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Development and implementation of a remote monitoring unit for cathodic protection applications

Desarrollo e implementación de unidad de monitoreo remoto para aplicaciones de protección catódica

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Abstract: This document presents the development of a Remote Monitoring System (RMS) for the monitoring and control of cathodic protection rectifier units (CPRUs). It also outlines the developmental stages from conception, implementation, laboratory validation, to industrial deployment. This system is based on an IoT network composed of hardware equipment responsible for acquiring input and output variables of CPRU operation (Remote Monitoring Units - RMUs), transmission of collected data via MQTT, and a web platform with complementary services for data acquisition and management of monitored assets.

Keywords: Corrosion, Cathodic protection, Rectifier units, IoT, Microcontrollers, MQTT, CBOR, Modbus.

Resumen: Este documento presenta el desarrollo de un sistema de monitoreo remoto (SMR) para el seguimiento y control de unidades rectificadoras de protección catódica (URPC). Asimismo, se presentan las etapas de desarrollo desde su concepción, implementación, validación en laboratorio e implementación en ambiente industrial. Dicho sistema se basa en una red IoT compuesta por un equipo hardware encargado de adquirir las variables de entrada y salida de la operación de las URPCs, llamado Unidad de Monitoreo Remoto (UMR), transmisión de la data recolectada vía MQTT y una plataforma Web con servicio complementarios para la adquisición de la data y la gestión de los activos monitoreados.

Palabras clave: Corrosión, Protección catódica, Unidades rectificadoras, IoT, Microcontroladores, MQTT, CBOR, Modbus.

1. INTRODUCTION

Corrosion is a phenomenon that generates annual economic losses on the order of trillions of dollars due to infrastructure deterioration [1]. An effective and widely disseminated technique in the Oil & Gas industry to protect metallic structures, both submerged and buried, is the use of cathodic protection (CP) [2] through the injection of current applied by cathodic protection rectifier units (CPRUs) [3]. The use of this technique requires constant current injection within a determined range for each system according to environmental conditions [4]. Alterations in operating parameters can trigger issues such as cathodic disbondment, corrosion, interference, stray currents, among other detrimental phenomena to the assets' lifespan; hence, constant monitoring of CPRUs operation is required [5].

For oil and gas pipelines, CPRUs and anodic beds are installed along the pipeline route, making their placement possible in remote and difficult-to-access locations [6]. Similarly, the inspection of this equipment requires trained personnel, leading to high costs for equipment monitoring and maintenance [7].

In Colombia, companies in the oil&gas sector have acquired and installed CPRUs developed in North America and Europe. However, adapting these products to the environmental conditions of the region has led to complications in their operation. These complications include vulnerability to atmospheric discharges, impedance coupling, inadequate resolution of measurement channels for the variables to be measured, and prolonged response times for local and headquarters support. Additionally, communication service costs and access to platforms have hindered the widespread adoption of the product at a national level, prompting the development of these technologies by both private and public sectors nationally [8].

The Corporación para la Investigación de la Corrosión, CIC, hereby presents its experience with the development and implementation of a cathodic protection system (SPC) monitoring system, from its conception to execution.

2. DESIGN REQUIREMENTS

The development of this RMU begins with the gathering of requirements, which are captured based on the state of the art and literature, commercially active equipment, collection of experiences from specialists in the field, and specific needs of the local market, with the aim of addressing international market demands.

2.1. Cathodic Protection Rectifier Unit

A cathodic protection rectifier is a machine that converts energy from an alternating current (AC) power grid into direct current (DC). The negative terminal of this machine is connected to the pipeline, and the positive terminal is connected to the anodic bed. By adjusting taps, the current injected into the anodic bed to protect the pipeline is configured [9]. Its configuration can be seen in Fig 1.

