interlockings, using advanced electronic components to control and monitor rail traffic. They offer a high level of automation and flexibility, allowing integration with other control and diagnosis systems. Rail logic is implemented in software, unlike relay interlockings where the logic is implemented in hardware [10].

1.4.2 Redundancy

Redundancy is an essential aspect of electronic interlocking, ensuring continuity of operation in case of failure. Electronic systems are designed with multiple levels of redundancy, allowing uninterrupted operation even under fault conditions.

The most common types of redundant structures used when implementing electronic interlockings are 2002 (2 out of 2), 2003 (2 out of 3) and 2*2002 [9] [10]. Each of these use hardware and software diversity methods to implement the functions of the interlocking. The results obtained by the parallel processing channels are compared at the end to assess their correctness. Depending on the redundancy structure, the system may operate in a degraded mode [9].

1.4.3 Electronic centralisation architecture

The architecture of electronic interlockings includes advanced hardware and software components integrated into a complex control system. They use programmable controllers, sensors and communication networks to monitor and control rail traffic in real time. The structure of such a system is divided into three main levels [9][10]:

- Operational level: This includes local or central command and control stations. It is considered a separate system because the functions of this level are usually provided by external systems.
- Interlocking level: Contains the equipment that implements the railway logic functions that are essential for the management of signals and switches.
- Element Control Level: Makes the connection to external elements such as switches, signals and track circuits.

Electronic control centres allow the implementation of diagnostic functions at all levels to monitor the states of different elements and the system as a whole [9]. These installations also allow interfacing with train protection systems.

The software for electronic interlockings is structured into several components [10]:

- Basic software: Allows physical components to work together to form the operating system.
- Interlocking software: Implements the security functions required by the installation, divided into general functions and specific functions for each infrastructure administrator.
- Location software: Contains data specific to the centralised area, including outdoor elements and paths.

Modern versions, e.g. ESTW installations, of these types of systems aim to physically separate data and power circuits to improve safety and reliability.

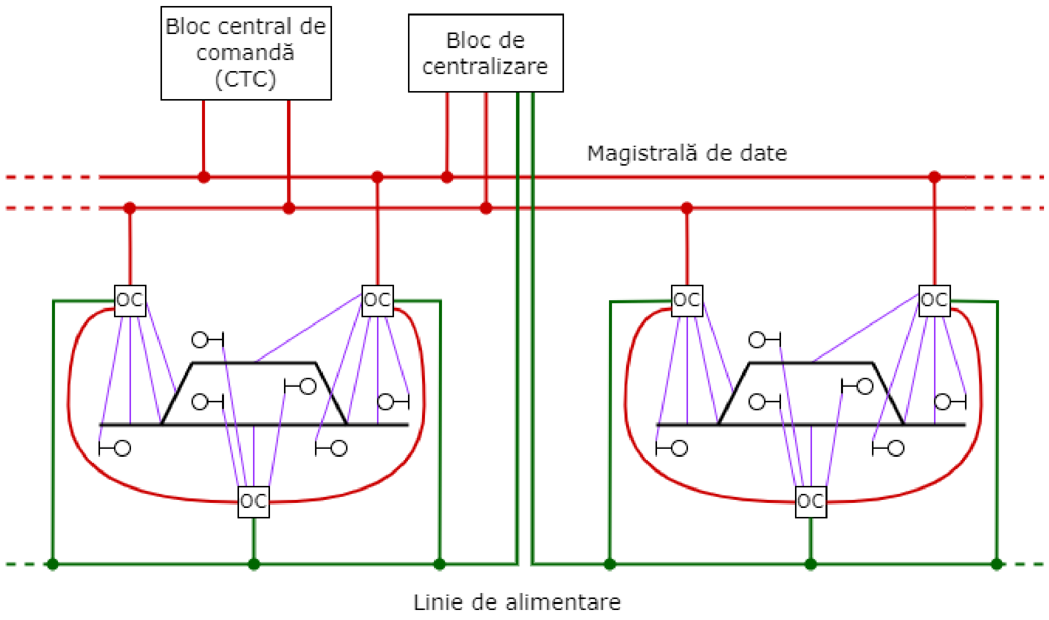


Figure 3. Structure of an ESTW interlocking [10]

Currently there is no hardware and software standardisation for electronic centralisation systems, which is an impediment to interfacing solutions from different manufacturers. [9].

The EULYNX project aims to standardise the interfaces used in rail safety to allow equipment from different manufacturers to be combined without compromising safety. EULYNX aims to define an XML language [24] whereby the specifications of customers, generally infrastructure managers, are clearly understood by the manufacturers of centralised installations and the manufacturers of related elements. Currently, infrastructure managers in 15 countries are involved in the development of the standard and are at various stages of national implementation [25].

1.5 Current state of interlockings

The current state of interlockings reflects a combination of old and new technologies. While many old installations are still in operation, the trend is to gradually replace them with modern electronic systems. This transition is driven by the need to improve the safety, efficiency and reliability of rail traffic.

Over time, national rail networks have developed specific features and challenges, and a major challenge is to harmonise the European network (over 200,000 km) to ensure interoperability. The 2020 analysis shows that mechanical and relay interlockings are still predominantly used, accounting for 27% and 38% of all installations. The study involved extracting data from official documents and classifying them into four categories: mechanical, relay, electronic and other. Data was analysed from 15 countries, representing more than 160,000 km of track. The results show significant differences between the types of interlockings in different countries, with no obvious correlation with geographical layout or overall network length. Although modern electronic interlockings accounts for only a quarter of the total, there is a trend to replace old mechanical and relay installations, especially on main transmission corridors, with electronic installations and the implementation of ETCS signalling.

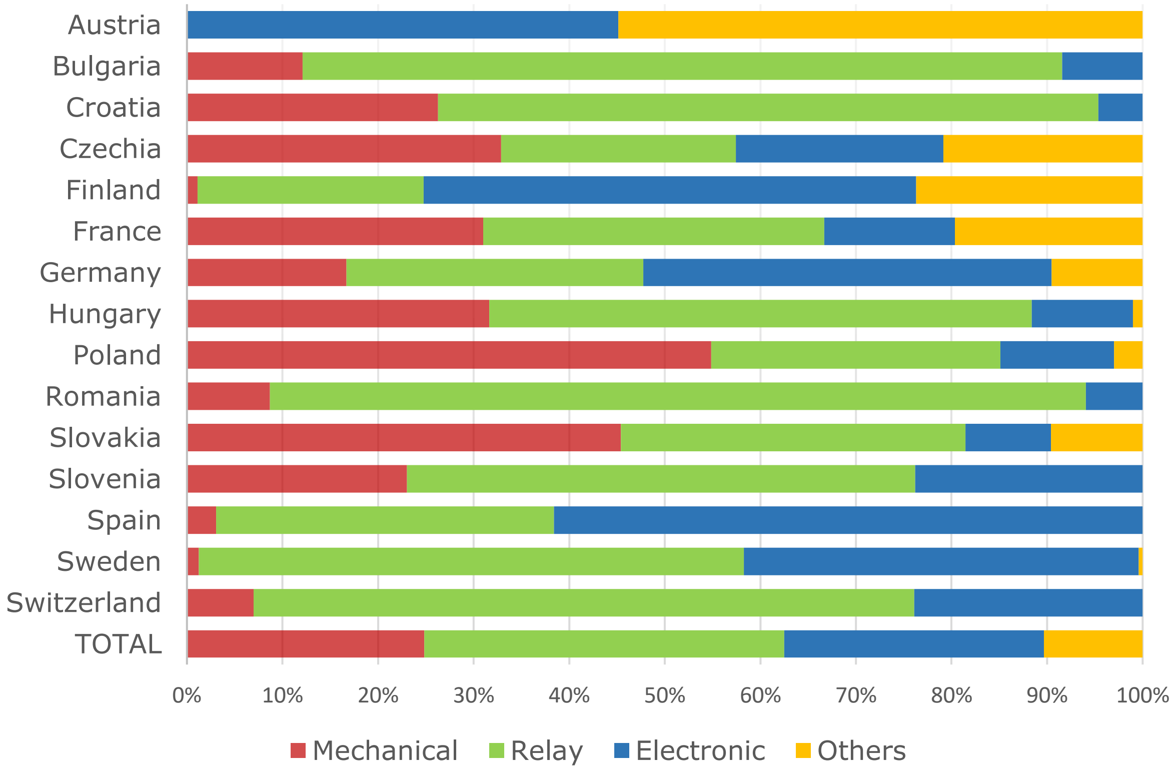


Figure 4. Distribuția tipurilor de centralizări

Chapter 2. Automation technologies

2.1 Wireless sensor networks

2.1.1 Description and general applications

Wireless Sensor Networks (WSNs) are systems that use a large number of sensors distributed in different locations to monitor various environmental or application-specific parameters. A node in a WSN is composed of one or more sensors monitoring the same area and connected to other nodes in the network. Networks can reach up to thousands of nodes, each with different roles: parameter monitoring (sensor node), data transmission (router node) and data exchange (base station or coordinator node) [26].

The structure of a sensor node includes a transducer, a microcontroller, a power supply (batteries) and a wireless communication interface. The microcontroller manages the data collected by the translator and transmits it to other nodes or base stations. Nodes can be equipped with real-time tracking and tracing elements, external memories for storing large amounts of data or actuators for control functions [26]. The addition of mobility units also allows nodes to move to change the monitoring area, turning the network into a Mobile Wireless Sensor Network (MWSN) [27].

Base stations in WSNs have the primary role of facilitating communication between sensor nodes and the end user. They differ from sensor nodes in additional communication, power and data processing resources [28].

WSN applications are classified into tracking and monitoring applications, used both indoors and outdoors in various fields [26]. Military applications include tracking enemy movements, evaluating military equipment and detecting biological, chemical or nuclear attacks. In the medical sector, WSN monitors patients and their vital parameters (e.g. heart rate, EKG/EEG signals, blood pressure, patient position).

Environment and agriculture are areas that benefit significantly from WSNs. Monitoring water quality in food and protected areas, air quality in urban and industrial areas, and monitoring natural disasters (fires, earthquakes, volcanic eruptions, tsunamis) are key applications for protecting health and biodiversity. In agriculture, WSNs are used to monitor the condition of crops, greenhouses and livestock to ensure the highest possible yields and quality [29].

In the urban environment, WSNs are essential for urban agglomeration management, traffic monitoring, parking management and monitoring of buildings at structural risk. Sensor nodes can provide information periodically in response to an event or user query. Thus, wireless sensor networks are versatile and effective solutions for monitoring and managing various domains, helping to improve quality of life and security.

2.1.2 Sensor network topologies

Wireless sensor networks (WSNs) have various topologies that influence how sensors are organised and connected, each with specific advantages and disadvantages. A node in a WSN can be of three types: coordinator (collects and aggregates data from all sensors), intermediate (facilitates communication between coordinator and end nodes) and final (takes information from the environment and passes it on to the coordinator) [26].

The star topology is the simplest, where each sensor communicates directly with a central node (coordinator node). It is easy to set up and suitable for small areas, but it is not scalable and can have problems if the central node fails. The tree topology organises the sensors in a tree structure, with a coordinator node and intermediate nodes (routers) [30]. This is more scalable than the star topology but can suffer from congestion and routing problems if the structure becomes too complex. The mesh topology allows each sensor to communicate with multiple sensors, providing redundancy and fault tolerance, but is difficult to configure and requires more resources [31].

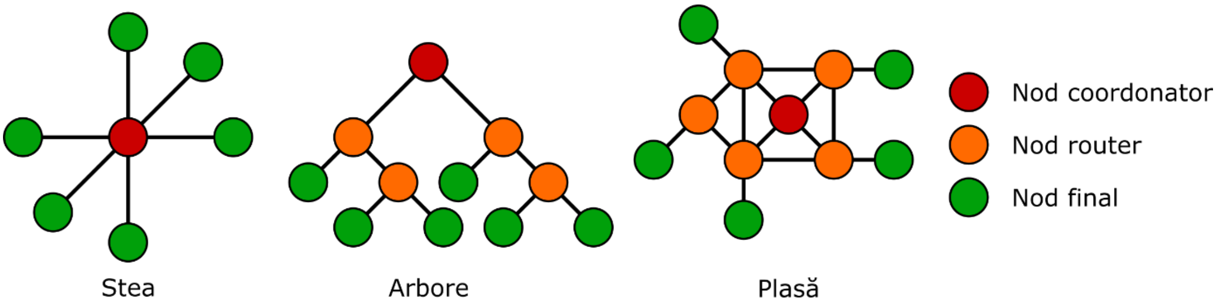


Figure 5. WSN network topologies

Choosing the right topology depends on specific application requirements such as coverage area, scalability, fault tolerance and power consumption. In ad-hoc WSNs, nodes organise themselves and communicate via multi-hop routing [32]. In clustering topologies, sensors are organized into clusters with cluster heads that aggregate and transmit data, reducing energy consumption and improving network efficiency.

Clustering algorithms can be static or dynamic, with dynamic ones adapting to topological changes. Examples of clustering algorithms include LEACH, TEEN, APTEEN, SEP, DEEC and HEED, each of which has strengths and weaknesses and is suitable for different types of WSN. Node clustering and cluster head selection are critical to the efficiency and longevity of WSNs [33], [34].

2.1.3 Communication technologies for WSNs

WSNs can be deployed using various communication technologies, each complying with the standard communication stack. The WSN protocol stack, derived from the OSI model, is simplified and comprises five levels: physical, data link, network, transport and application. Each layer performs specific tasks independent of the others [35].

Table 1. Correspondence between the OSI stack and the WSN stack

OSI stack	**WSN Stack**
Application Level	Application Level
Presentation Level	
Level Session	
Transport Level	Transport Level
Network level	Network level
Data link level	Data link level
Physical level	Physical level

The IEEE 802.15.4 (2003) standard is essential for LR-WPANs, which are intended for low-volume, power-constrained applications. It defines the physical (PHY) and medium access control (MAC) layers and includes two types of devices: full-function devices (FFDs) and reduced-function devices (RFDs). FFDs can become network coordinators, while RFDs perform simple tasks and have limited resources [26] [36].

ZigBee networks, based on IEEE 802.15.4, are used for automation and control in diverse environments. The ZigBee protocol stack includes the PHY and MAC layers (defined by IEEE 802.15.4), and the network (NWK) and application (APL) layers specified by ZigBee. ZigBee allows unicast, multicast and broadcast communication and uses extended and shortened addresses to identify devices[37] [38].

Wi-Fi HaLow (IEEE 802.11ah) is designed for IoT applications, providing wide-area connectivity and high energy efficiency. Uses frequency bands below 1 GHz, enabling speeds of up to 347 Mbps [39] and battery lifetimes of 5-10 years. These networks are suitable for remote measurement, environmental monitoring and extending WLAN coverage.

The choice of WSN network technology and topology depends on specific application requirements, including coverage area, expandability, fault tolerance and power consumption.

2.1.4 Railway applications

Due to the growing demand for freight and passenger transport, the railway industry is essential in transport systems. Harsh environmental conditions, high passenger flows and various security threats require the implementation of modern systems and adaptable solutions. In this context, WSN railway applications are crucial and fall into three broad categories: station monitoring, passenger applications and track monitoring.

In railway stations, WSN can help prevent fires by monitoring carbon monoxide concentration, airborne particles and ambient temperature. Systems can be complemented with mobile cameras for additional information. WSN can also monitor other hazards such as floods, earthquakes and terrorist attacks, activating equipment such as access gates and alarms [40] [41].

For the track, the integrity of the rails is essential for safe transport. Early detection of cracks and weaknesses prevents accidents. Assessment methods include ultrasonic and visual sensors, usually installed on mobile platforms [42]. The proposal to use WSN along the railway for constant monitoring is under evaluation [43].

In the case of sensitive elements of the rail network, WSN-based applications can provide information about their status. The specific topology for WSN along railways is linear (LWSN) [44], classified into thin, dense and very dense, depending on the arrangement of nodes.

The limited lifetime of the network, due to the independent supply of nodes, is a major impediment. Strategic node placement and clustering can optimise energy consumption. An alternative power supply method could be to convert rail vibrations into useful energy [45].

The main challenges for WSN in rail include wireless data transmission and power consumption. Rail Communication and Control (RCC) systems use the 802.15.4 standard and are designed to operate over distances of more than 50 km with transfer rates of up to 1 Mbps, even for vehicles travelling at up to 600 km/h [46].

In RCC systems, trains and track equipment are the end nodes and base stations serve as coordinators. RCC networks have a hybrid topology [46], operating in star topology when nodes are within range of the base station and in peer-to-peer topology in areas without coverage.

2.2 Programmable Logic Controllers (PLC)

2.2.1 Overview

Programmable Logic Controllers (PLCs) are essential electronic equipment in industrial automation. Initially, automation was done with relays, but these had major disadvantages in terms of flexibility and the need for rewiring in case of changes. PLCs, developed in the 1960s, replaced these technologies, offering many advantages, including increased reliability, flexibility, low cost, communication functions, fast response time, easy fault detection and easy testing.

Compared to microcontrollers and personal computers, PLCs are specialised for industrial automation, operating in harsh environments and have high reliability [47]. PLC costs are high, but they offer dedicated ports for industrial equipment and are programmed to IEC 61131.

The architecture of a PLC includes a central processing unit (CPU), input and output modules, power module and programming module. PLCs can be modular or integrated and the CPU is built around a microprocessor with RAM and ROM. Input and output modules link to external devices and can be located close to them to reduce the amount of wiring required. These modules are protected by optocouplers to isolate incompatible voltages.

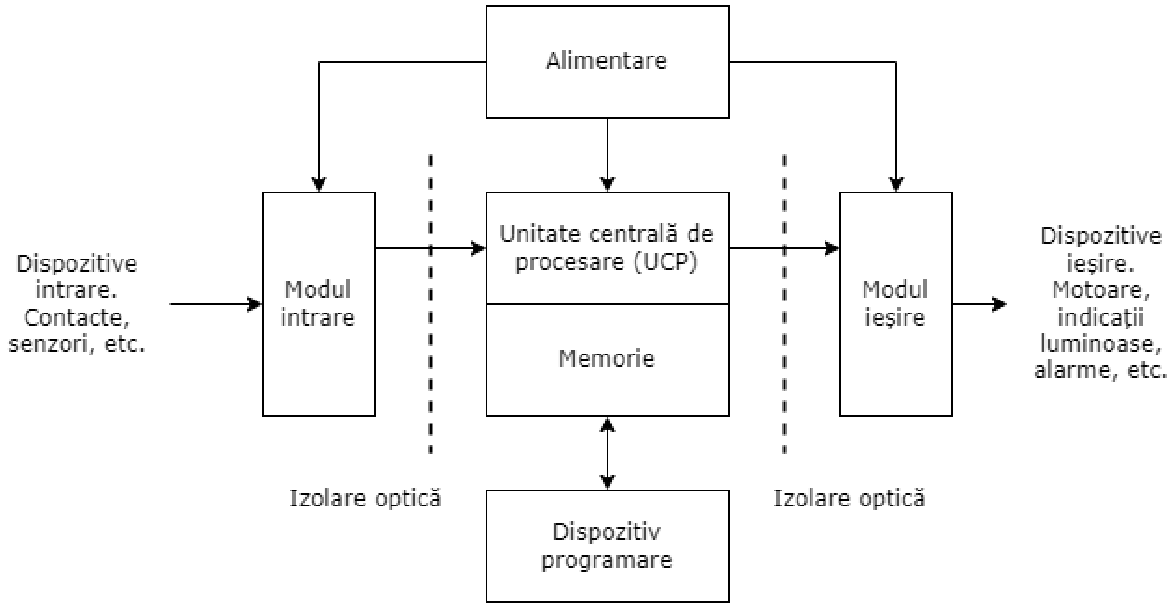


Figure 6. Typical PLC architecture [47]

Input and output module specifications include rated voltage, threshold voltages, rated current, operating temperature, switching time, output voltage and current, inrush current, short circuit protection, leakage current and electrical isolation. Analog modules are characterized by number of channels, input and output current/voltage range, input protection, resolution and impedance [47].

The programming device of a PLC can be a mobile terminal or a computer with specific software. HMI (human-machine interface) systems are used to monitor and control parameters during operation, in the form of touch screens programmed separately from the PLC.

2.2.2 PLC programming

PLCs operate based on the program loaded into their memory. The way the PLC program runs is called the scan cycle and is carried out in a continuous loop with the following steps [48]:

- Scan entries - evaluate the status of the entries specified in the entry table;
- Program run - performed based on the data from the previous step;
- Output update - update outputs via the output table based on the results obtained from the program run;
- Diagnostics and communications - evaluate PLC status and send data to predefined devices.

The duration of a scan cycle varies depending on the number of inputs and outputs, the complexity of the main program and the performance of the PLC, with typical values ranging from 1 to 20 ms [47].

The languages used in PLC program development are defined according to IEC 61131-3. According to this document, there are five programming languages organised as follows [49]:

- Text languages:
    - Instruction List (IL) - low-level language similar to assembly language;
    - Structured Text (ST) - similar to PASCAL and BASIC languages;
- Graphical languages:
    - Functional Block Diagram (FBD) - represents data flows through functional blocks;
    - Sequential Function Chart (SFC) - describes the sequential behaviour of the system;
    - Ladder Diagram (LD) - reproduces the logic of relay circuits.

PLC programs are generally structured in two parts: data files, which contain information about inputs, outputs, various states and variables, and program files, which contain the main program and subroutines. Subroutines are separate program sequences that are called by the main program under different conditions.