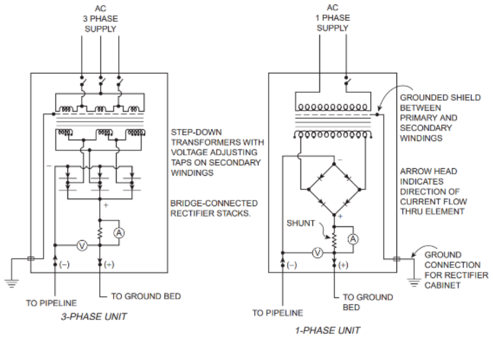


***Fig. 1**. Schematic circuits of three-phase and single-phase CPRUs. **Source:** Peabody's Control of Pipeline Corrosion, 3rd Edition*

2.2. Parameters to Monitor

To properly configure the current intensity to be supplied by the CPRU, the industry has adopted the recommendations outlined in the NACE RP-01-69 standard [10]:

- Structure potential of -850mV or more electronegative, measured with respect to a copper-sulfate saturated copper electrode (Cu/CuSO4).
- Polarized structure potential (On Potential) should measure -850mV or more electronegative, measured with respect to a copper-sulfate saturated copper electrode.
- There should be a differenceof -100mV between the On Potential and the potential measured once the rectifier is turned off (Instant Off).

As mentioned in the NACE Standard criteria, potential measurements are made with respect to a Cu/CuSO4 electrode. Typically, a permanent electrode is installed near the protected structure [11].

Because this potential depends on factors such as humidity, climate, soil, among others, it is valuable for the CPRU operator to know the output variables of their machine, such as the potential and current of DC output. This knowledge enables them to identify changes in the impedance of the protected system. Since the output variables depend proportionally on changes in the RMS input potential of the CPRU, it is also relevant to monitor the input AC potential and current [12]. Table 1 lists the ranges, resolutions, impedances, and accuracies required for rectifier monitoring.

Tabla 1: *Variables to measure and requirements*

Variable	Range	Resolution	Input Impedance	Precision
Input Voltage	0-600V	0.1V	20Mohm	0.1%FS
Input Current	0-100 mV	0.1mV	20Mohm	0.1%FS
Output Voltage	±100V	0.1V	20Mohm	0.1%FS
Output Current	±100 mV	0.1mV	20Mohm	0.1%FS
Potential On	±10V	0.01mV	20Mohm	0.1%FS
Potential Instant Off	±10V	0.01mV	20Mohm	0.1%FS

V = Voltage. FS= Full Scale

Source: *Authors' own creation*

It is worth noting that for current measurement, a shunt resistor will be used. Therefore, the equipment to be designed will measure potential instead of current.

2.3. Synchronised Cycling Between Units

To validate the effectiveness of the cathodic protection system, tests are conducted to verify whether the protection criteria are being met along the pipe route. This involves cutting off the current supply from the sources that protect the system and locally measuring instant off potentials for subsequent comparison with On potentials. Since more than one CPRU can be installed in an area, synchronous turning off and on is necessary. Hence, each RMU must have an actuator to safely disconnect the CPRU and a time reference for synchronous control of the actuator [13].

2.4. Communication

The RMU device to be designed will be installed in areas where cellular network coverage or other types of wireless networks are not available, so it must be compatible with satellite communication.

2.5. Useful Life and Maintainability

The equipment to be designed must be robust, considering the less-than-ideal conditions of temperature, humidity, and network stability. Potential sources of damage include overvoltages from the power supply and the CPRU, as well as possible atmospheric discharges.

Given the foreseeability of the equipment requiring intervention for preventive and corrective maintenance, as well as on-site repairs and calibrations, the design must facilitate safe handling of the equipment in the field.

2.6. Fail-Safe Mode

The designed RMU shall not affect the operation or availability of the power supply to the CP system in the event of a failure. Nor, under no circumstances should it pose risks to its operators or associated equipment if handled properly.

2.7. Functionality

The main function of the RMU is to periodically measure the operating variables of the CPRU, store them locally as a backup, and transmit the collected information [14]. Additionally, it must allow for asynchronous receipt of commands and control the opening and closing of outputs from the CPRU.

2.8. Data Capture and Visualization

The project entails the development of a web solution that integrates and manages data from multiple distributed monitoring devices. This solution will offer real-time visualization of monitored parameters and an early warning system for potential anomalies [15]. It aims to facilitate remote and collaborative access to information, allowing manipulation of historical and current data for comparative and predictive analysis. Additionally, the web solution must support two-way communication with monitoring devices via different standard protocols and provide role-based authorization and authentication mechanisms for users. Finally, it should enable the execution of control and configuration actions on the monitoring devices according to user needs.

Initially, a service availability of more than 95% must be guaranteed, with plans to increase this percentage in the medium term.

3. DESIGN

3.1. Hardware Distribution

The proposed design is distributed into pluggable modules to partially safeguard the RMU against overvoltages at one or more connection points of the monitoring equipment to the CPRU. A block distribution is illustrated in Fig. 2.

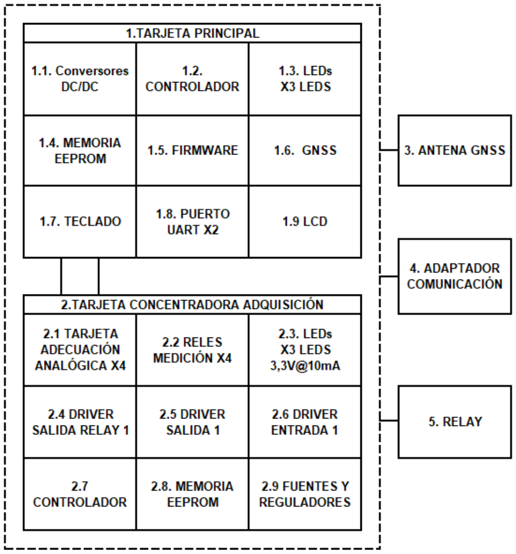


***Fig. 2**. Distribution by design blocks Hardware of the UMR device.*
***Source:** Authors' own creation*

3.1.1. Main card

The first module is responsible for communication logic, LCD screen control, matrix keyboard reading, concentrator plate reading, synchronization of cycling signals based on configuration parameters, and GNSS receiver reading for date, time, and synchrony pulse reception.

3.1.2. Acquisition Hub Card

This board contains the analog acquisition modules for capturing the variables to be measured, input and output terminals for power supply and connection with URPC, relays for galvanic isolation with output terminals, minor modules for digital input and output. Additionally, it has its own circuit for power adaptation and microcontroller for control of the acquisition modules and communication with the main controller board.

3.2. Analogue Acquisition

For the acquisition of analog variables from the CPRU, an analog adaptation module with variable gain and galvanic isolation is designed. This galvanic isolation enables simultaneous measurement of multiple variables without concerns about generating floating earth or short circuits when installing the RMU on the rectifier and isolating surges. The block distribution of this plate is shown in Fig. 3.

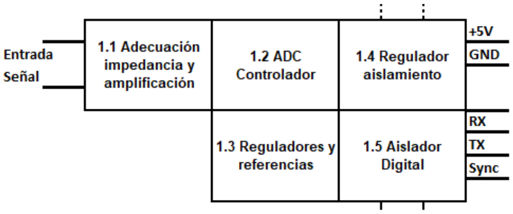


***Fig. 3**. Distribution by design blocks Hardware of the UMR device.*
***Source:** Authors' own creation.*

The analog design consists of a differential amplifier that receives the signal to be acquired, an analog selector to adjust the gain of the circuit, varistor, and Zener diode to protect the circuit at the input of the analog terminals. As for the digital components, there is a microcontroller with a 16-bit ADC responsible for gain selection, UART communication, synchronized measurement with an external pulse for the measurement of On and Instant Off parameters, calculation of true RMS, DC and AC values of the variables to be measured, and a digital isolator for communication with a centralizing board. In the power component, we have an isolation source, regulators, and reference sources.