2.2.3 Ladder language

Specified in the IEC61131-3 standard, Ladder is the most widely used programming language for PLCs. This language was developed with the main purpose of reproducing relay-based automation schemes. For this reason the structure and operation of the two techniques are similar.

The name of the language comes from the way the programs are written, which looks like a ladder (*en: ladder*) with several rungs (*en: rung*). The rungs are enclosed between two power bars and contain input and output instructions.

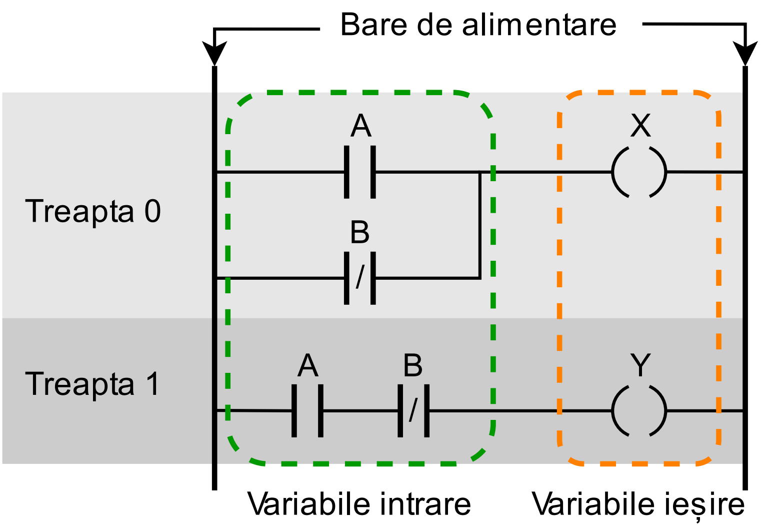


Figure 7. Sample Ladder program

Input instructions, also called contacts, are variables that are read and evaluated by the program before the instructions are executed. There are several types of contacts that can be used in Ladder programs, the main types being normally open contacts and normally closed contacts. The names and operation of each type of contact are as follows:

- Normally open contacts - open state corresponds to logic state 0 (default state) and closed state to logic state 1 for the associated variable;
- Normally closed contacts - open state corresponds to logic state 1 (default state) and closed state corresponds to logic state 0 for the associated variable;
- Rising edge sensing contacts - Switches to the state of logic 1 when the associated variable changes its value from 0 to 1, after which it returns to 0;
- Falling edge contacts - Switches to a logic 1 state when the associated variable changes its value from 1 to 0 and then returns to 0;

Depending on the application, different contacts of the same variable may be found in a Ladder program. The use of a particular type of contact depends on the implemented function, each behaving differently.

The output instructions, also called coils, are the variables written after the execution of the instructions in the program. The types of coils used in the Ladder language are:

- Normal coils - Pass the associated variable in the state of logical 1 when the logical step function results in the value of logical 1 and with logical 0 otherwise;
- Negated coils - Pass the associated variable in the state of logic 1 when the logic function of the step results in a value of logic 0 and logic 1 otherwise;

- Set coils - Pass the associated variable in the state of logic 1 when the logic function of the step results in the value of logic 1. The variable remains in this state even after the function goes to logic 0, and can only be changed via a reset coil;
- Reset coils - switch the associated variable to the logic 0 state when the step logic function results in a value of logic 1. The variable remains in this state even after the function goes to logic 0, and can only be changed via a set coil;
- Rising edge detection coils - Switch the associated variable to the logical 1 state when the logical step function changes its value from 0 to 1, after which it returns to 0;
- Coils with falling edge detection - Pass the associated variable in the state of logic 1 when the step logic function changes its value from 1 to 0, after which it returns to 0;

A Ladder program executes from top to bottom and left to right, step by step. The number of contacts and parallel lines for a step is determined by the memory characteristics of the PLC [47].

The behaviour of conventional relay schemes is modelled using Boolean logic. Since the Ladder language was inspired by this type of circuitry, functions that are implemented in Ladder language can also be modelled according to the same principle.

Simply implementing logic functions is not enough to develop advanced automation applications. They often require timing certain processes, counting different variables to adjust operating parameters, and implementing complex arithmetic functions. The IEC61131-3 standard allows these functions to be implemented through timer, counter and selection function blocks [49].

2.2.4 Communication technologies for PLCs

In the design of automation systems, it is essential that sensors and actuators are located close to the controlled or controlled elements. Input and output modules should also be installed close to associated equipment to minimise distances and reduce wiring requirements. In complex applications, system elements are spatially distributed, requiring communications to be established between the central PLC and remotely located input and output modules.

Serial connections are used for these communications, with two main types: RS 232 and RS 485. RS 232 is designed for point-to-point communications between two devices over distances of up to 20 m. Requires three ports (Tx, Rx, GND)[50] and uses asymmetrical voltages for data transmission. RS 485 allows the creation of bus-type networks with up to 32 devices and can cover distances of up to 1200 m. Uses differential signals transmitted over twisted wire pairs, allowing both half duplex and full duplex communications [51].

Ethernet is becoming increasingly popular in automation systems due to its ability to handle traffic through switches and use CSMA/CD technology to avoid collisions [30]. Ethernet uses Manchester coding to transmit data and is the most common type of local area network (LAN).

Modbus is the most widely used protocol in industrial automation due to its free license and efficiency [52]. Modbus RTU works with RS 232 and RS 485 standards and is used for communication between PLC and external equipment. Modbus TCP operates on TCP/IP networks and is used for communication between PLCs or with external systems using port 502.

Often complex automation systems use both implementations of the Modbus protocol. The transition between implementations is done using equipment called gateways. The standard configuration is where Modbus RTU is used for PLC - external equipment communication and Modbus TCP for communication between PLCs, computers and servers. The totality of all these modules [47] and components make up a SCADA (Supervisory control and data acquisition) system.

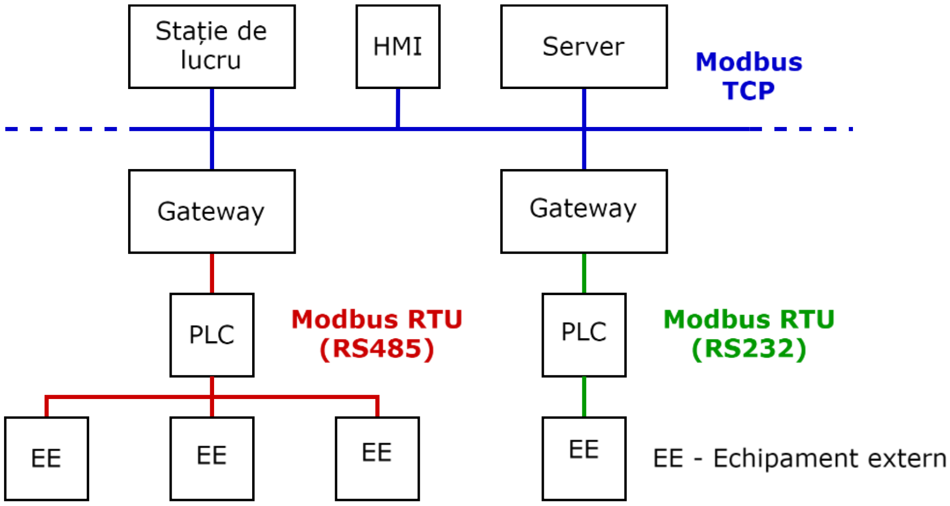


Figure 8. Typical SCADA system architecture

2.2.5 *Railway applications*

The evolution of industrial and railway automation systems is similar, but safety requirements are much stricter in the railway sector. PLCs, originally developed to replace relay automation systems, can be useful in railway automation. The development of railway control and signalling systems presents challenges, including long design, testing and implementation times, high costs and compatibility issues between different products [53].

Maintenance problems arise as systems age and specialised equipment ceases production, making it difficult to replace faulty components [54]. The use of PLCs in railway automation offers advantages such as: experience in the transition from hardware to software logic, robustness in harsh environments, modularity, diversity of manufacturers and compatibility between equipment due to communication standards such as Modbus.

Eurolocking is an electronic centralisation system based on SIL 4 certified PLCs. The pilot system was implemented at Santpoort Noord station (The Netherlands), controlling signals, switches, track circuits and level crossings. To take full advantage of the benefits offered by PLCs, Eurolocking is designed around the principle of commercial off-the-shelf parts (COTS) [54]which means that only generic modules and components are used, which are available from several manufacturers.

The Eurolocking architecture uses various communication protocols [55]Frauschler Safe Ethernet, SafeEthernet and PROFINET. The system was tested in parallel with the old relay installation and the results prompted the network administrator to replace all remaining relay centralisation installations with the Eurolocking system.

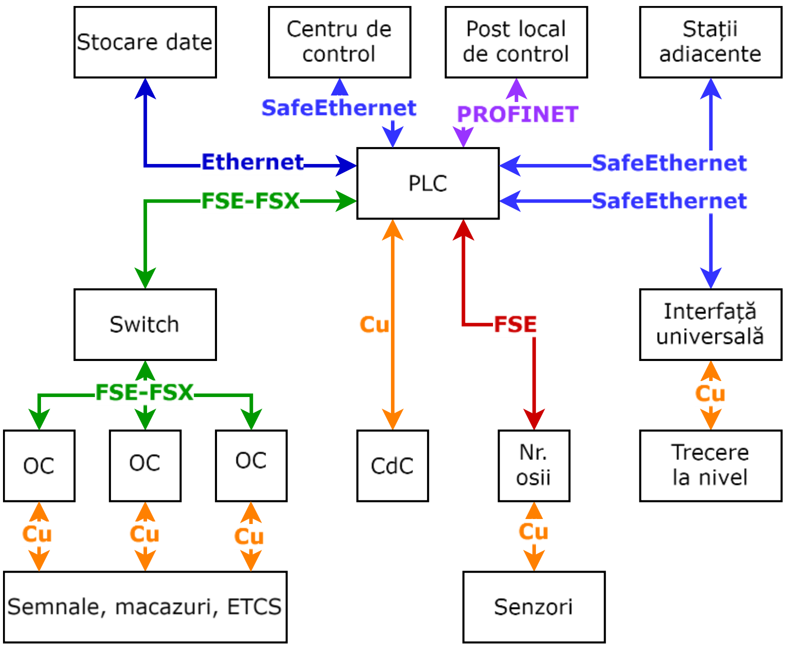


Figure 9. Eurolocking Architecture

Chapter 3. Contributions on monitoring and diagnosis of CED Interlockings

3.1 Purpose and motivation

In this paper it is proposed to implement a monitoring and diagnostic system for CED interlockings. The solutions proposed for implementation in the system are evaluated from both hardware and software point of view.

Interlockings are the main safety elements in the railway sector. As described at length in the previous chapters, these systems have undergone continuous development. While mechanical centralisation systems will largely be replaced within a time horizon of 15 to 20 years, the same cannot be said of relay centralisation systems [56].

For countries with extensive rail networks and which currently have a large proportion of relay interlockings still operational, the full transition to electronic systems is expected to take much longer. Priority for modernisation will be given to stations on the main traffic corridors. It is likely that on secondary lines, where there is no heavy traffic, relay installations will persist for decades to come.

For stations that will not be upgraded in the very near future, it is necessary to consider and implement transitional solutions that will allow traffic to run safely without high implementation and maintenance costs.

The solution proposed in this paper is conceived as a support system, allowing a much easier monitoring and diagnosis of CED installations. In this way, plant malfunctions can be identified and solved much faster, even by less experienced maintenance personnel.

The solution combines the monitoring part via a WSN network and the reproduction of CED interlocking railway logic via PLC devices. As detailed in the previous chapters, PLCs have already replaced relay logic in most industrial processes, and there are now electronic control systems implemented using them.

The main stages of the research carried out to achieve the proposed objectives were:

1. Identification and evaluation of suitable detection methods for the proposed CED interlocking;
2. Adaptation of traditional CED logic into software logic suitable for PLC use;
3. Development and testing of hardware equipment required to implement the proposed solution;
4. Functional integration of the WSN monitoring network with the PLC logic core.

3.2 Block diagram of the monitoring and diagnostic system

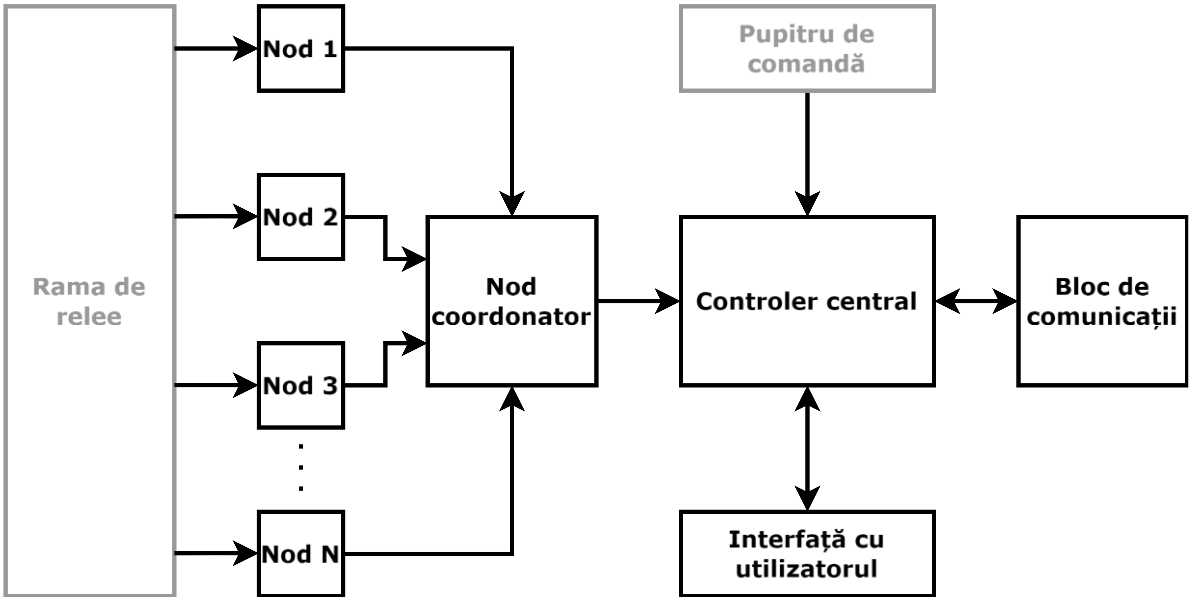


Figure 10. System block diagram

The block diagram of the proposed solution is illustrated in Figure 10. The system consists of a WSN that monitors the status of the relays in the CED interlocking using non-invasive techniques. The coordinator node is responsible for retrieving and interpreting data from the sensor nodes distributed on the relay frame.

In parallel with the monitoring of the rail relays via the WSN there is a monitoring of the commands given by the IDM via the control panel. The commands are taken via a central controller running a software replica of the hardware logic implemented at the CED interlocking.

Based on the comparison of the two information flows, an evaluation of the expected operation of the installation (virtualised logic) versus the real one (via the WSN network) takes place. In case of correct operation of the interlocking, the two flows show the same values. If discrepancies exist, they can be identified at the individual relay level. An operation history recording solution can also be implemented.

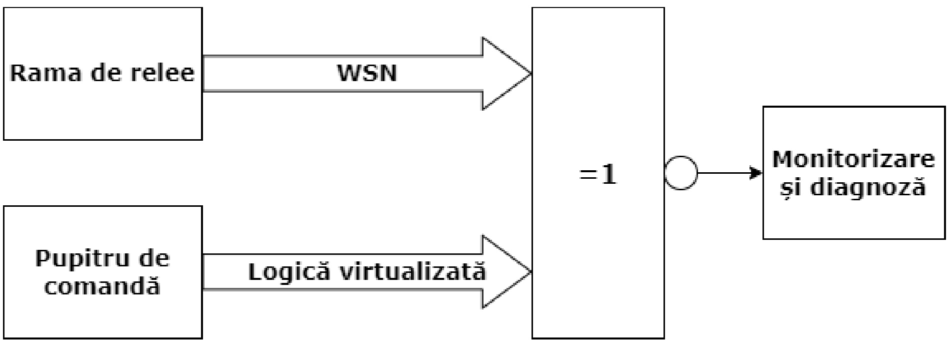


Figure 11. Main information flows of the proposed system

A human operator can interact with the central controller via a special interface. The relevant data can then be passed on to a centralised system at district or regional level.

3.3 Relay rack and control panel

The Department of Department of Telematics and Electronics for Transports of the Transport Faculty, NUST Politehnica Bucharest is in possession of a CR-2 type relay control panel manufactured in 1961. The installation consists of a relay frame, an EM-2 switch electromechanism and a vertical control panel.

The centralised station, designated A, is located on a single line traffic section with a simple configuration. The station (Figure 12.) contains two guard lines with a single switch at the X end and two paired switches at the Y end, giving a total of nine isolated sections. There are no shunting signals, only entry and exit signals.

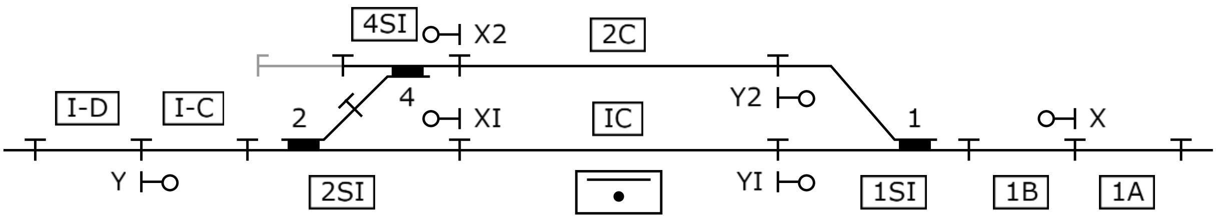


Figure 12. Plan of station A

The interlocking is provided with a single relay rack (Figure 13.) containing 77 NF type relays, 24 code relays and several relays related to a signal cabinet. On an adjacent wall is installed the artificial snow clearing button panel.

Figure 13. The TET department's relay rack

To be able to build the installation using a single relay array, its designers made a number of modifications compared to conventional installations in service:

- The impossibility of making shunting routes in the absence of all shunting signals;
- Absence of the sections of the shunting signals after the sections of the input signals, which implies the absence of the corresponding relays C, KS, P, Z and DA;
- Combination of the functions of relays Y SA and Y SD into a single relay Y S;
- Absence of the signal fire supervision relays for Y (Y F2G, Y FV1G, Y FRA), YI (YI FRG, YI FVG) and Y2 (Y2 FRG, Y2 FV1G) signals.

The vertical control panel is specific to CR-2 type interlockings and is provided with a series of buttons and levers for controlling the elements and with indicator lights for controlling them.

Figure 14. CR-2 vertical control panel

The status of isolated sections and guard lines is provided by three types of light indications:

- Trace off - the track section is clear and not included in a route;
- White trace - the track section is free and is included in an ordered route;
- Red trace - the section of track is occupied.

The switches are controlled by the corresponding levers positioned on the station diagram on the vertical console. Operating the switches involves positioning the lever in the desired direction and pressing the button inside the lever. Control of the correct handling of the crane is indicated on the console. If the position of the lever does not correspond to the position of the mast in the field, the mark in the mast section corresponding to the wrong position lights up flashing red.

The signal control buttons are positioned on the light tracks. They consist of an outer hexagonal button and an inner button. Pressing the inner button checks whether the route can be set from the signal. If all safety conditions are met, the route trace lights up white. To switch the signal to the permissive indication press the outer signal button. To cancel a set course is done by pulling the signal button on the console.

Control of the signals is achieved by illuminated indications of miniature signals on the front of the control desk. For the input signal there are three lights: green (permissive indications), red (stop indications) and white (call). The output signals are provided with a single green light which is lit for permissive indications and extinguished for stop indications. If the filament of the red signal lamp burns out, the green lamp shall flash.

Controlling a route via the vertical control panel involves several well-defined steps:

1. Positioning the cranks to the appropriate positions and operating the switches by pressing the buttons inside the cranks;
2. Pressing the inner signal button to check that safety conditions are met on the course ordered;
3. Pressing the outer signal button to light permissive fires after checking safety conditions.
4. The normal cancellation of an ordered run is by the train consuming it section by section. Track section occupancy is simulated by a series of switches on the right-hand side of the console.

For artificial unlocking there is an additional panel mounted separately in order to avoid accidental operation of the switches. Each section of track fitted with a latching relay is provided with an artificial defrost button. On the same panel, but grouped separately, are the emergency buttons for operating the station cranes.

The connection of all the elements of the centralisation installation is made by means of the controllers located at the bottom of the relay frame and at the bottom behind the control panel. Part of the strips on the relay frame are dedicated to the distribution of the different supply voltages used in the installation.

3.4 Central controller

3.4.1 General requirements

The selection of the central controller must take into account the use of existing power supplies, the provision of an adequate number of physical inputs for monitoring IDM commands, the ability to communicate with sensor nodes for relay array monitoring, and the availability of a programming environment. CED interlockings are powered by direct current from a 24 V battery with a median outlet [5]. It is desirable that any controller can be supplied with the same voltage to avoid the need for additional power supplies.

3.4.2 Portenta Machine Control

Portenta Machine Control (PMC) is an industrial controller produced by Arduino. It belongs to the Arduino PRO range of controllers and development boards for commercial IoT applications in industry, aviation, healthcare, agriculture, automotive and smart cities.