3.3. Synchronised Cycling

To achieve synchronization between devices, the use of a GNSS positioning receiver (SICLA) is proposed. This component not only delivers position, date, and time but also generates a pulse-per-second (PPS) signal. This signal is synchronous between different receivers regardless of their location and is captured by the microcontroller of the main controller module to generate the control signal for the output actuator.

3.4. Communication

Communication channels are established: a Bluetooth channel for local control of the device and a Modbus UART channel, which connects to an ad hoc Modbus to MQTT converter with output to an Ethernet port for connection to a satellite or cellular communication modem.

The decision to include a Modbus channel is made to provide equipment with a standard communication protocol for use in stations or locations that have an internal communication network, either Modbus RTU or TCP/IP. The Bluetooth communication channel is offered for configuring the equipment using an application that offers a more user-friendly control interface.

MQTT communication is chosen due to the ease it offers in sending data from different equipment through differentiated topics and the ease of packet exchange without the need to use fixed IP addresses for each device [16].

3.5. Lifespan and Maintainability

3.5.1 Lightning

Among the most common causes of failures in this type of equipment are atmospheric discharges [17]. A cathodic protection system for a oil pipeline has entry points including the pipeline, the anodic bed, and the connection for electricity supply. Additionally, inadequate grounding of the CPRU can serve as an additional access point [18].

Considering that the RMU must be connected to the CPRU at 8 different points (for the measurement of 4 values simultaneously) plus the power supply connection, there are a total of 10 potential points for atmospheric discharge input. Therefore, in addition to conventional protection techniques such as the use of varistors, TVS diodes, and arresters [19], the use of mechanical relays to isolate the acquisition cards of the CPRU when it is not taking a measurement is proposed to reduce the exposure time of the monitoring equipment.

Under this scheme, the first protective barrier that the RMU will have will be an arrester, which will attempt to dissipate the energy of the discharge. The second barrier would be the isolation offered by the acquisition relays, the third would be the electrically isolated acquisition module, and finally, the analog acquisition concentrate.

3.5.2 Lifespan

The selection of RMU components was made taking into account operating conditions, such as high temperature and humidity, with priority given to components with a higher MTBF (Mean Time Between Failures), higher resistance to static loads and corrosion resistance [20]. The design prioritizes the functionality of the main module over the others, i.e., in the event of a module failure the RMU is able to communicate its operational status and the failure of one of the acquisition modules should not alter the operation of the machine. At the firmware level, each of the microcontrollers has safeguards for proper state recovery and watchdogs for soft and hard reboots in the event of unexpected events.

3.5.3 Maintainability

The arrangement of components inside the RMU provides ample space for proper handling of the relays and various modules, facilitating quick replacement when necessary. Affordable and readily available materials are used, enabling repairs to be conducted without incurring major costs.

3.6. Web Platform

A minimalist, customer-oriented design that offers a clean, simple and professional appearance, with a focus on essential functionality and an intuitive user interface, is proposed. The platform will consist of four modules.

3.6.1. Geolocation on map

This module will allow you to visualize the geographical location of the devices according to their coordinates, as well as their alarm status and cycling configuration using markers. Their interaction will allow you to visualize a modal window with the latest data acquired from the monitoring variables.

3.6.2. Device management

This module will facilitate the management of devices, communication channels, and monitoring variables through CRUD (create, read, update, and delete) operations.

3.6.3. Visualization Dashboard and Reports

This module will allow you to create dynamic dashboards for data visualization, which can be customized by users with three types of graphs (line, table, pie chart). In addition, it will generate predefined reports in a range of dates in an easy and timely manner.

3.6.4. User management

This module will allow the administration of the different users according to their access levels and assigned roles. Due to the projection and nature of the platform, high traffic and data volumes are expected, for which data manipulation strategies should be adopted, such as a dynamic database for the diverse storage of monitoring variables and JSON-formatted data flow optimization mechanisms.