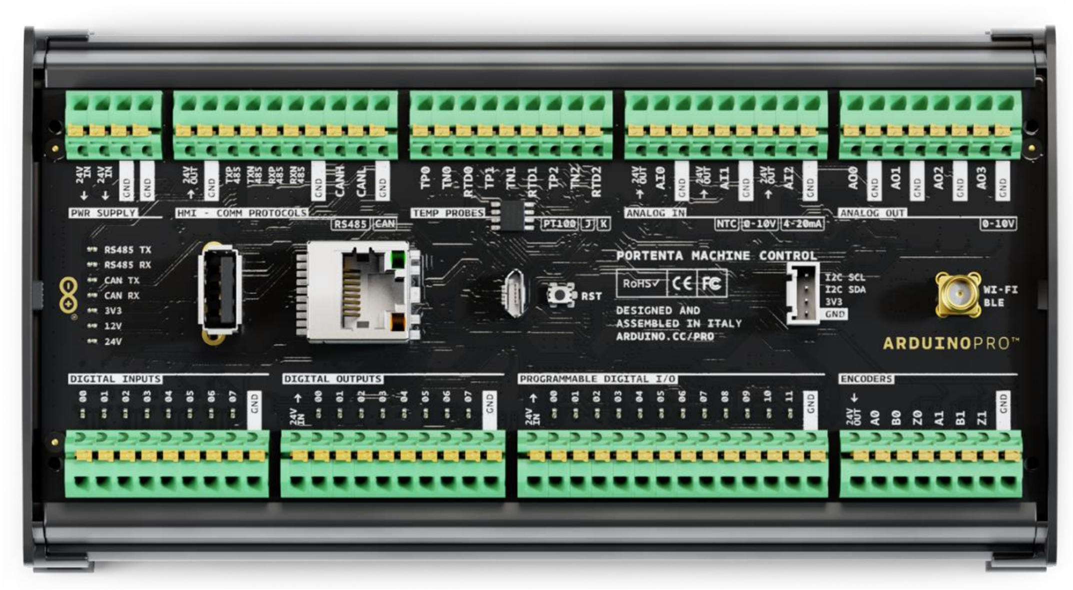


Figure 15. Portenta Machine Control [57]

PMC is an extension of the Arduino Portenta H7 board, extending its functionality for industrial applications [58]. The digital input channels use a resistive divider to convert 0-24 V voltages to 0-3 V. The output and programmable channels have separate power supply pins. It has a configurable 12- to 16-bit analog-to-digital converter, and can operate in 12 or 24 V CAN networks with transfer rates up to 5 Mb/s. Programming is done through the Arduino IDE using the *Arduino_PortentaMachineControl.h* library [59] or Arduino PLC IDE.

3.5 Sensor node core

3.5.1 General requirements

Each sensor node must coordinate relay monitoring and data transmission, be able to be interfaced with sensors and allow the definition of a WSN. Compact size and low power consumption are crucial for easy placement and device autonomy.

3.5.2 Sparkfun ESP8266 Thing Dev Board

The ESP8266 Thing Dev board produced by Sparkfun is one of the most widely used solutions in IoT application development [60].

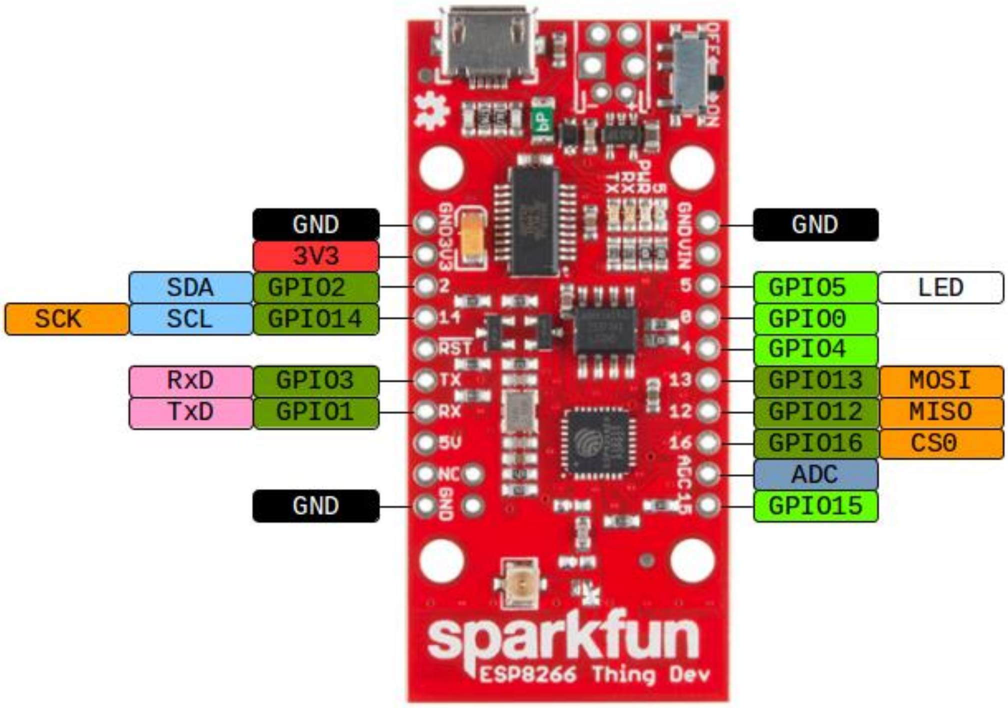


Figure 16. ESP8266 Thing Dev Board [61]

The development board can be powered by micro USB (5 V) or external connector (3.7-6 V, usually LiPo batteries). I2C communications use digital pins 2 (SDA) and 14 (SCL), and for serial communications, pins Rx and Tx. The SPI bus uses digital pins 12 (MISO), 13 (MOSI), 14 (SCK) and 16 (CS).[62]. The board includes a built-in antenna and a U.FL connector for external antennas.[63]. Programming via Arduino IDE requires manually added configuration files.

3.6 Magnetometer

3.6.1 Principles of operation

Magnetic sensors, used to measure changes in magnetic fields, are often integrated into magnetometers, such as compasses. The most common types are based on the Hall effect and magnetoresistive materials [64]. Hall sensors use a thin semiconductor wafer, generating a voltage (V_H) proportional to the magnetic induction (B) and the current flowing through the semiconductor (I).

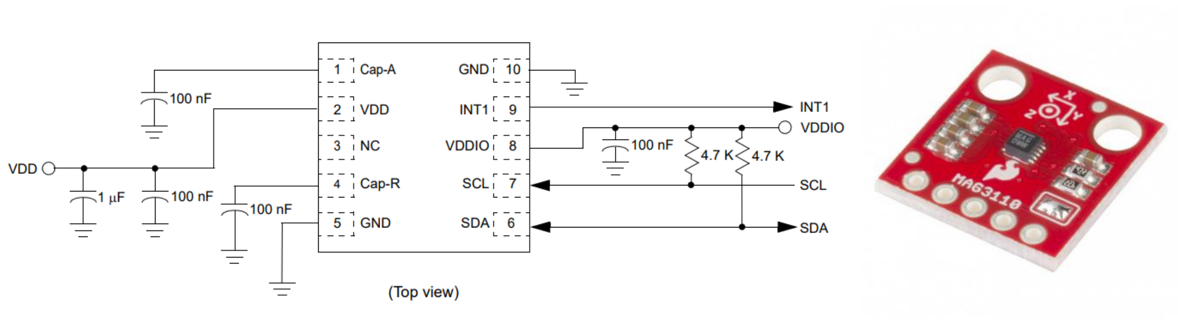
$$V_H = R_H \left(\frac{IB}{d}\right) \quad (1)$$

Due to low Hall voltage values, additional circuits are required for amplification [65]. Hall sensors can be linear analogue, providing voltages proportional to the magnetic field, or digital, switching between states when a threshold is exceeded. Magnetoresistive sensors change their resistance according to the strength and angle of the magnetic field [64].

3.6.2 Equipment used - MAG3110

Freescale's MAG3110 is a compact three-axis digital Hall magnetometer. It can be used in applications such as digital compasses, where it complements a three-axis accelerometer. The device communicates via I2C serial interface[66]. The maximum magnetic field reading frequency of this sensor is 80 Hz.

The system was tested and evaluated with the MAG3110 module provided by Sparkfun [67]. It is designed and built (Figure 17.) as specified by the manufacturer in the component's catalogue sheet[66].



a) b)

Figure 17. Schematic (a) and layout (b) of the MAG3110 module[66][67]

3.7 Arduino IDE platform

Arduino IDE is a software platform developed by Arduino to facilitate the development of microcontroller applications. Used by both hobbyists and industry, the platform uses a C/C++-derived language adapted for interaction with microcontroller pins [68]. The programs created, called sketches, have the .ino extension and consist of the setup() and loop() functions. The Arduino IDE has a simple graphical user interface and allows programming of various devices via USB. Features include downloading configuration files and libraries, as well as real-time monitoring of applications via the serial monitor and graphical serial monitor.

3.8 Arduino PLC IDE platform

The Arduino PLC IDE development environment can be used to program Arduino PLC devices. The current version (1.0.3.0) allows the development of applications for the PMC and the Arduino OPTA series of devices (Lite, RS485, WiFi).

Arduino PLC IDE has a more complex structure than Arduion IDE and is dedicated to the development of industrial applications. The interface (Figure 18.) is structured into several windows and toolbars.

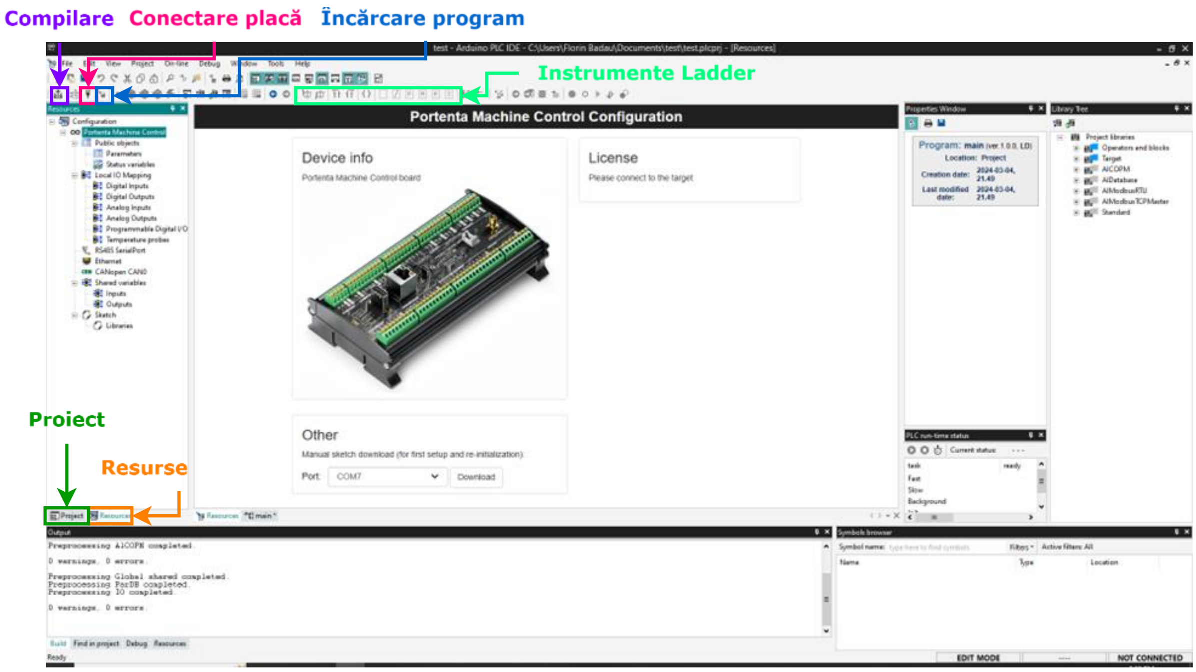


Figure 18. Arduino PLC IDE interface

The main workspace is on the left of the interface and is structured in two tabs: Resources and Project. The Resources tab includes functions for the PMC, such as managing public objects for the Modbus protocol, associating physical inputs and outputs with software variables, configuring the RS485 serial communication interface, configuring Ethernet for Modbus TCP and configuring the CAN bus. It also allows management of shared variables between Arduino and PLC languages.

The Project tab is for the programs that make up the application, including the main program, sub-programs, global variables, and specifying the execution period of each program. Device programming is done via USB, software connection is initialized via the Connect to target button, and application loading is done via Download PLC Code after compilation. For Ladder programs, there is a dedicated toolbar for inserting and configuring contacts and coils, facilitating application development.

A special feature of the Arduino PLC IDE is the ability to develop applications using both standard PLC languages and the classic Arduino language. The two programming modes are used for different functions. The main application logic is implemented using the IEC 61131-3 standard languages, while the Arduino language can be used to configure and implement communication functions between the PLC and the external environment (WiFi, BLE, I2C, etc.).

In the development of the application it is possible to define shared variables (*Shared varaibles*) for input or output that can be used by both the PLC program and the Arduino sketch. In this way the two levels of the application can exchange information with each other (Figure 19.).

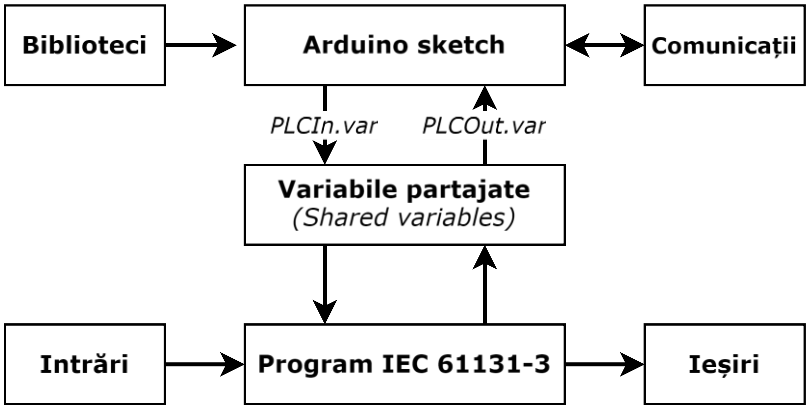


Figure 19. Structure of an application developed with Arduino PLC IDE

Shared variables can be included in PLC programs like local variables, they appear in a separate category in the *Project* tab (*SharedVars*). In the Arduino sketch the PLCIn.variable_name and PLCOut.variable_name commands are used to write and read shared variables respectively [69].

The Arduino language programming level allows the use of external libraries to implement specific functions. In addition to the normal declaration at the beginning of the program, these libraries must be specified in the *Libraries* table in the *Resources* tab. In addition to the library name, the library version must be specified. Only libraries publicly listed on arduinolibraries.info can be called [70].

3.9 Development of the centralisation programme

3.9.1 Previous experiences

In the dissertation[23] we have succeeded in developing a simulator that reproduces with a very high degree of accuracy the operation of a CR-3 type centralization plant. The development involved the following steps:

1. Drawing up of the layouts for the centralisation plant;
2. Definition of logic functions for each relay;
3. Implement logic functions in the development environment;
4. System testing

While the first stage did not present any major difficulties due to the existence of guidelines and standards for the design of relay centralisation installations, subsequent stages presented specific challenges.

Defining the logic functions associated with each relay in the installation presented difficulties in complex schemes, especially P-schemes with a two-wire structure. The number of terms required to define the logic functions was in the order of dozens for relays with advanced functions.

The implementation of the functions and the development of the centralization program were carried out in LabVIEW. The graphical programming language allowed the faithful reproduction of the operation of a real installation. The implementation difficulties came from the large differences in representation between the centralization schemes and the graphical logic of LabVIEW.

A number of relevant conclusions were drawn from the experience of developing this simulator. First of all, it has been demonstrated that it is possible to develop an electronic centralisation system respecting the structure and logic of CR relay installations.

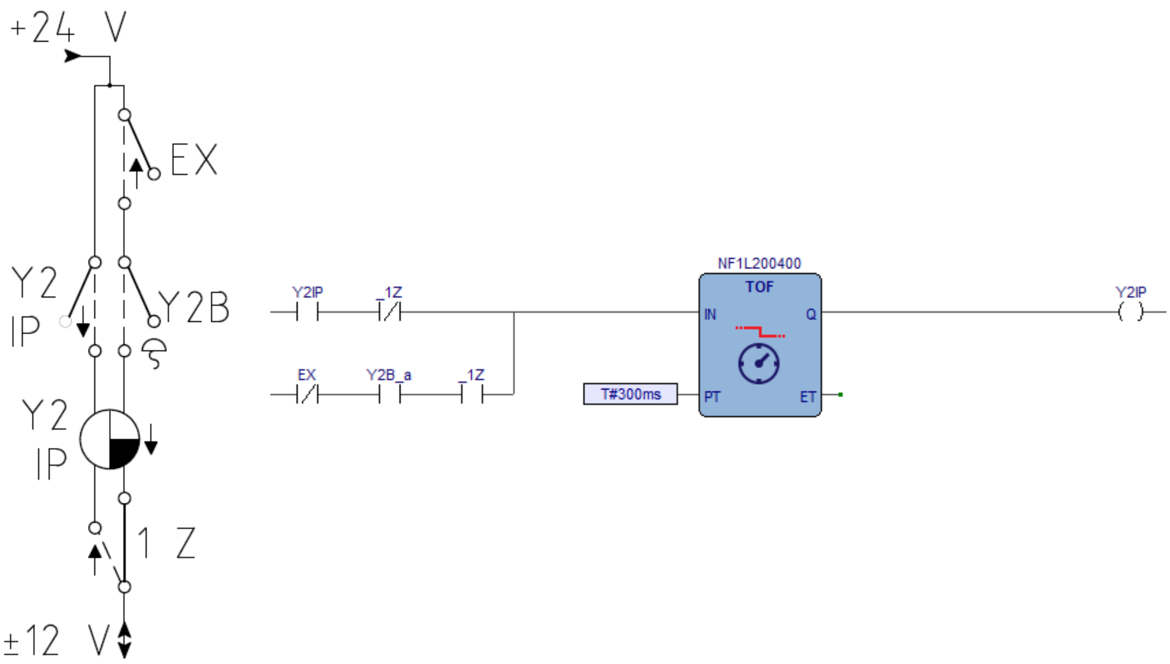
The limitations of the development environment became apparent especially in the later stages of development through the very high number of variables and connections. The impossibility of realizing several sub-programs involved the full development of the centralization logic in a single block diagram. This made it difficult to modify the centralisation software on a one-off basis despite organising the areas associated with the relay schemes.

3.9.2 Establishing development principles

The similarities between relay schemes and the Ladder language for PLCs make it much easier to translate relay logic into software logic. Before the actual development, a number of "translation" rules had to be established.

Repeating schemes (IP, EF, Z, DA) can be translated into Ladder language while keeping largely the same structures and links.

IP relays are used to store the command of a path from a given signal. Each signal, regardless of its type, has such a relay associated with it. They are normally down and are attracted when a path is commanded from that signal. The relays return when the section behind the signal is cleared. In the case of station A there are a total of six IP relays. In Figure 20. is illustrated the similarity between the rail relay scheme and the Ladder program.



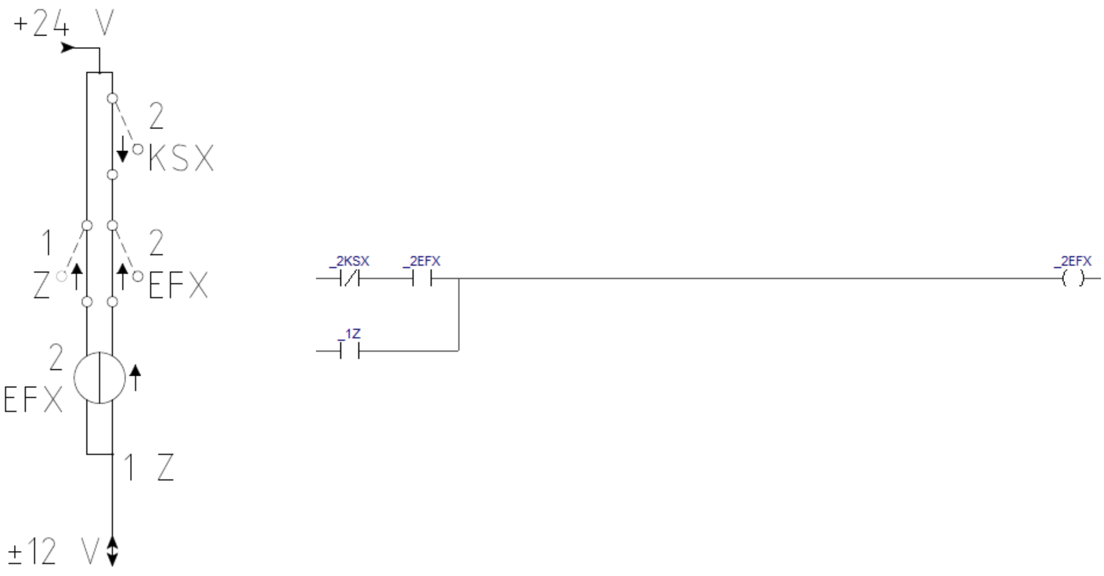
a) b)

Figure 20. Y2 IP - schematic with relays (a) and Ladder (b)

The delay of about 300 ms corresponding to the NF1L-200/400 relays, which are used for the IP relays, is introduced into the Ladder language by means of a time-to-off (TOF) block. This is the only notable adaptation change of the relay schemes for the Ladder language, the Y2 IP variable (relay) still works according to the logic function below.

$$Y2\ IP = (\overline{EX} \cdot Y2\ B \cdot 1\ Z) + (Y2\ IP \cdot \overline{1\ Z}) \tag{2}$$

EF (front exclusion) relays are used in the exclusion of incompatible paths, each station end being allocated one such relay per station end. Their default state is drawn and is changed when an incoming path to that line is established. The adaptation of these relays in Ladder language does not present any adaptations or introduction of additional elements.



a) b)

Figure 21. 2 EFX - scheme with relays (a) and Ladder (b)

Z-brakes (latches) are used to brace sections and switches in the station when setting a route, holding in a drawn state and dropping when the route is activated. They return to the pulled state after the train has released the sections. DA (artificial route release) relays are intended to release snow from sections in the event of complete snowing, and are normally dropped and pulled only at the command of the IDM. They return to the fallen state when the de-icing process is complete. The Z and DA relays operate complementarily and are located in the same circuit, each section having a pair of Z - DA relays.

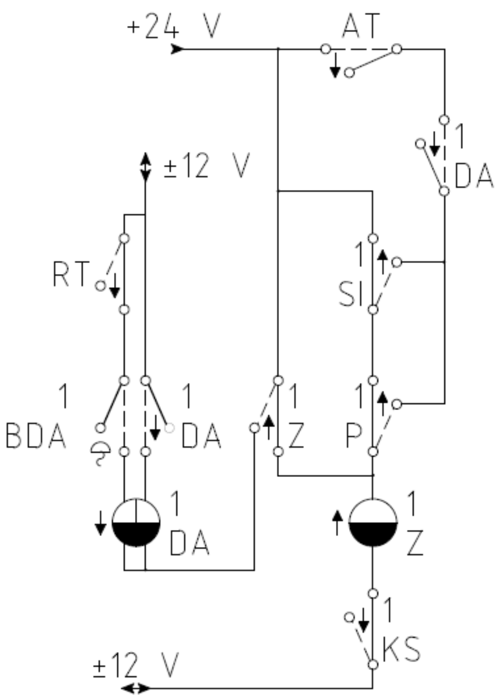


Figure 22. 1 Z and 1 DA - relay schematic

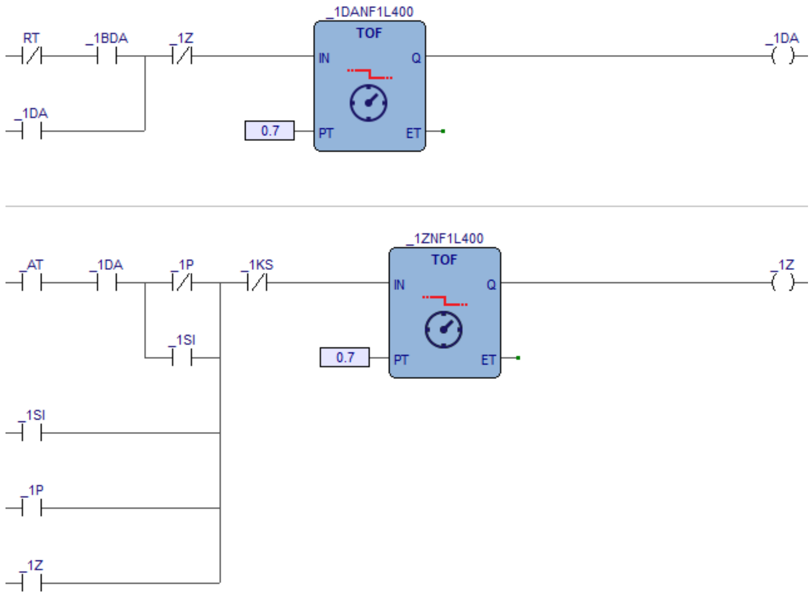


Figure 23. 1 Z and 1 DA - Ladder

The Z relay logic function in Figure 22 was simplified using the distributivity property and the complement theorem from Boolean algebra, resulting in a simpler expression for 1 Z in Ladder language (Figure 23). The logic function of the DA relay (10) does not require simplification. Both Z and DA relays use NF1L-400 relays, which have a drop-out delay of about 700 ms, and use a stop delay block.

The thermal group is used in centralised relay installations in artificial route cancelling operations. In Figure 24. the four relays that are part of the thermal group can be seen: T (thermal), RT (thermal repeater), RDA (artificial defrost repeater) and AT (thermal helper).

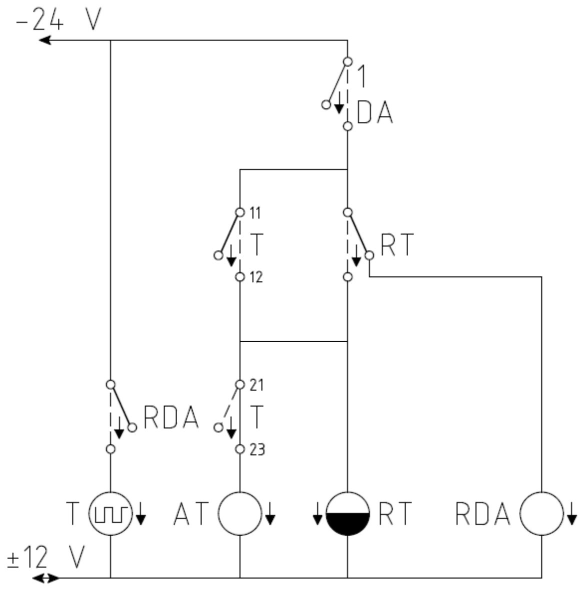


Figure 24. Thermal group schematic

The normal state of all relays in the thermal group is fallen, they change their state during the execution of artificial defrosting. The RT relay is of type NF1L-400, which gives it a fall time of 700 ms, while the AT and RDA relays are of type NF1-800.

The T relay is a TL-2 type relay which has a different construction and mode of operation than the NF or plug code relays. The make contact (11-12) closes approximately 90 seconds after the relay is energised, while the break contact (21-23) closes after the same time after the loss of power. This timing is implemented by manufacturing the contacts from materials with a different coefficient of temperature expansion [1].

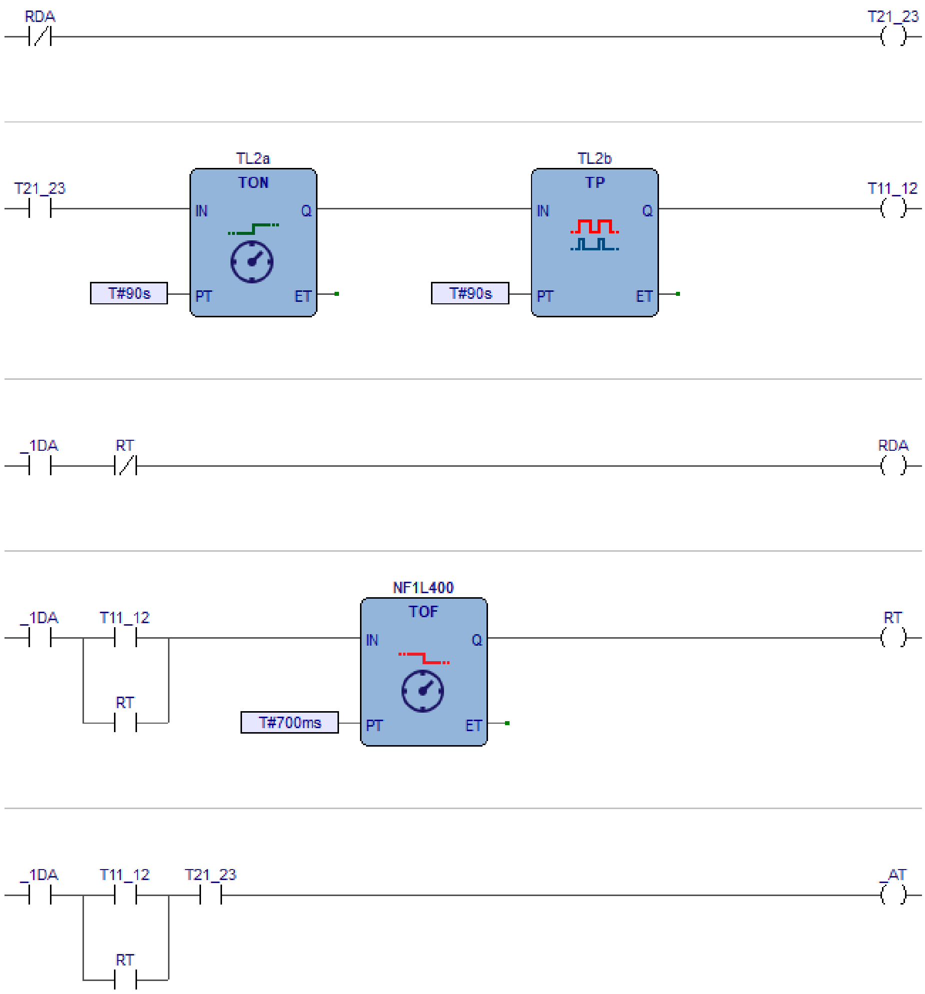


Figure 25. Implementation of the thermal group in Ladder

Geographic centralization schemes (KSC, KS, P, S) are more complex in structure than standard schemes, which presents a challenge for Ladder Logic implementation. Geographic schemes are composed of typed scheme elements (input signals, output signals, isolated sections, path sections, etc.). From an electrical point of view the branches of geographic schemes can be classified into:

- Guard branches:

  - Entrance sub-branches
  - Output sub-branches
- External branches
  - Entrance sub-branches
  - Output sub-branches
- Common branches

Although it is possible to define functions in the same way as they have been defined for previous schemes, this approach has a disadvantage by repeating common scheme structures. From Figure 26. It can be seen how the pull-in circuits of relays 1 KS and IB KS have a lot in common with the pull-in circuits of the other relays.

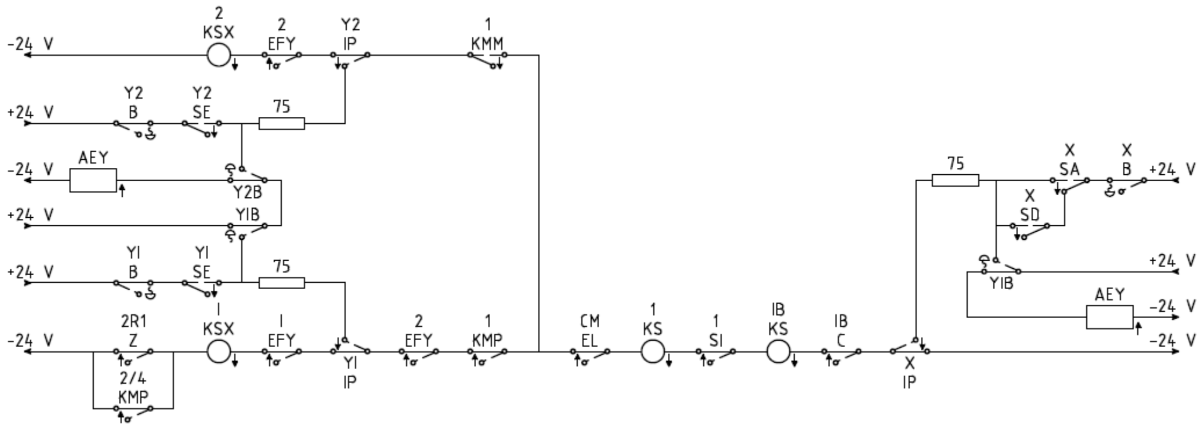


Figure 26. KS schematic of station A (end X)

The sharing of circuit elements is also reflected by the logic functions associated with the relays in the schematic. In formulae (3-5) a distinction has been made between the press (A) and pull (T) positions of the signal buttons.

$$2\ KSX = 2\ EFY \cdot \overline{Y2\ IP} \cdot 1\ KMM \cdot CM\ EL \cdot 1\ SI \cdot IB\ C \cdot X\ IP \cdot \left(XB_A + \left(\left((X\ SD \cdot \overline{X\ SA}) + X\ SA \right) \cdot \overline{XB_T} \right) \right) \quad (3)$$

$$I\ KSX = (2R1\ Z + 2/4\ KMP) \cdot I\ EFY \cdot \overline{YI\ IP} \cdot 2\ EFY \cdot 1\ KMP \cdot CM\ EL \cdot 1\ SI \cdot IB\ C \cdot X\ IP \cdot \left(XB_A + \left(\left((X\ SD \cdot \overline{X\ SA}) + X\ SA \right) \cdot \overline{XB_T} \right) \right) \quad (4)$$

$$\begin{aligned} 1\,KS = IB\,KS = \Bigg(\bigg(&(2\,EFY \cdot \overline{Y2\,IP}) \\ &+ \Big(Y2\,IP \cdot \big((\overline{YIB_A} \cdot Y2IB_A) + (\overline{Y2\,B_T} \cdot Y2\,SE)\big)\Big) \cdot 1\,KMM\bigg) \\ &+ \big((2R1\,Z + 2/4\,KMP) \cdot I\,EFY \cdot \overline{YI\,IP}\big) \\ &+ \bigg(\Big(\big(YIB_A + (\overline{YI\,B_T} \cdot YI\,SE)\big) \cdot YI\,IP\Big) \cdot 2\,EFY \cdot 1\,KMP\bigg) \cdot CM\,EL \\ &\cdot 1\,SI \cdot IB\,C \\ &\cdot \Bigg(\overline{X\,IP} + \bigg(X\,IP \cdot \Big(XB_A + \Big(\big((X\,SD \cdot \overline{X\,SA}) + X\,SA\big) \cdot \overline{XB_T}\Big)\Big)\bigg)\Bigg)\Bigg) \end{aligned} \tag{5}$$

Directly implementing these functions in Ladder would generate program steps with many variables. In the case of centralisation programs for medium and large stations, the complexity of these functions is increased by adding additional variables, which would make it even more difficult to translate them into Ladder.

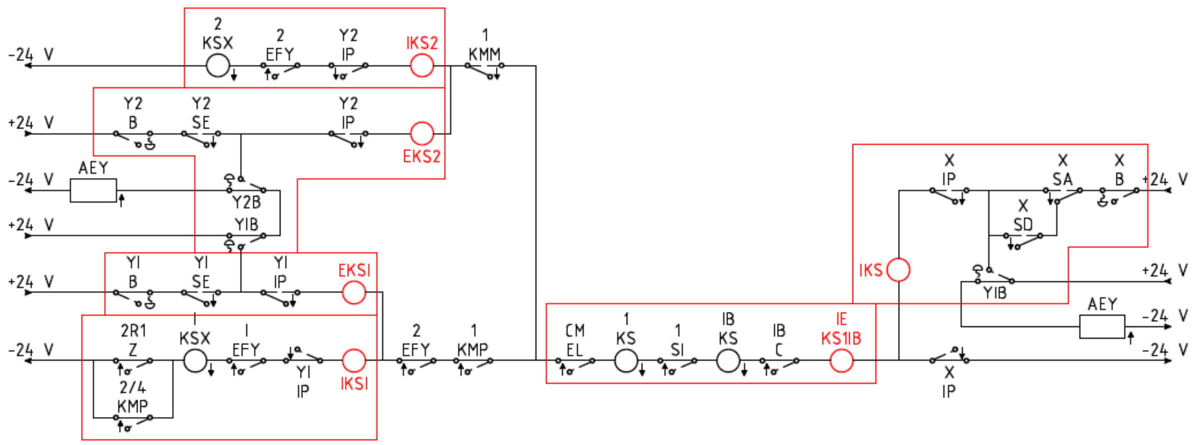


Figure 27. Introduction of totalising variables (relays) per branch

For common schematic segments, and by function extension, branch totalizer variables (Figure 27.). These indicate the fulfilment of the conditions on that branch and can in turn be used to define the main variables.

The variable names were determined taking into account the related sub-branches (I - input, E - output, IE - common) and the elements considered as defining them (guard lines, common sections, input signals). In the case of the KS scheme exemplified above, six summing variables were defined (6-8).

$$IKS2 = 2\,EFY \cdot \overline{Y2\,IP} \tag{6}$$

$$EKS2 = Y2\,IP \cdot \big((\overline{YIB_A} \cdot Y2IB_A) + (\overline{Y2\,B_T} \cdot Y2\,SE)\big) \tag{7}$$

$$IKSI = (2R1\,Z + 2/4\,KMP) \cdot I\,EFY \cdot \overline{YI\,IP} \tag{8}$$

$$EKSI = \left(YIB_A + (\overline{YI\ B_T} \cdot YI\ SE)\right) \cdot YI\ IP \tag{9}$$

$$IEKS1IB = CM\ EL \cdot 1\ SI \cdot IB\ C \tag{10}$$

$$IKS = X\ IP \cdot \left(XB_A + \left(\left((X\ SD \cdot \overline{X\ SA}) + X\ SA\right) \cdot \overline{XB_T}\right)\right) \tag{11}$$

By first defining the totalizing variables, it is possible to simplify the functions of the main relays (12-14).

$$2\ KSX = IKS2 \cdot 1\ KMM \cdot IEKS1IB \cdot IKS \tag{12}$$

$$I\ KSX = IKSI \cdot 2\ EFY \cdot 1\ KMP \cdot IEKS1IB \cdot IKS \tag{13}$$

$$\begin{aligned} 1\ KS = IB\ KS = &\left(\left((IKS2 + EKS2) \cdot 1\ KMM\right)\right. \\ &\left. + \left((IKSI + EKSI) \cdot 2\ EFY \cdot 1\ KMP\right)\right) \cdot IEKS1IB \cdot (\overline{X\ IP} + IKS) \end{aligned} \tag{14}$$

In the case of station A the traditional definition of the logic functions according to the wiring diagrams assumes a dependence of the four KS relays on 83 variables. By using totalizer variables six new variables are introduced with a dependency of 24 variables, while the KS relay functions can be equated considering 29 variables. By using this technique a 37% reduction in variable requirements is achieved. In the case of schemes associated with medium and large stations, the number of variables needed to monitor is halved.

Often in relay centralisation installations the number of contacts required in the schemes exceeds the number of contacts available on a single relay. In these cases repeater relays are used which replicate the state of the main relay, increasing the number of contacts available. Software variables are not limited in terms of number of uses. In the case of the IKSI variable defined above (8), the Ladder language implementation directly used the variable 2Z.

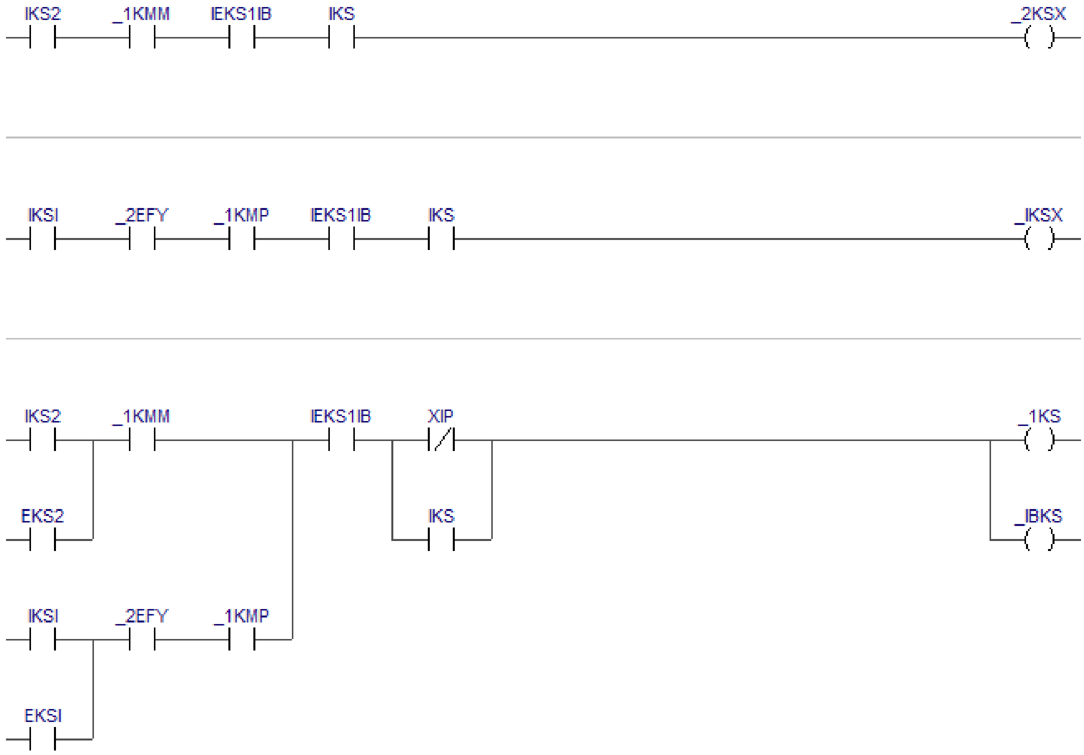


Figure 28. KS schematic in Ladder

The main role of the KS schematic is to verify the safety conditions necessary to perform the ordered route. These include the correct positioning of the cranes, the free condition of the sections of the run and the exclusion of incompatible runs. Information from the KS scheme is taken over by the S scheme, which checks the snowiness of the sections of track, the status of the signal lamps and controls the signals in the field.

The relays belonging to the S-schematic have, like the KS relays, common circuit parts which can be represented by defining summation variables. Thus, the four main relays have been defined according to them.