4. IMPLEMENTATION

4.1. Analog Acquisition Module

The analog acquisition board is designed to have 2 electrically isolated power planes: a floating plane for the analog component of the circuit and a common plane for connection to the acquisition hub module. The selection of components, their arrangement on the printed circuit board and the design of the traces was carried out in such a way as to maintain a breakdown voltage of 2KV between the analog signal input terminals and the power and digital control terminals. Fig. 4 shows the 3D design of the board and its final implementation.

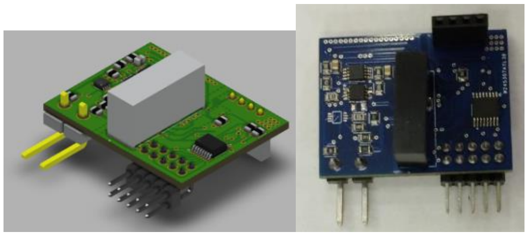


Fig. 4*. Analog acquisition card.*
Source: *Authors' own creation.*

4.2. Acquisition Hub Module

The printed circuit board was designed by sectoring relays, acquisition boards, digital inputs and outputs, microcontroller and regulation components. On the right side of the design are the components related to signal acquisition, on the left with the power input and power regulation and in the center the components associated with digital control. This arrangement of components is done in such a way as to allow easy replacement of some of the components and to isolate electric arcs generated by surges. Measures are also taken to reduce the effects of arc flash and safeguards to minimize potential short circuits. Figure 5 shows the 3D design of the board and its final implementation.

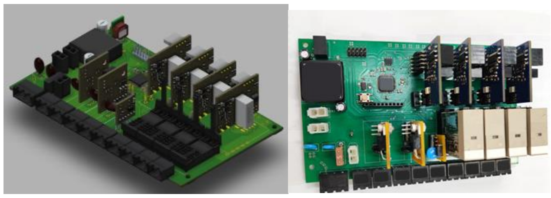


Fig. 5*. Acquisition Concentrator Card.*
Source: *Authors' own creation.*

4.3. Main Controller

The design of this module is mostly digital, except for the adaptation that is made to the signal receiver coming from the antenna of the GNSS receiver. Because much of the electrical protection is found in older modules, the electrical protections are limited to minor TVS.

5. INTEGRATION

5.1. Integration Testing

The different modules of the equipment are programmed and interconnected to test the functional and operational characteristics of the complete device. During the development of the code, the modularity requirement was taken into account, which dictates that a lower or slave module should not impact the performance of higher or similar modules, which is why the necessary safeguards were adopted.

Overall, compatibility in communication protocols, non-interference in the event of induced failures in one or more modules, and the stability of the main module in the event of partial or total failures of the acquisition hub board and analog acquisition boards are checked.

5.2. Cycling and Synchronization

At the laboratory level, synchrony between devices is initially evaluated by verifying the stability of the PPS signal and synchrony between RMUs. The results obtained, once the GNNS receiver obtained time with a number greater than 5 satellites, showed deviations between pulses no greater than 2uS in the case of equipment with equal antennas and 15uS for antennas with a difference in length of 5 meters. For the generation of the actuator control signal, it is determined that the deviations are in the order of 15 and 25uS for signals with a period between 1 and 10 seconds.

Synchronization with commercial switches and RMUs was achieved by leaving an additional variable to control the signal shift with respect to the PPS with a resolution of milliseconds.

In the field, on CPRUs connected to real CP systems, synchrony signals were obtained in orders of less than 1mS for signals with periods of less than 10 seconds.

5.3. Acquisition of Analogue Signals

Acquisition tests are performed for signals with output impedance between 10 and 10kOhms, under which no attenuation or alteration of the signals is observed once connected to the analog suitability cards, whether they are turned on or de-energized. In the short-circuit measurement test, a measurement of zero with an error of 1 significant figure for all scales was verified, while with injected signals a maximum deviation of 10 significant figures was observed, partially attributed to the linearity of the analog acquisition circuit.