In this case, we can define summation variables (Figure 29.) for the input signal (SIX) and for sections 1SI and IB (SIE1IB). The expressions of these variables are described below (31-32), as well as the functions of the S relays considering the summing variables (33-36).

$$SIX = (XB \cdot XFRA) + \left(XFV1G \cdot \left((X\,SA \cdot XF2G) + X\,SD\right)\right) \quad (15)$$

$$SIE1IB = IB\,KS \cdot IB\,DA \cdot IB\,Z \cdot 1\,KS \cdot 1\,DA \cdot 1\,KS \quad (16)$$

$$X\,SD = SIX \cdot 1KMP \cdot X\,IP \cdot SIE1IB \cdot \left((1\,KM \cdot \overline{YI\,IP} \cdot \overline{I\,EFX} \cdot I\,KSX \cdot IC) + (\overline{1\,KM} \cdot \overline{Y2\,IP} \cdot \overline{2\,EFX} \cdot 2\,KSX \cdot 2C)\right) \quad (17)$$

$$X\ SA = SIX \cdot \overline{1KMP} \cdot X\ IP \cdot SIE1IB \cdot \left((1\ KM \cdot \overline{YI\ IP} \cdot \overline{I\ EFX} \cdot I\ KSX \cdot IC) + (\overline{1\ KM} \cdot \overline{Y2\ IP} \cdot \overline{2\ EFX} \cdot 2\ KSX \cdot 2C)\right) \quad (18)$$

$$YI\ SE = (YI\ SE + YIB) \cdot YI\ IP \cdot 1\ KM \cdot \overline{X\ IP} \cdot SIE1IB \cdot IAC \cdot ISX \quad (19)$$

$$Y2\ SE = (Y2\ SE + Y2B) \cdot Y2\ IP \cdot \overline{1\ KM} \cdot \overline{X\ IP} \cdot SIE1IB \cdot IAC \cdot ISX \quad (20)$$

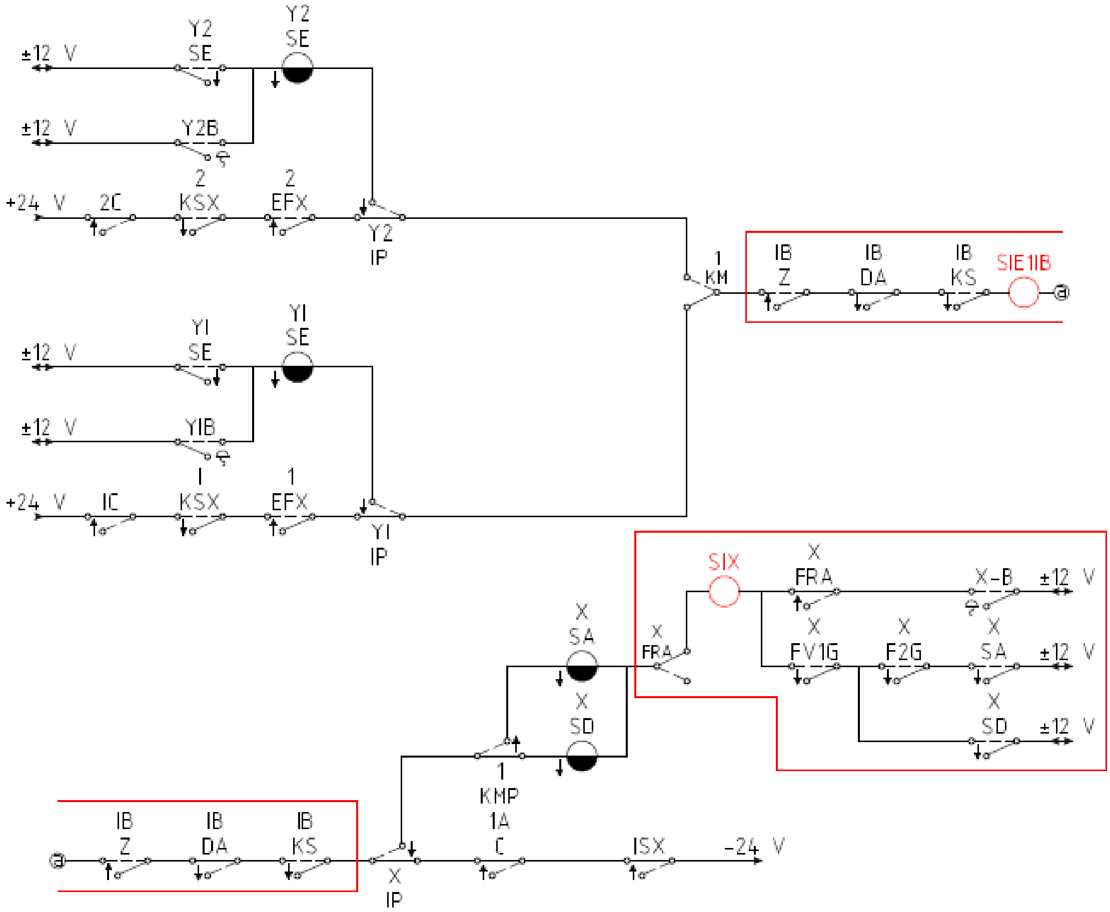


Figure 29. Location of the summation variables in the S schematic

The most complex scheme of a CR type interlocking is the P schematic. The main role of the relays in this scheme is to permanently energise the track sections as well as to de-energise sequentially (section by section) as the paths are consumed. To implement these functions, the circuit of each P relay (corresponding to a single section) has several supply branches. The ZAIX relay is useful in the case of snowfall for station crossings.

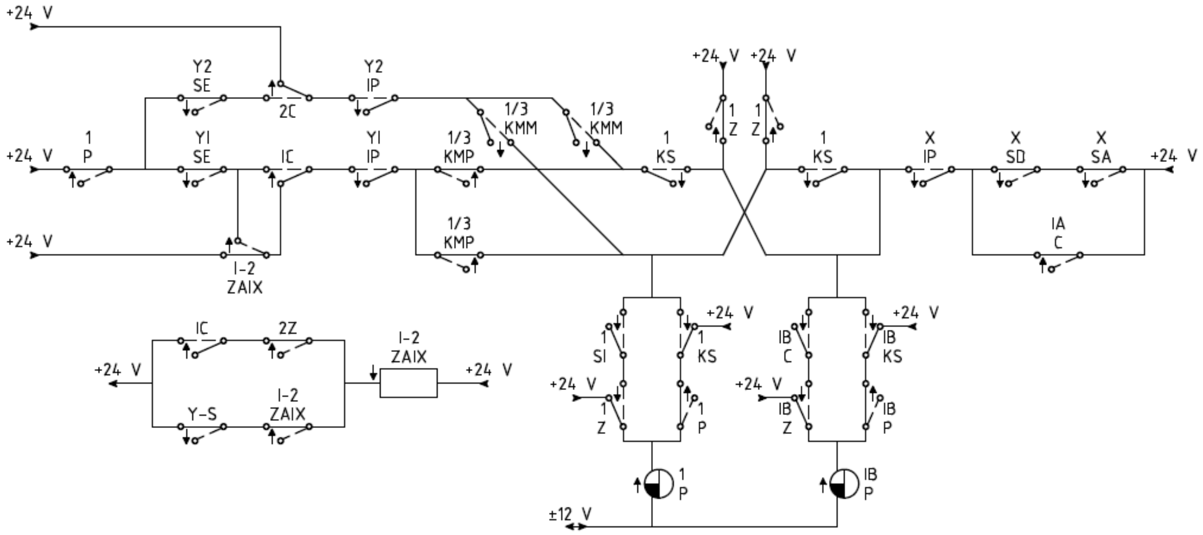


Figure 30. P schematic of station A (end X)

For station A two totaliser variables can be defined: PX for incoming paths and PI2 for outgoing or incoming paths. The logical functions of the variables are given below (40-43) as well as the reduced functions of the main variables (44-45).

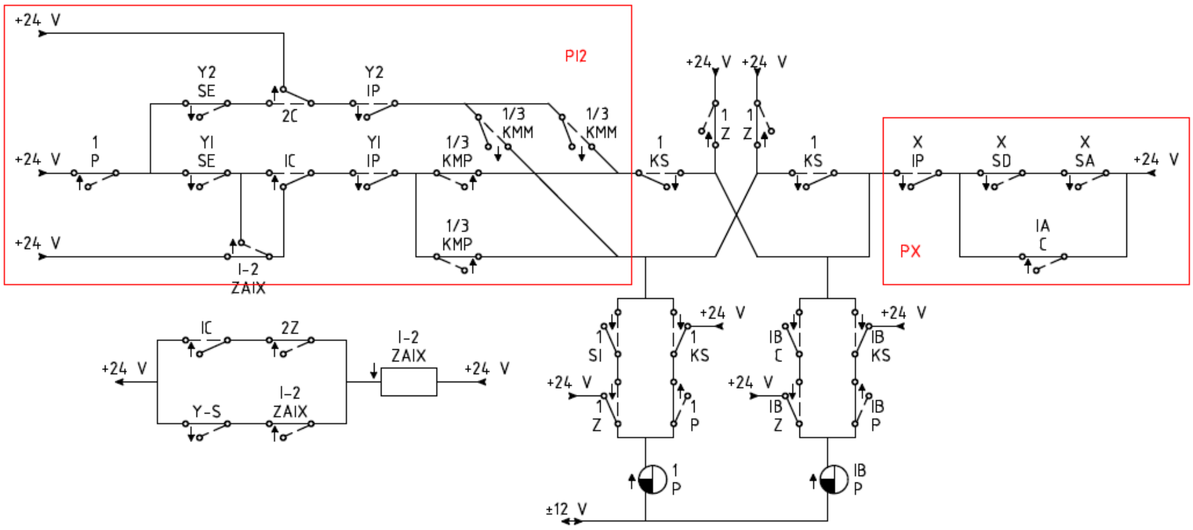


Figure 31. Placement of totalising variables in the P schematic

$$PI2 = \left(1\,KMM \cdot Y2\,IP \cdot \left(2C + \left(\overline{2C} \cdot \overline{Y2\,SE} \cdot 1\,P\right)\right)\right) + \left(1\,KMP \cdot YI\,IP \cdot \left(\left(\left(\left(IC \cdot \overline{ZAIX}\right) + \overline{IC}\right) \cdot \overline{YI\,SE} \cdot 1\,P\right) + \left(IC \cdot ZAIX\right)\right)\right) \quad (21)$$

$$PX = X\,IP \cdot \left(IAC + \left(\overline{X\,SD} \cdot \overline{X\,SA}\right)\right) \quad (22)$$

$$1\,P = 1\,Z + (\overline{1\,P} \cdot \overline{1\,KS}) + \left(\left((\overline{1\,Z} \cdot \overline{1\,SI}) + (\overline{1\,P} \cdot \overline{1\,KS})\right) \cdot (IB\,Z + (IB\,KS \cdot PX) + PI2)\right) \quad (23)$$

$$IB\,P = IB\,Z + (\overline{IB\,P} \cdot \overline{IB\,KS}) + \left(\left((\overline{IB\,Z} \cdot \overline{IB\,C}) + (\overline{IB\,P} \cdot \overline{IB\,KS})\right) \cdot \left(PX + 1\,Z + (1\,KS \cdot PI2)\right)\right) \quad (24)$$

For compliance with the layers of information processing, each of the schemes detailed above are defined as independent programs within the same Ladder project. The overall project structure for Station A is shown in Figure 32.

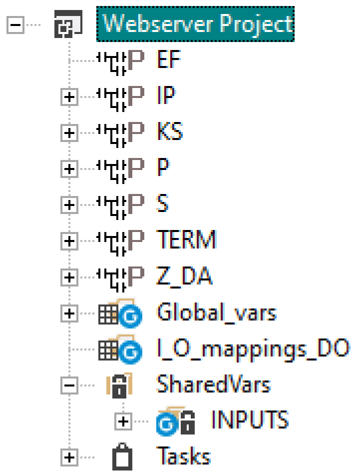


Figure 32. General structure of the Ladder project

The main program variables are those corresponding to relays in traditional CR schemes. Since they are involved in several schemes (Ladder programs) simultaneously, they are defined as global variables. In this way they can be accessed by all project programs.

Totalising variables, introduced to simplify the simulation of schemes, are only useful within the scheme. For this reason they are declared as local variables, which can only be used by the program inside which they are defined.

The programs presented so far, with the exception of the thermal group, correspond to the schemes at the X end of station A. In the Ladder programs, however, there are also variables associated with the other end of the station. In the case of these, the default values of true or false have been defined based on the schemes in which they are found.

3.9.3 Communication settings

As mentioned in subchapter 3.8, the communication functions of the PMC device are implemented using the classic Arduino development language. In the case of the proposed system, the PMC serves as the coordinating node of a WSN.

The configuration of the PMC as a central node was achieved by setting it as a WiFi access point using the WiFi.h library and defining the initial parameters. The access point is created at initialisation and remains active permanently. If it fails, the PMC sends a message on the serial interface. Sensor nodes connect to this access point using the ESP8266WiFi.h library, with connection data declared as constant pointers. Communication between the nodes and the coordinating node is via the UDP protocol, using the WiFi.h library for the PMC and WiFiUdp.h for the sensor nodes. Messages include the node ID and magnetic induction on the Z-axis, formatted as "ID:induction_z". Messages are composed and transmitted by sensor nodes to the coordinator's IP address, 192.168.3.1, and decomposed using the ":" symbol as a delimiter.

```
int packetSize=Udp.parsePacket();//detect message size
if (packetSize) {
  int len = Udp.read(buf, 255);//save message
  if (len > 0) {
    buf[len] = 0;
    }
  //Message decomposition with value saving
  String data=buf;
  IDnod = data.substring(0, data.indexOf(':')).toInt();
  ind_z = data.substring(data.indexOf(':') + 1).toFloat();

  sens_read(nodeID,fx);
}
```

The last function in the previous sequence is used to interpret the data received from the sensor nodes and modify the Ladder program variables accordingly. For the performance evaluation of the system described in subchapter 4.2 function has been implemented for four sensor nodes.

Chapter 4. Data testing and validation

4.1 Monitoring of railway relays by magnetometers

4.1.1 Theoretical considerations

The construction and operation of general purpose relays as well as those used in railway applications have been detailed in the first part of the paper. In the case of all types of relays the essential element for its operation is the coil. Coils, together with resistors and capacitors, make up the group of passive components that are essential to all electronic applications.

In order to use magnetometers to monitor railway relays, it was necessary to first model the behaviour of the magnetic fields generated by the relay coils, followed by laboratory measurements to assess actual operating conditions.

The characteristic parameter of a coil is the inductance. This is the electrical property of a component to resist the change of direction of electric current through it. For a typical coil the inductance has the following form[65]:

$$L = N\frac{\Phi}{I}\ [H] \tag{25}$$

where N is the number of turns of the coil, Φ the magnetic flux generated by the coil and I the current flowing through the coil.

Like many fields in physics, the magnetic field is a vector field. Any point within it is characterised by a magnitude and direction by the vector B, also called magnetic induction. Magnetic fields can easily be studied by looking at their shapes and the changes produced within them by different elements (coils, magnets, metal objects, etc.). The B vector is used to represent these magnetic field lines, the unit used for magnetic induction being Tesla[71]. For a surface of area A, the magnetic induction is defined as:

$$B = \frac{\Phi}{A\cos\theta}\ [T] \tag{26}$$

where θ is the angle formed by the magnetic flux Φ and the perpendicular to surface A at the point of calculation.

The magnetic inductance is closely related to the magnetic field strength (H) by the relation:

$$B = \mu_0\mu_r H\ [T] \tag{27}$$

where $\mu_0$represents the magnetic permeability of the vacuum and μ_r the relative magnetic permeability of the medium.

For a solenoid (coil without ferromagnetic core) of finite ℓ length consisting of N turns of diameter d, the magnetic field strength at its centre can be expressed as [72]:

$$H = \frac{NI}{\sqrt{\ell^2 + d^2}} \overset{d \ll \ell}{\Longrightarrow} \frac{NI}{\ell} \;\; [A/m] \tag{28}$$

In the case of a solenoid the magnetic induction will exhibit components exclusively along the axis running lengthwise through the middle of the solenoid. If this axis is called Ox, the magnetic induction along it follows the rule [71]:

$$B_x = \frac{\mu_0 N I r^2}{2(x^2 + r^2)^{3/2}} \;\; [T] \tag{29}$$

where x is the position along the Ox axis, originating at the centre of the solenoid, and r is the radius of a loop.

In the case of multilayer coils the induction along the Ox axis depends on both the internal (r_i) and the external (r_e) radius [73]:

$$B_x = \frac{\mu_0 N I}{2\ell(r_e - r_i)} \left(A \, ln \frac{r_e + \sqrt{r_e^2 + A^2}}{r_i + \sqrt{r_i^2 + A^2}} + B \, ln \frac{r_e + \sqrt{r_e^2 + B^2}}{r_i + \sqrt{r_i^2 + B^2}} \right) \;\; [T] \tag{30}$$

where:

$$A = \frac{L}{2} - x \tag{31}$$

$$B = \frac{L}{2} + x \tag{32}$$

4.1.2 Modelling railway relays

Magnetic modelling of railway relays was carried out using Python and the Magpylib package, which allows the modelling of complex magnetic systems by defining magnets, current conductors and various sources. Magnets can have various shapes such as rectangular parallelepiped, cylinder, cylinder segment, sphere, tetrahedron and triangular mesh. Current conductors include loops and lines of multiple segments, and miscellaneous sources include dipoles, triangles of uniform charge density and custom sources. Sensors measure the magnetic field at specific positions. Until version 4, Magpylib did not fully use standard SI units, which could lead to errors. Version 5 has fixed this by fully complying with the SI standard. Modelling the magnetic field of railway relay coils requires the definition of the components of the magnetic system, with typical dimensions given for NC coils used in relay switchgear, having a 1.6 cm diameter silicon steel core.

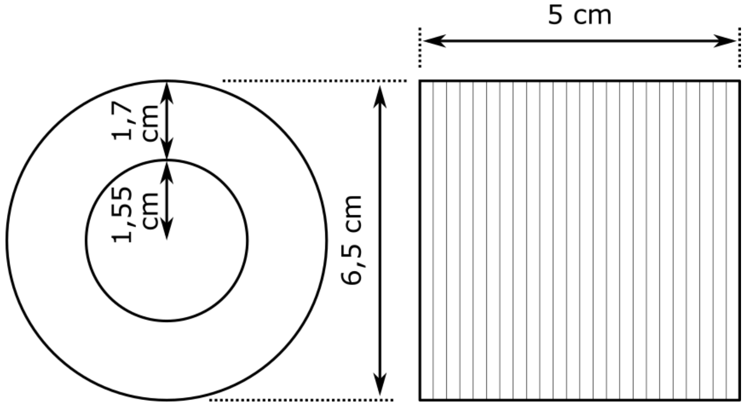


Figure 33. Coil sizes used in two-coil NC relays [74]

Some of the relay parameters (conductor diameter, number of turns, coil resistance) were taken from existing standards[1]. The current was calculated based on the resistance of the coils, the preferred coil connection configuration and normal supply voltages (12 V).

For the most realistic modelling it is necessary to determine the exact number of layers (S_L) and turns per layer (N_S) needed to make the coils. These can be approximated by taking into account the dimensions of the winding housing(ℓ_C- length, a_C- depth) and the diameter of the conductor used for the coils with all its insulation (d_C).

$$S_L = \frac{a_C}{d_C} \; [layers] \tag{33}$$

$$N_S = \frac{\ell_C}{d_C} \; [turns/layer] \tag{34}$$

In the case of NC relay coils the values ℓ_C= 4.6 cm and a_C= 1.3 cm can be considered. These differ slightly from the values shown inFigure 33. by subtracting 4 mm from the edges of the winding housing. For NF1-800 relay coils the conductor used has a total diameter of approximately 0.25 mm.[65], the two parameters having values of $S_L \cong 50$ and$\ell_C \cong 180$.

The code sequence below shows how to define a coil (L13) of NF-800 relay considering known parameters.

```
#Magpylib collection definition with label "coil13"
coil13 = magpy.Collection(style_label="coil13")
#Loop for defining coil layers (50)
for n in np.linspace(1,50,50):
    #Loop for defining single layer coils (180)
    for z in np.linspace(0, 46, 180):
        #Individual definition of each loop by adding to the collection
```

```
        coil13.add(magpy.current.Circle(current=0.015,     diameter=61-
n*0.25, position=(0, 0, z)))
    #Collection positioning
    coil13.position = (0, 0, 0)
    #Rotation of the collection relative to the y-axis
    coil13.rotate_from_angax(90, "y")
```

The second coil (L24) is defined identically, except that its positioning is different so that the 2 coils do not overlap.

```
    coil24.position = (-50, 0, 0)
    coil24.rotate_from_angax(90, "y")
```

For the highest possible fidelity, the core of the coils was also modelled as a magnet with 0 magnetization. All elements were integrated into a collection and the whole model was displayed to assess the correctness of the model (Figure 34.).

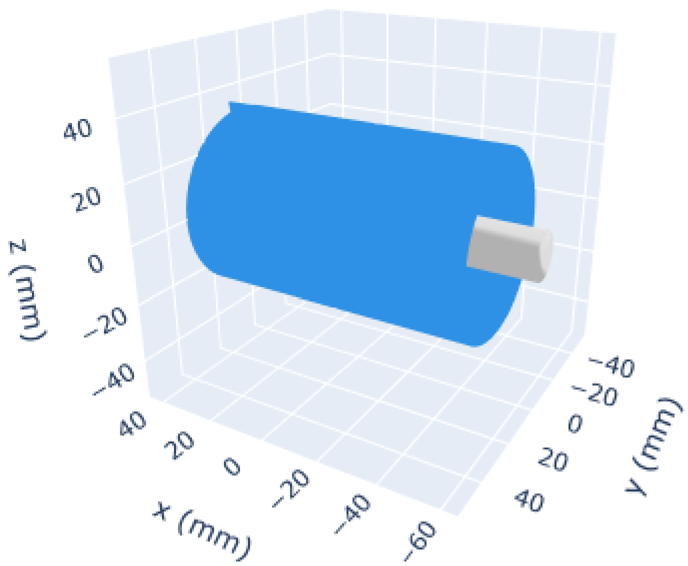


Figure 34. 3D model of the NF1-800 coils

After modelling the magnetic system of the relay it is possible to evaluate the behaviour of the magnetic field generated by them. Magpylib can perform detailed analysis and representation of the magnetic field in two dimensions. The contours of the coils and the relay housing have also been defined within the representations.

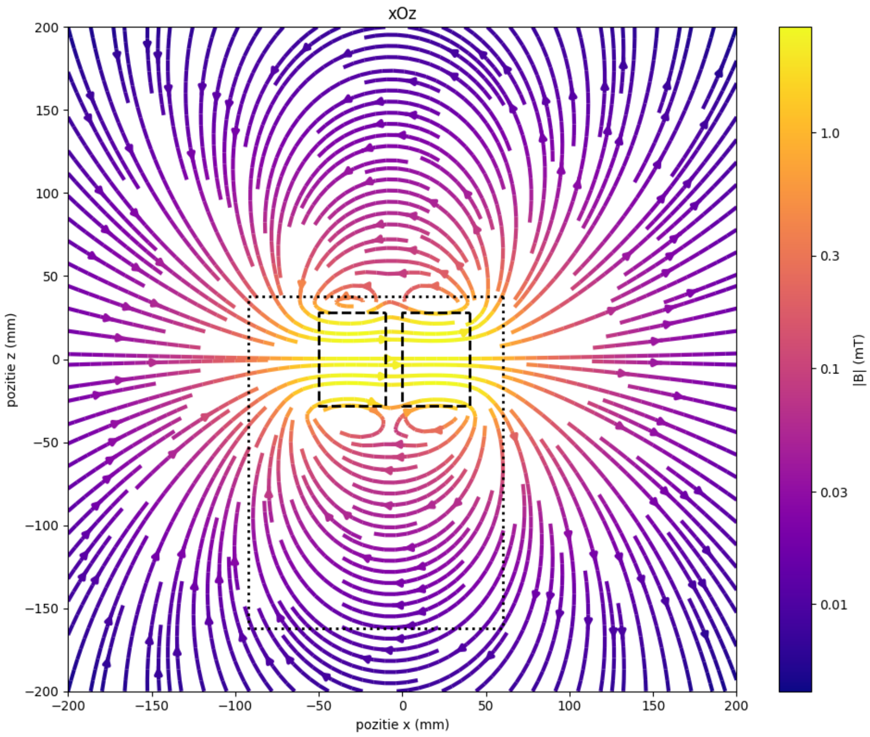


Figure 35. Simulated magnetic induction in the xOz plane (NF1-800)

All planes section the model along an axis. To evaluate induction on parallel planes it is necessary to change the constant parameter in the definition of the analysis space.

Simulations show that the induction in the centre of the relay coils reaches values of about 2.5 mT. The inductance around the relay housing, in areas where magnetometer-type sensors can be placed, shows values between 250 - 300 µT.

In practice relays are compactly mounted in relay frames. Using magnetometers to monitor the status of a relay requires minimal magnetic field influences from adjacent relays. Since the upper and lower neighbouring relays have a large distance from the reference relay, only the side relays were modelled. They have been defined identically to the model shown above.

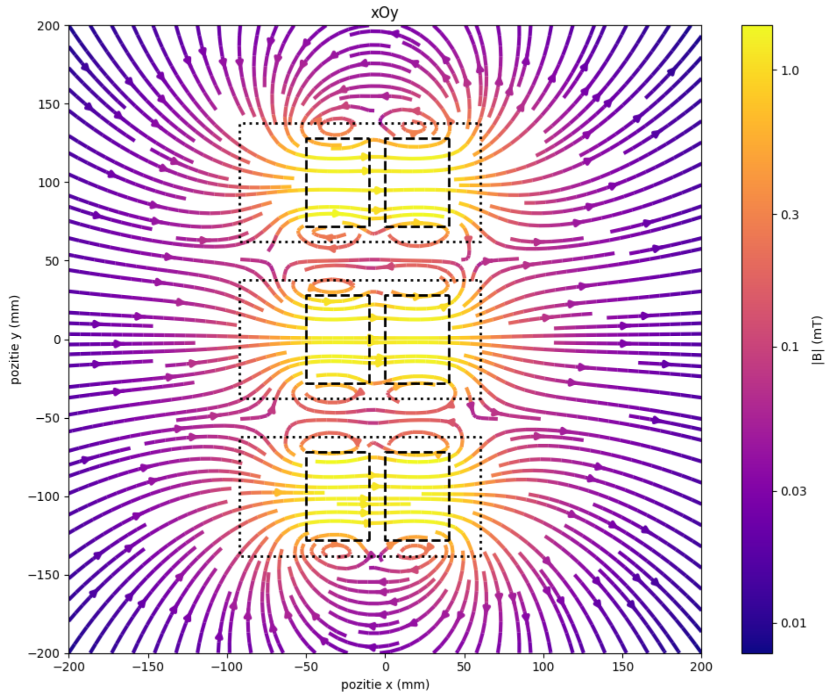


Figure 36. Influence of adjacent relays in the xOy plane

From the analysis of the results it is evident that the influences of adjacent relays on the inductance of the reference relay are negligible, below 10 µT. A final simulation of the external influences was performed also in the xOy plane, but at a distance of about 1 cm above the fed coils. This distance corresponds to the relay housing and allows to estimate the values that can be recorded by a magnetometer.

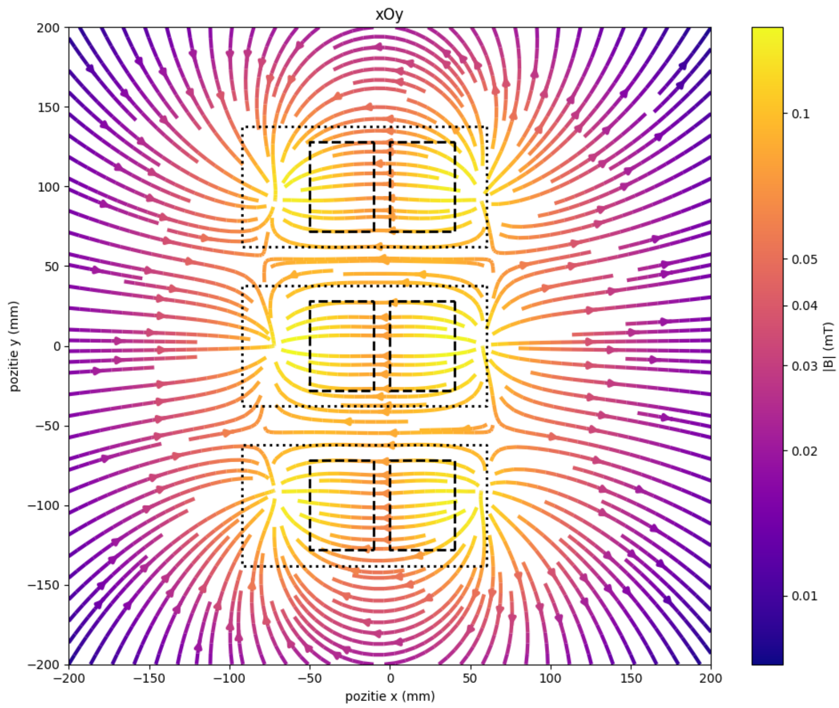


Figure 37. Influence of adjacent relays in the xOy plane on the relay housing

4.1.3 *Taking measurements*

By means of the previously created model it was possible to evaluate the ideal behaviour of the magnetic field generated by the NF relays. In order to evaluate the accuracy of the model and to decide on the parameters of use of the magnetometers in detecting the state of the relays, a series of measurements were carried out. The results of these measurements were reported in a paper by the author in 2022 [74].

In order to determine the shape of the magnetic field around the rail relays and its changes during operation, a spatial distribution of the measurements was required. The measurement space was defined around a gravity rail relay and taking into account the characteristics of the sensor used.

The measurement grid (Figure 38.) contains 420 individual points where measurements were taken. The points were spaced 4.5 cm apart along their length and width (x and y axes) and 2 cm apart along their height (z axis). In total, the measuring grid measures 27 cm (x-axis), 18 cm (y-axis) and 22 cm (z-axis), which far exceeds the dimensions of a rail relay. This makes it possible to assess the influence of the magnetic field produced by a relay on its neighbours.

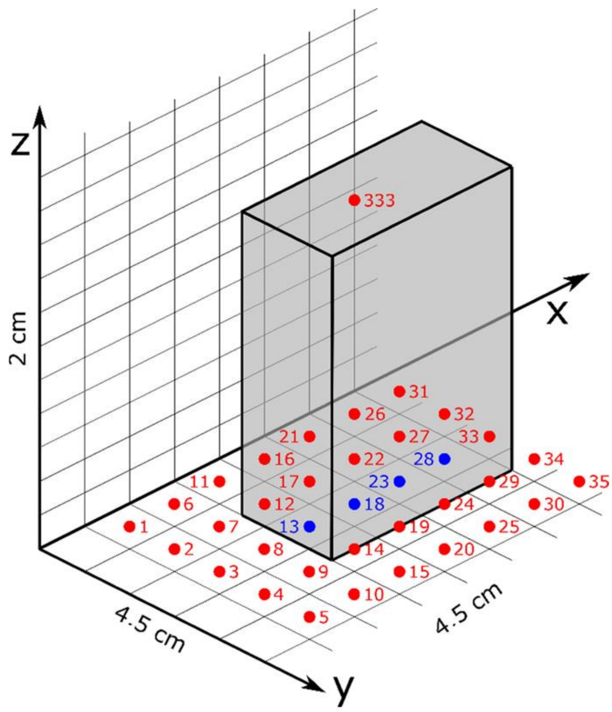


Figure 38. Measurement grid defined around a rail relay[74]

The relay was placed on the grid so that the longer side was parallel to the Ox axis and the narrower side to the Oy axis. Where measurement points fell inside the relay (e.g. 13, 18, 23. 28), the values at that point were estimated by averaging adjacent points.

The magnetic field components on each axis were saved for each measurement point in a .csv table. The data were then processed and interpreted to highlight the main observations.

The measuring grid and supporting elements were constructed using LEGO components, which allowed for flexibility in sensor placement as well as secure positioning on a predetermined size support.

Four separate sets of measurements were made corresponding to the following relay states: relay not energized, relay energized with coil 1-3 energized only, relay energized with coil 2-4 energized only, and relay energized with both coils energized.

Magnetic field data collection was performed using the MAG3110 magnetometer together with the Arduino Nano development board. Communication between the two devices was done via the I2C interface, and a logic level conversion element was required between them (3.3 V for MAG3110, 5 V for Arduino Nano).

For each point defined on the measurement grid, three consecutive measurements were automatically taken. The average of these measurements was sent to the computer via the serial interface and recorded in a .csv file using the ArduSpreadsheet extension [75].

4.1.4 Data processing and interpretation

The four sets of measurements were processed in a first step using a spreadsheet program to perform arithmetic averages corresponding to the positions where the magnetometer could not be placed. Based on the data, a series of graphs illustrating the shape of the magnetic field for the evaluated cases were generated in Python.

The first set of measurements corresponds to the unpowered relay. In this case, the field lines shown are generated exclusively by the planet's magnetic field. Their appearance is almost identical for each position of the planes represented. The deformations that occur correspond to the alteration of the field lines by the metal components of the relay (Figure 39.).

When the relay is fully energised with both coils energised, the magnetic field changes significantly, both in strength and shape. The differences from the previous scenario are mainly observed in the xOz plane.

In Figure 40. the deformation of the field lines as the planes approach the centre of the relay is clearly visible. The maximum field deformation occurs at the y=9 cm position, where the xOz plane bisects the relay precisely in two identical halves with respect to the Ox axis.

Pulling the relay using only one of the coils also produced a noticeable change in the field lines. Again, the yOz and xOz planes showed the most obvious changes (Figure 41. Figure 42.).

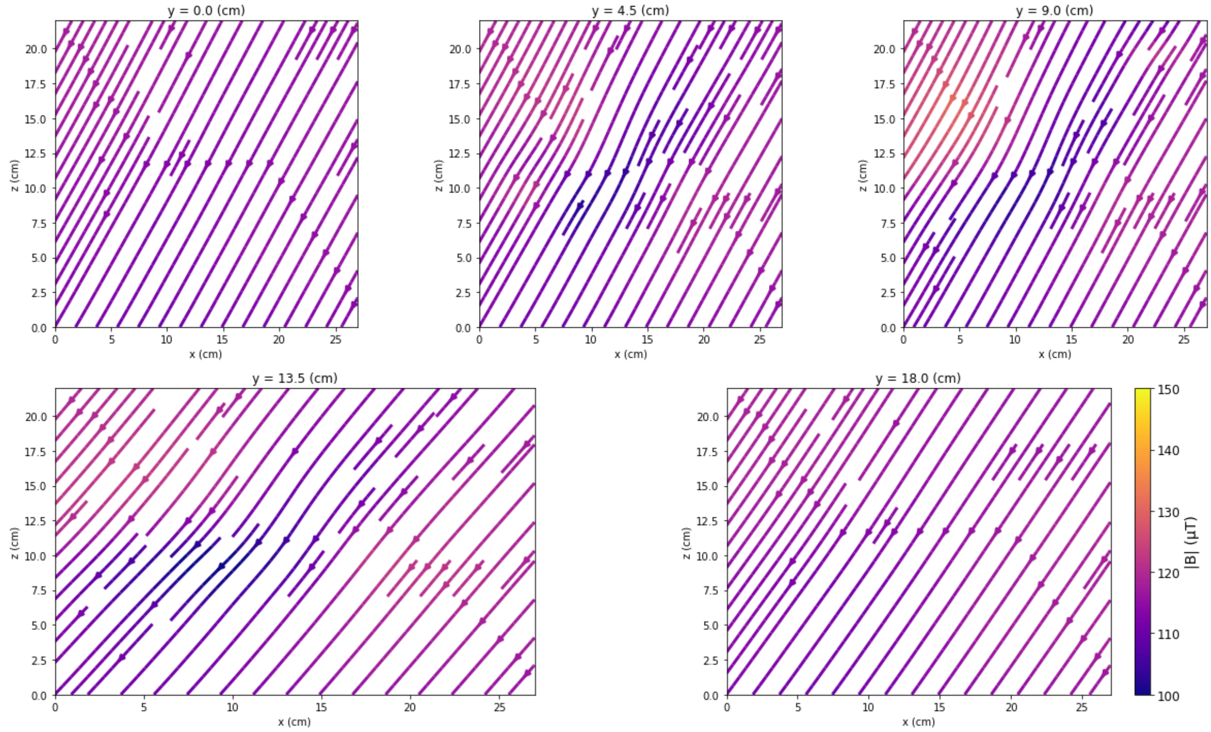


Figure 39. Field lines for xOz plane - Unpowered relay

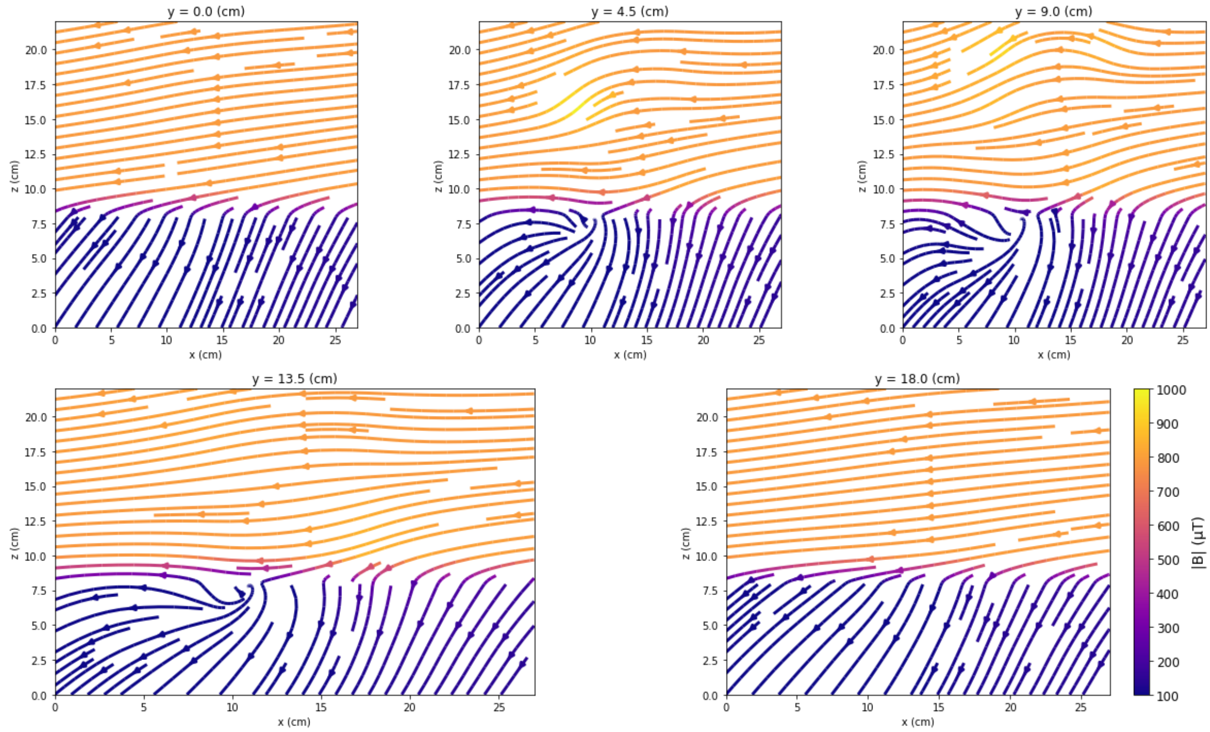


Figure 40. Field lines for xOz plane - Fully energised relay

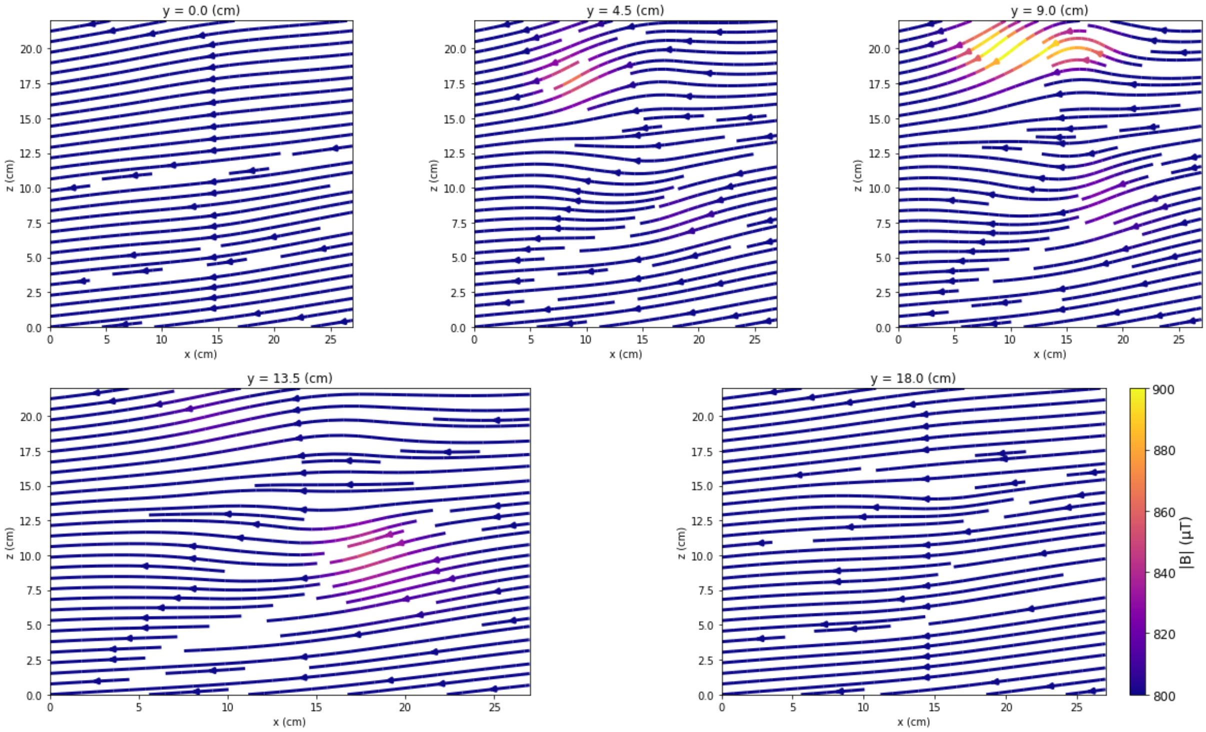


Figure 41. Field lines for xOz plane -L1-3 energised

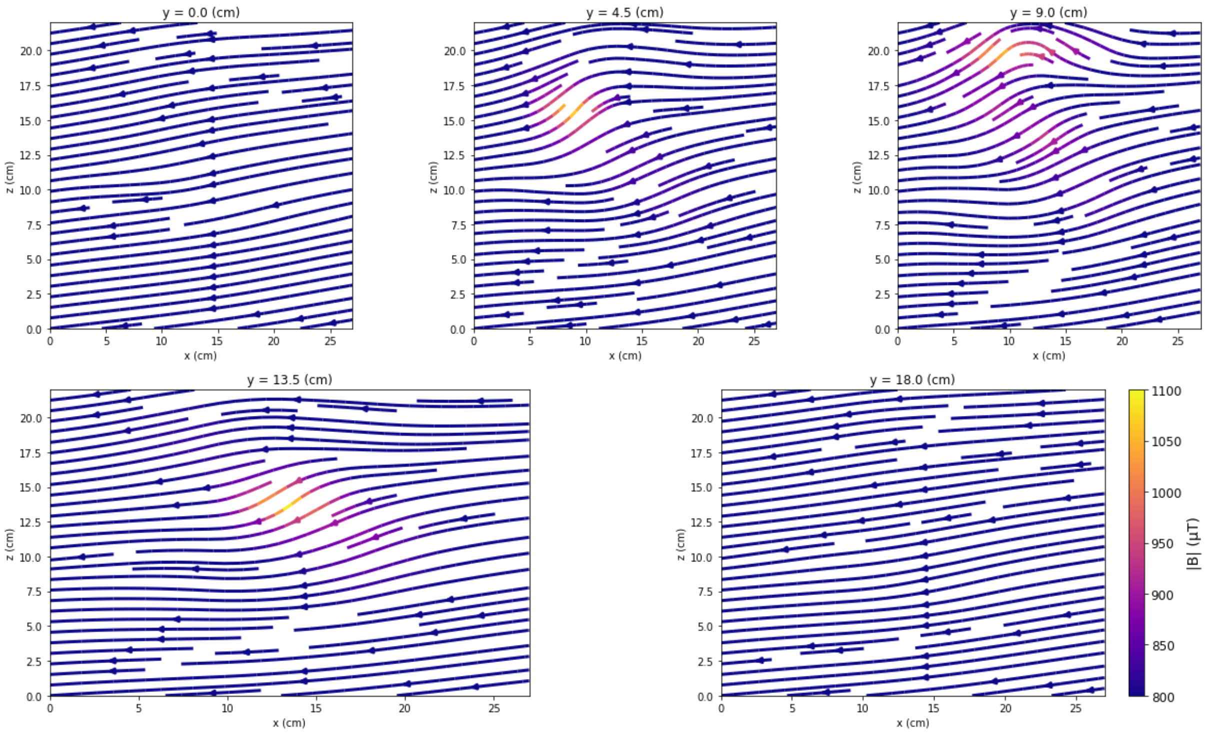
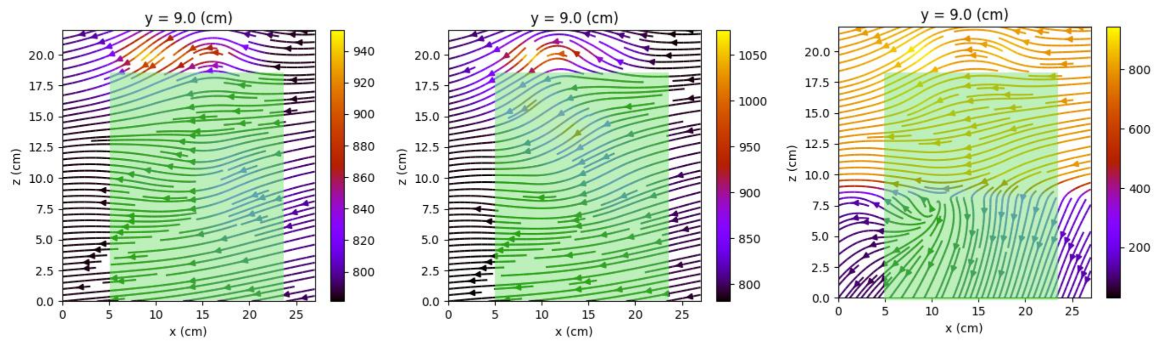


Figure 42. Field lines for the xOz -L2-4 energised

Based on the data presented in the previous sub-chapter, a number of observations can be made about the usefulness of magnetometer-type sensors. The first observation is that the most obvious magnetic field deformations were recorded in the xOz planes. From the graphical representations it is possible to distinguish, including the relay power supply mode. Figure 43. compares the shape of the field lines for the same xOz plane in the three possible feed variants.



a) b) c)

Figure 43. Magnetic field for feeding through: L1-3 (a), L2-4 (b) and complete (c) [74]

Deformations in the yOz planes are also noticeable, but without a substantial difference depending on the coil supply. The smallest changes are recorded in the xOy plane. As such, discrimination between different relay states can be achieved by measurements of magnetic induction in the xOz plane, with possible secondary measurements in the yOz plane.

The optimal positioning of the magnetometer is on top of the relay housing. It should be placed above the transition area between the two relay coils. The table below contains the measured values on the three axes in the recommended mounting position and the calculated inductance based on them in the three planes.

Table 2. Inductance measured at measuring point 333 [74]

Relay state	**x**	**y**	**z**	**||xOz||**	**||yOz||**	**||xOy||**
Deenergised	-57.99	799.2	-96.59	112.661	805.016	801.301
L1-3 energised	-783.28	798.765	-193.605	806.852	821.893	1118.728
L2-4 energised	-782.34	797.84	25.46	782.754	798.246	1117.410
Fully energised	-783.38	798.86	-78.83	787.336	802.740	1118.866

From the shape of the magnetic field in the yOz and xOz planes it can be seen that the influence of the energized coils decreases rapidly outside the relay. Thus their influence on neighbouring relays can be neglected.

The measurements confirm the behaviour of the magnetic field in the vicinity of the NC relay and the negligible influence of adjacent relays on the reference relay. Differences between the model and the measurements can be observed in the general shape of the field lines, especially in the xOy plane, but also in the higher measured values of the magnetic induction. These can be explained by the absence from the model of all constructive elements belonging to the relay, but also by the non-existence of the influence of the earth magnetic field on the model.

The conclusions of the modelling and measurements confirm the potential use of magnetometers for detecting the state of railway relays, also providing an optimal possibility of placing the magnetometers on the NF relay housings above the two coils.

4.2 Implementation of a WSN for CED interlockings

4.2.1 General consideration

The structure of the whole monitoring system of a CED interlocking through a WSN has been detailed in Figure 9. . This subchapter describes the testing of the system for the purpose of evaluating its performance.

As described above, the proposed system implements two distinct data channels related to the operation of the CED interlocking. The first channel takes the electrical signals from the control panel and uses them to run the centralization program developed in Ladder language, while the second channel takes the data received from the WSN network mounted directly on the plant relays. Three main objectives were evaluated:

- Accuracy of the centralization program developed in Ladder language;
- WSN network performance;
- Comparison of results obtained through the two data channels.

4.2.2 Conducting measurements

The tests were carried out on the CED interlocking of the Department of Telematics and Electronics for Transports. The structure and components of this installation, as well as how to develop the centralization program for PLC type equipment have been presented previously. The evaluation of the system was chosen for the Y2 output path.

The centralisation program loaded on the PLC requires the commands given by the IDM to be taken from the control panel. The physical link between the PLC and the console was implemented by means of the existing terminal strips at the bottom of the console. The status of the Y2 signal button was monitored via the PLC digital inputs. A link to the PMC (Figure 44.).

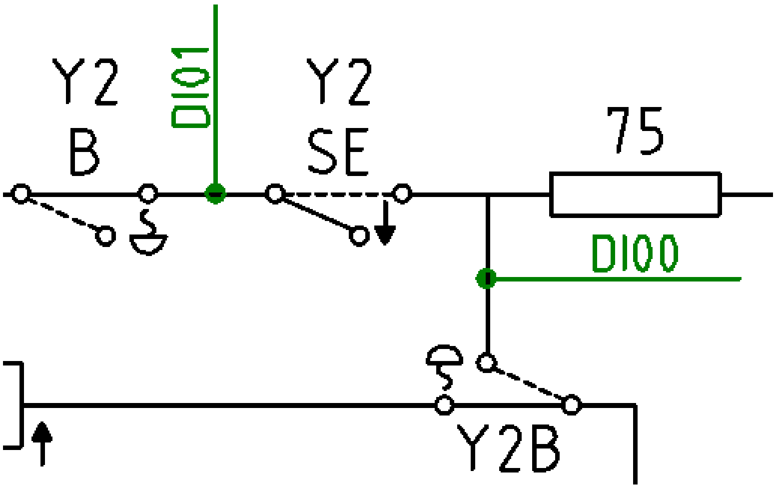


Figure 44. Place of connection of PMC digital inputs (KS scheme)

In order to allow the easiest possible connection to the CED interlocking, the PMC was mounted in the relay frame using a DIN rail. The power supply terminals (+24 and GND) of the PMC were connected to the +24 V and ±12 V terminals of the CED installation respectively.

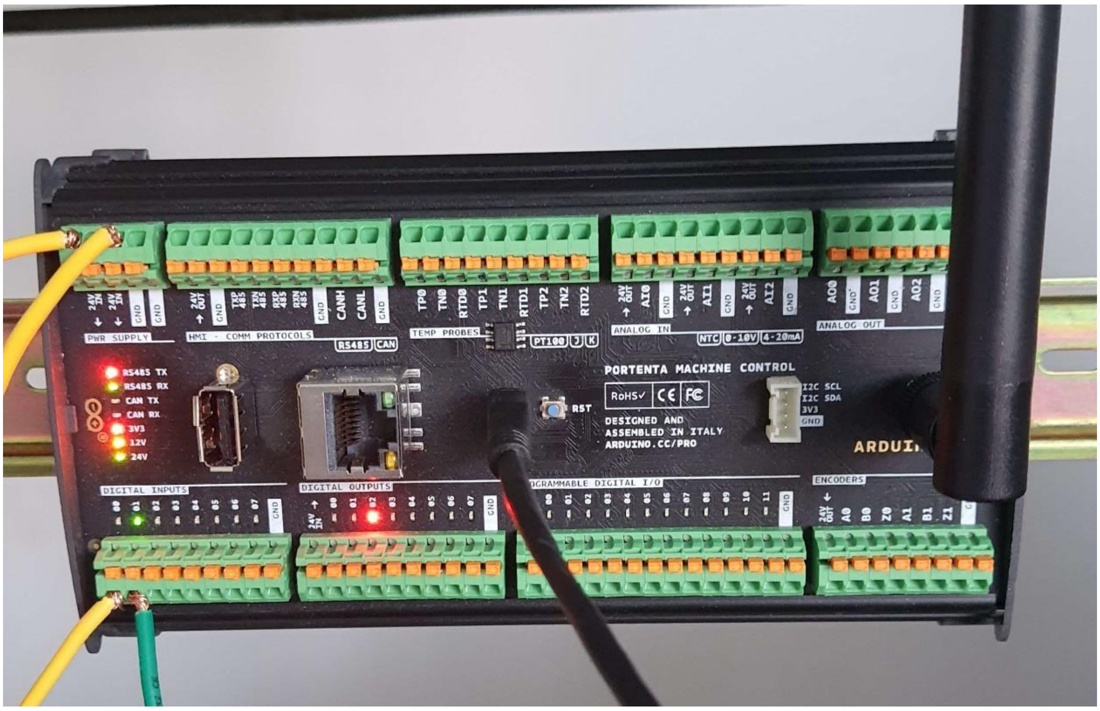


Figure 45. PMC mounted in CED rack

To evaluate the performance of the WSN network, four separate nodes were placed on the relays most relevant to establishing the output path from Y2. The relays monitored were Y2 IP, 1 KS, 1Z and Y2 SE.

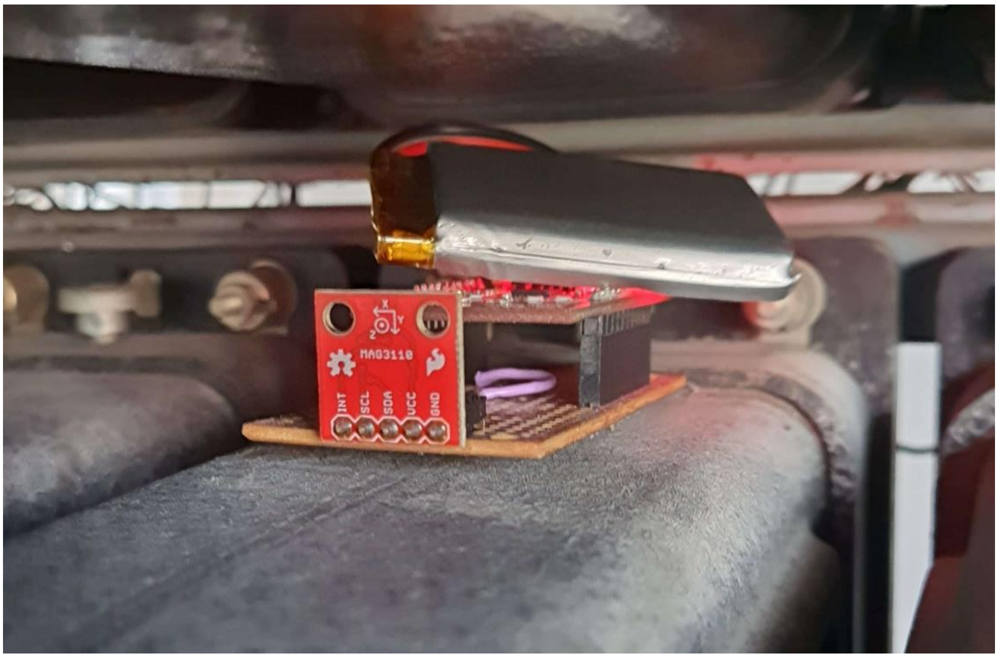


Figure 46. Placing the sensor node on an NF relay

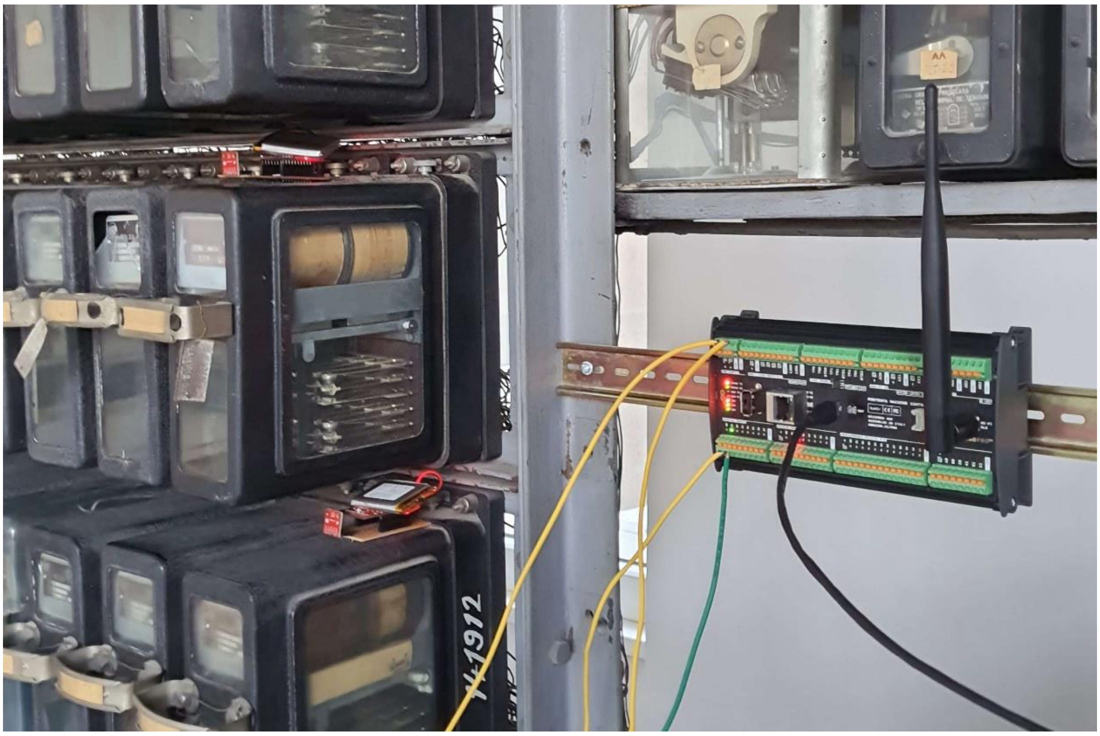


Figure 47. Test setup

4.2.3 Data processing and interpretation

The Arduino PLC IDE allows real-time communication with the PMC via USB serial connection. It can monitor both physical variables, which correspond to physical inputs and outputs, and variables that are strictly software.

In the operation of a CED installation there is a sequence of operation of schemes, so that changing the state of some relays causes changes in the states of other relays. Figure 48. shows the sequence of operation of the main relays related to the output path from Y2.

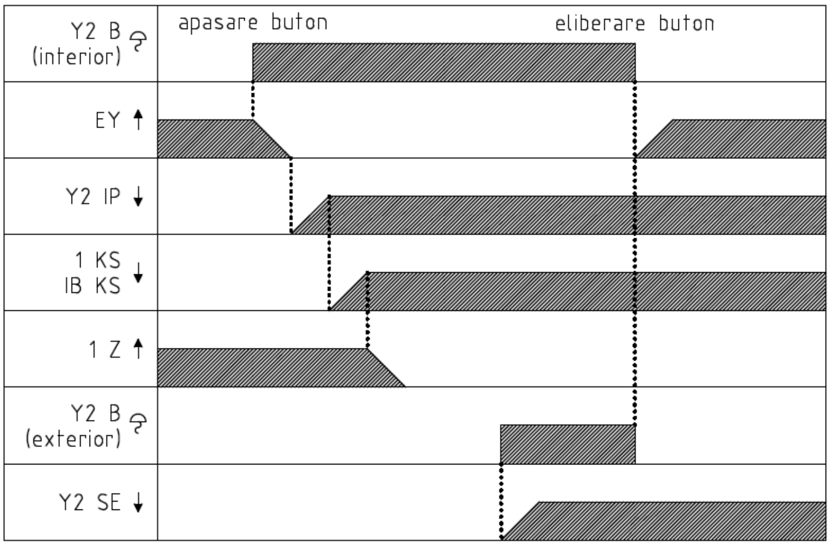


Figure 48. Relay operating sequence for Y2 output route

The first series of tests involved evaluating the accuracy of the centralisation program developed in Ladder. The variables associated with the relays mentioned in the previous figure were monitored. For route control (Figure 49.) the digital input of the PMC (Y2_a_f) as well as the variable associated with the program button (Y2B_a) were additionally represented.

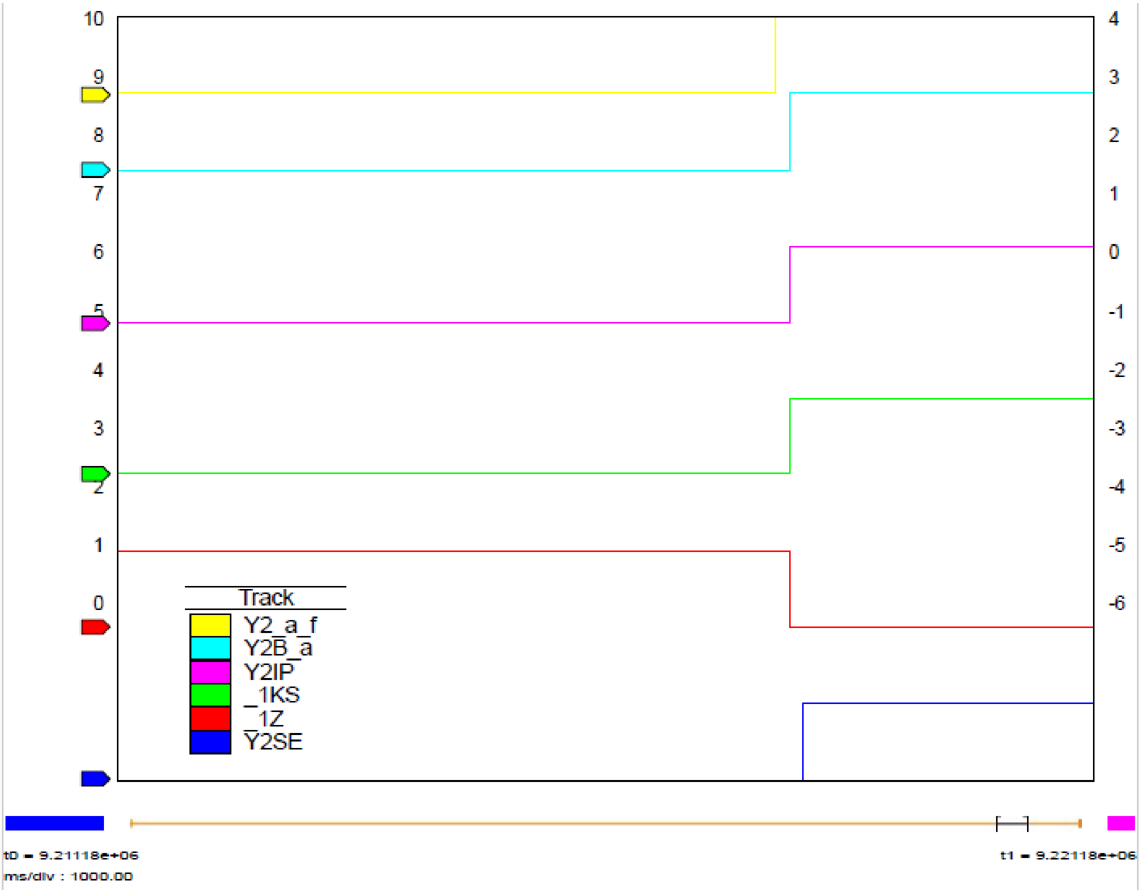


Figure 49. Status of Ladder variables when controlling output route Y2

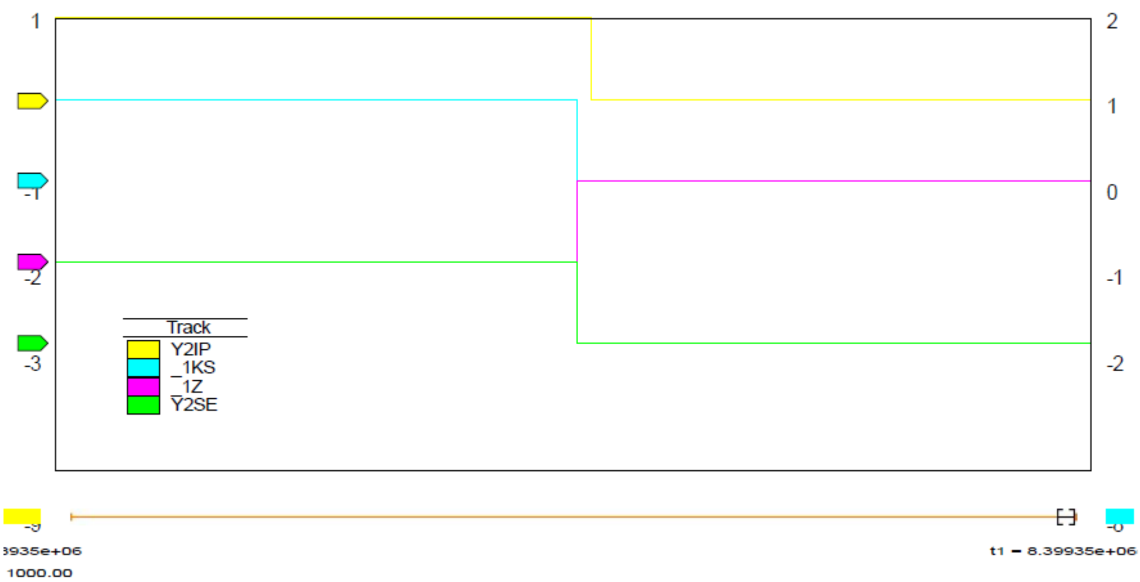


Figure 50. State of Ladder Variables when output route Y2 is cancelled

From the relay status view when setting the route (Figure 49.) and in case of cancellation from the console (Figure 50.) it can be seen that the centralisation program works identically in terms of the sequence of variables to the real CED installation. The main difference comes from the much lower response time of the Ladder program, which is explained by the non-existence of the intrinsic pull delay of the real relays.

The second set of tests (Figure 51. and Figure 52.) involved recording data received from WSN nodes. The names of the network nodes have the following correspondences:

- S1 - Y2 IP;
- S2 - 1 KS;
- S3 - 1 Z;
- S4 - Y2 SE.

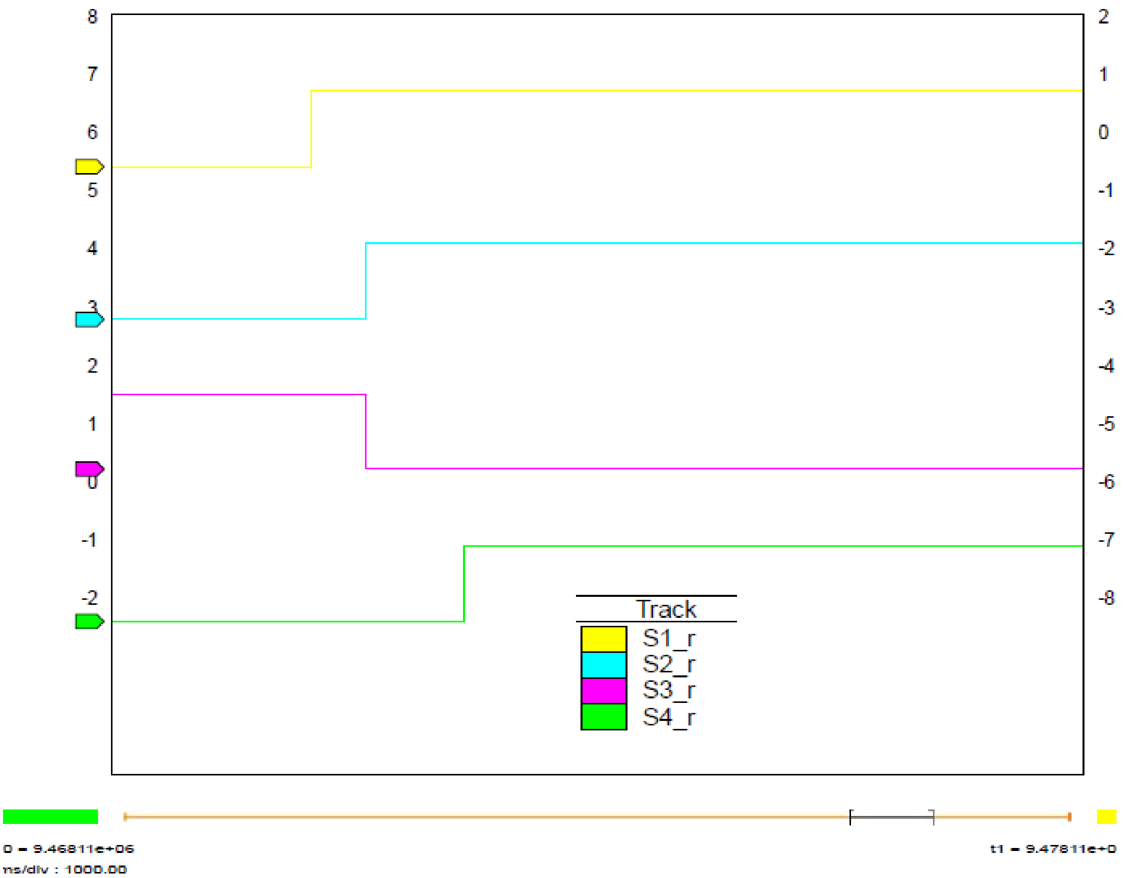


Figure 51. Establishing the exit route from Y2 - WSN network

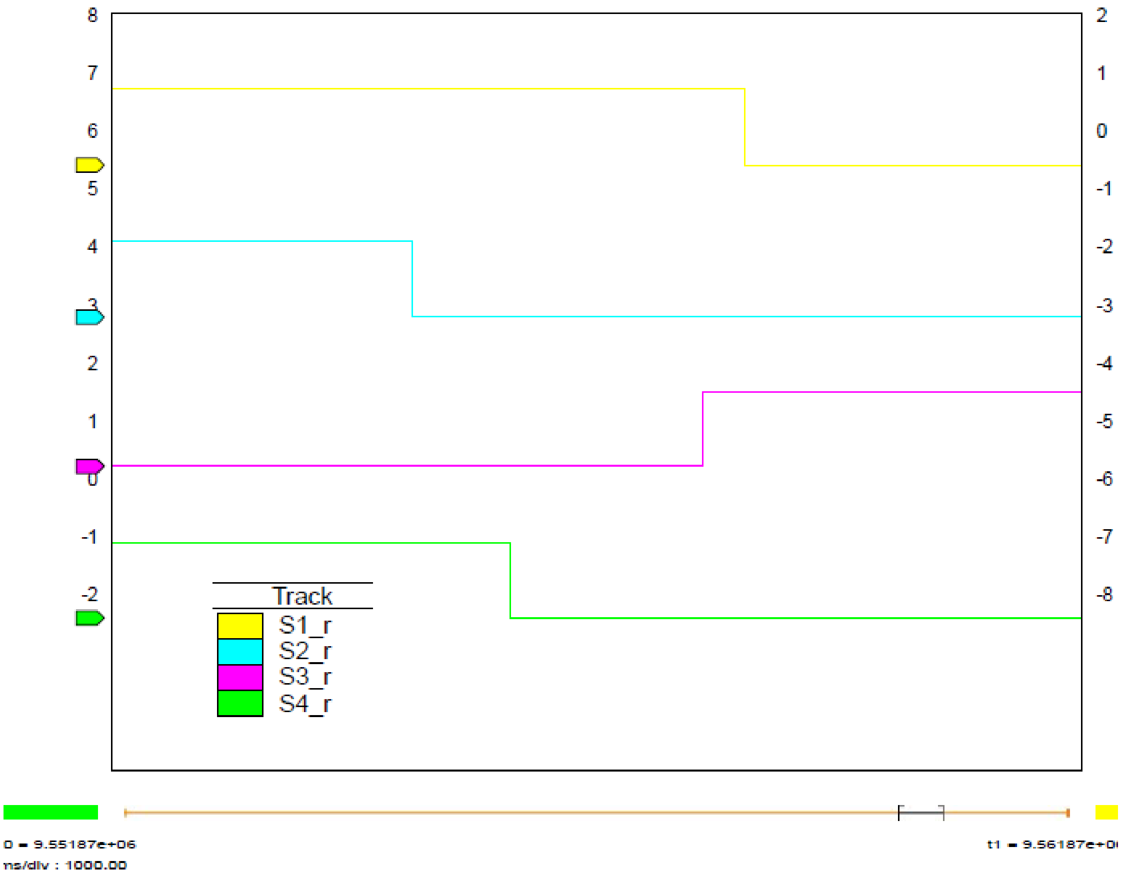


Figure 52. Cancel outgoing path from Y2 - WSN network

The data received from the sensors show a typical operating sequence for a CED CR-2 plant. Unlike the Ladder program variables, the WSN network experiences a slight delay in relay state change. This phenomenon is explained by the intrinsic actuation times of the rail relays.

The last set of measurements evaluated simultaneously the two methods presented above. From the observation of the behaviour at setting (Figure 53.) and cancellation (Figure 54.) path considered, an overall delay of the WSN data can be observed compared to the corresponding variables in the Ladder program. Table 3. centralises delay data at the monitored variable level.

Table 3. Time difference between Ladder and WSN variables

Monitored variables	Δt [ms]	
	Route setting	Route cancelling
Y2 IP	200	3000
1 KS	1000	700
1 Z	1000	2600
Y2 SE	2800	500

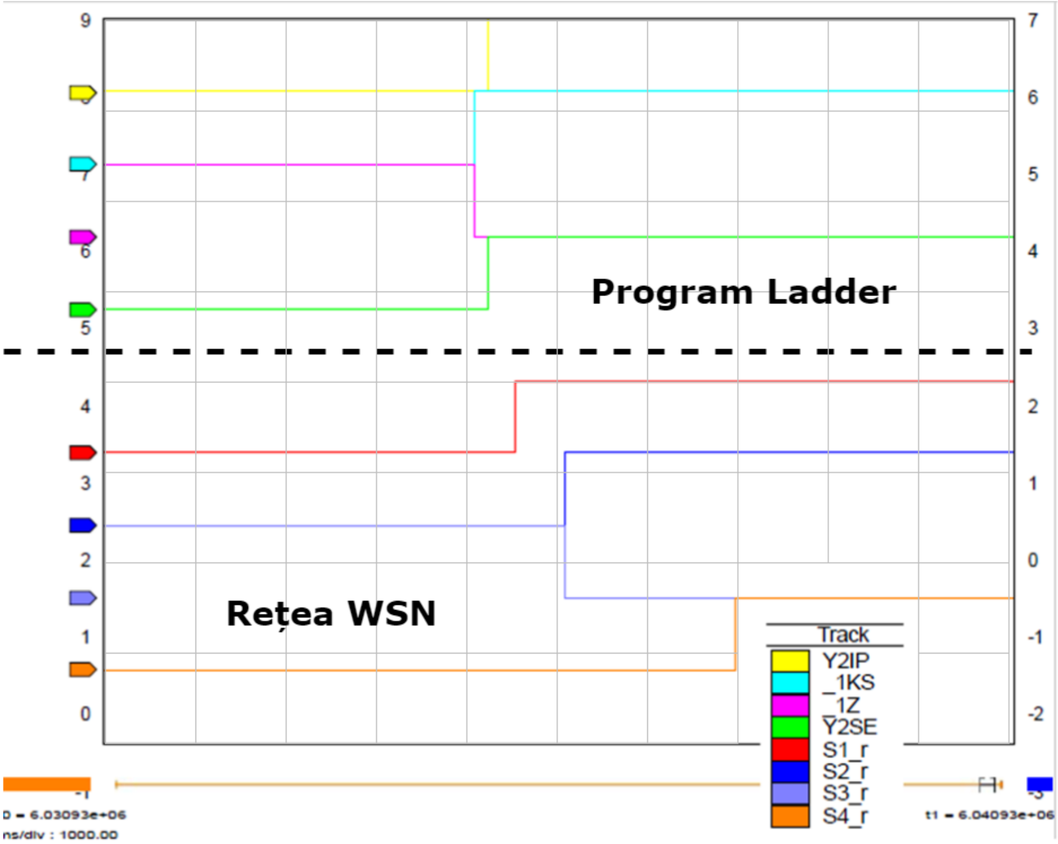


Figure 53. Route setting Ladder vs. WSN

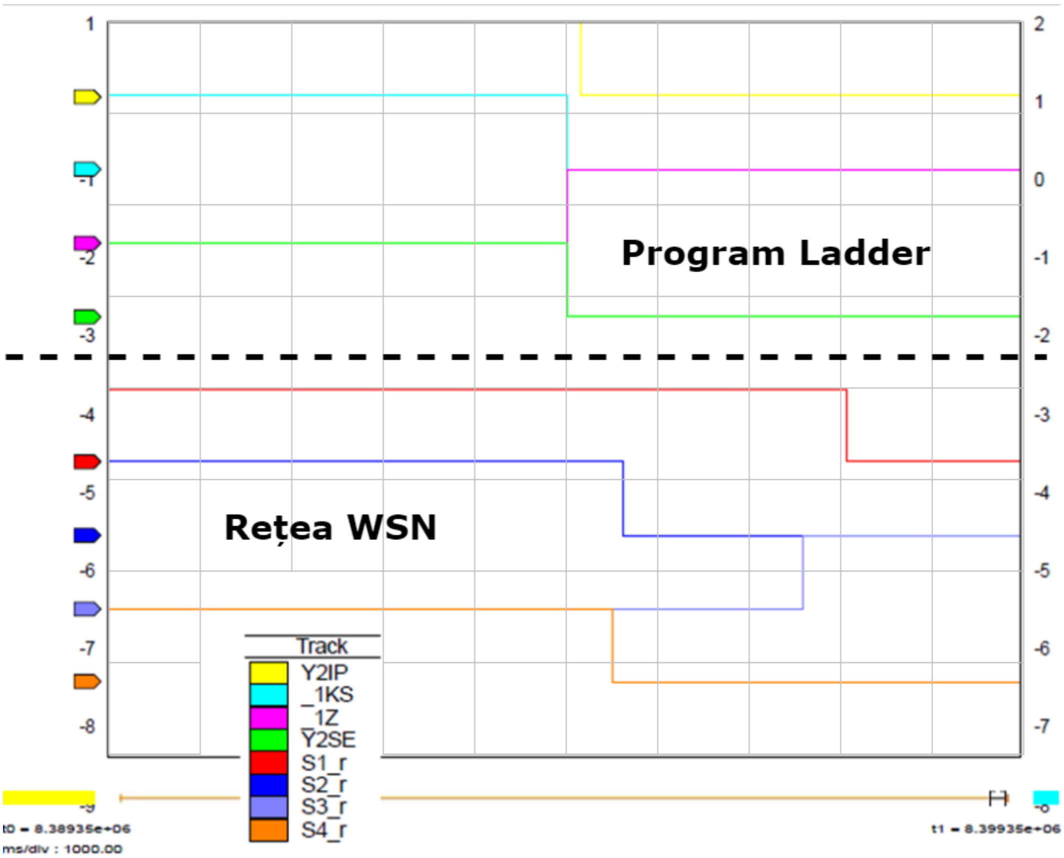


Figure 54. Route cancelling Ladder vs. WSN

Similar to the previous cases, the state change delay of the real relays, compared to the corresponding Ladder variables, is explained by the intrinsic timing of the relays at attract and drop.

The fault detection in the CED interlocking is performed by comparing pairs of Ladder variables with the relays monitored by the WSN. From the point of view of logical operations, the correct response of the system corresponds to cases where the two variables in a pair have the same logical value. This behaviour corresponds to the logical negated or exclusive function (Figure 55.).

Figure 55. Comparison of Ladder variables with WSN variables

Chapter 5. Original contributions and research directions

The present work represents the final stage of a ten-year academic career in the Faculty of Transport at the National University of Science and Technology POLITEHNICA Bucharest. The field of railway telematics has been a constant concern throughout all cycles of higher education, starting from the undergraduate thesis in the field of Electronic Engineering and Telecommunications, specializing in Telecommand and Electronics in Transport (*Signalling system for urban rail transport*, under the coordination of S.l. dr. eng., Maria Claudia Surugiu), continuing with the dissertation in the master's program Intelligent Transport Systems (*Electrodynamic Electronic Centralization Simulator (ECED)*, under the coordination of S.l. dr. eng. Valentin Iordache) and culminating in the present work.

My four years of work as an academic assistant in the Department of Telecommand and Transport Electronics helped me to consolidate the knowledge acquired in previous cycles of study. The experiences gained by supporting the Railway Traffic Control Systems and Station Centralisation labs, as well as the Station Centralisation project, were essential in defining the central theme of the thesis. The development of the Digital Signal Processing lab allowed me to acquire the necessary knowledge to work in Python. The experience of working with PLC devices, necessary for the development of the solution proposed in the thesis, was acquired thanks to the development of the Automation and Telecommunications laboratory.

The following original contributions stand out from the theoretical and practical research carried out during the present work:

1. Drafting of a documentary study on essential principles in the design of railway centralised systems;
2. Elaboration of a study on WSNs, illustrating general aspects of physical and communication architecture and applications in the railway domain;
3. Writing technical and scientific documentation on PLC devices and their usefulness in the railway sector;
4. Development of a model useful for the magnetic simulation of railway relays in order to evaluate the disturbances introduced by them during operation in the magnetic field. The model was developed in Python using the Magpylib library (version 4);
5. Conception, design and implementation of a magnetometer-based WSN for individual relay monitoring in CED installations;
6. Propose and exemplify a method for digitizing contact and relay schemes specific to CED installations in Ladder language suitable for the implementation of railway logic via PLC type devices;
7. Evaluation of the accuracy of the centralization software developed in Ladder language by comparing the results obtained from the program with those of the real CED installation based on the same commands;

8. Evaluation of the correct monitoring of the CED installation through the WSN by comparing the expected state of the supervised relays from the reproduction of the railway logic in Ladder.

During the 4 years of the PhD, the author enjoyed the constant guidance of the scientific supervisor, prof. dr. eng. Corneliu Mihail Alexandrescu, as well as by the members of the supervision committee (Conf. dr. eng. ec. Florin Codruț Nemțanu, S.l. dr. eng. Claudia Maria Surugiu and S.l. dr. eng. Laurențiu Dorin Burețea). In addition to these, the author has benefited from the support of the entire staff of the Remote Control and Transport Electronics Department. In particular, the advice and guidance of the Department Director, Prof. Dr. Eng. Marius Minea, Prof. Dr. Eng. Andrei Răzvan Gheorghiu, Prof. Dr. Eng. Angel Ciprian Cormoș and S.l. Dr. Eng. Valentin Iordache.

5.1 Research directions

Two main directions for future development can be distinguished from the research carried out during this work.

The first is related to the realisation of a complete support system for CED installations via the WSN. Tests have confirmed the usefulness of magnetometers in monitoring the individual state of neutral plug relays. By virtualising the railway logic it is possible to monitor and evaluate the status of individual relays on a permanent basis, which gives an advantage in the case of troubleshooting, even by personnel less experienced with CED installations. Non-invasive monitoring of relays is an essential aspect for eventual large-scale deployment in that the installation of sensor nodes does not affect the normal operation of relay frame elements.

Currently the Arduino PLC platform is in an early version, which implies some limitations on the use of all functions available on compatible PLC devices. A big challenge in this respect has been related to the implementation of communications between the central controller and WSN nodes. It is expected that the platform will be gradually optimized, like other Arduino products and services.

The proposed solution can be further developed by:

- Energy optimization of nodes by implementing sleep mode, with data transmission taking place only when the relay state changes;
- Use of a better performing communication protocol. One option would be to use the MQTT protocol which is already used in many IoT applications;
- Using a dedicated frequency band. The system has been tested with free-band communication technologies. This is currently used by many applications, which can affect network performance. For rail applications there are usually reserved bands set aside by the local telecoms regulator. Using a dedicated band would reduce the possibility of interference with other services;
- Develop a plug code relay monitoring solution. Due to their geometry, it is not possible to use the same method of placing sensor nodes as for neutral relays.

The second research direction that emerges from the present work is to simplify the design of software elements for electronic control systems. Romania has the advantage of having a standardized architecture at the level of centralization installations with relays, which allows the establishment of rules to translate their logic into software logic. The methods proposed in the thesis can be used as starting points for the development of such standards.

Among the advantages of establishing such transitional standards are:

- Reduced software development time (if the station topology does not change substantially from the current situation);
- Reduced upgrade costs by allowing several manufacturers to participate in the development of electronic centralisation systems. Currently the market is structured as an oligopoly of a few manufacturers, which leads to high costs of implementing electronic exchanges.

Works published by the author

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2. Răzvan Andrei Gheorghiu, Florin Bădău, and V. Iordache, "Applicability of Magnetic Sensors in Interlocking Systems," *Sensors*, vol. 22, no. 12, pp. 4314–4314, Jun. 2022, doi: https://doi.org/10.3390/s22124314. WOS: 000818179400001
3. Florin BĂDĂU, "Railway Interlockings – A Review of the Current State of Railway Safety Technology in Europe," *Promet*, vol. 34, no. 3, pp. 443–454, Jun. 2022, doi: https://doi.org/10.7307/ptt.v34i3.3992. WOS: 000810060800007
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