5.4. Modbus and MQTT Suitability

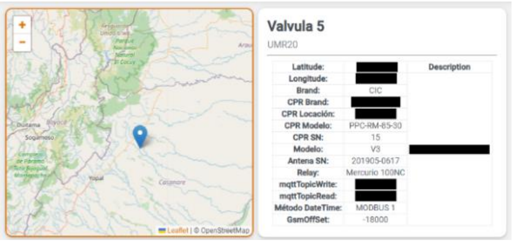
By default, the equipment communicates using a serial Modbus protocol through a UART channel with 3.3V digital logic, designed for connection with an RS-232, RS-485, or similar transducer to offer local connectivity. Communication tests were conducted by connecting the equipment to a PC with a Modbus application, allowing testing of different commands and responses to validate compliance with the standard.

However, since Modbus is not suitable for IoT connectivity due to its slave-master protocol with latency restrictions, a Modbus-MQTT adapter is utilized. This adapter periodically queries all records of the RMU equipment, encrypts the information in CBOR, and further encrypts the message to transmit it to a broker. Additionally, the adapter periodically communicates to another topic operating parameters associated with its performance, such as transmission retries, transmitted frames, failed Modbus queries, among others.

For receiving commands, there are two other topics: one for configuring the adapter and the other for configuring the Modbus registers of the RMU. Parameter configuration can be done individually or in a group, indicating the registration number and new value.

5.5. Data Capture and Visualization

The process of geolocating the devices was carried out using an open-source JavaScript library that facilitates the creation of interactive maps on the web with various functionalities and customization options. Additionally, the GeoJSON format was employed, which is an open standard for encoding simple geographic data structures and their non-spatial attributes, based on JavaScript Object Notation (JSON). This geolocation can be observed in Fig. 6.



Valvula 5

UMR20

Latitude:	[redacted]	Description
Longitude:	[redacted]	
Brand:	CIC	
CPR Brand:	[redacted]	
CPR Locación:	[redacted]	
CPR Modelo:	PPC-RM-85-30	
CPR SN:	15	
Modelo:	V3	[redacted]
Antena SN:	201905-0617	
Relay:	Mercurio 100NC	
mqttTopicWrite:	[redacted]	
mqttTopicRead:	[redacted]	
Método DateTime:	MODBUS 1	
GsmOffSet:	-18000	

Fig. 6. *The device displayed on the platform.*
Source: *Authors' own creation.*

The web platform aims to display the data collected by different monitoring variables in real-time, using graphs that allow observing the evolution and behavior of the measured variables. To achieve this integration, the following technologies and tools were used:

- A dynamic database that stores data sent by the sensors quickly and efficiently.
- A web server responsible for receiving data from the MQTT broker and decoding it from CBOR for further processing and manipulation in JSON format.
- A JavaScript library that facilitates the creation and updating of line charts in the web interface, using the HTML5 canvas element.
- Bidirectional communication protocol that allows real-time data exchange between the server and the broker, without the need to reload the page.

This web platform provides a dynamic and interactive visualization of real-time data, which can be useful for analysis, monitoring, and decision-making, as well as the possibility of remotely configuring different parameters. This visualization can be observed in Fig. 7. An example of remote configuration from the platform can be seen in Fig. 8

Fig. 7. *Data during a day of AC Voltage from a device displayed on the platform*
Source: *Authors' own creation.*


Configuración de Periodicidad
Dispositivo: Select a Device
Transmision Period Record: 0 min
Reset: False / True
Transmision Period Status: 0 min

Fig. 8. *Device configuration from the platform.*
Source: *Authors' own creation.*

Mapled is positioned as a platform that facilitates management and monitoring, with a focus on the Industrial Internet of Things (IIoT). Connected devices can be of various types and communicate through different communication protocols. The platform offers a flexible and customizable solution that allows configuring and linking each device with its specific characteristics, making it particularly attractive for users whose business model requires scaling their different components independently and flexibly, according to their needs. An example of device customization is shown in Fig. 9, where data is entered for a new RMU.

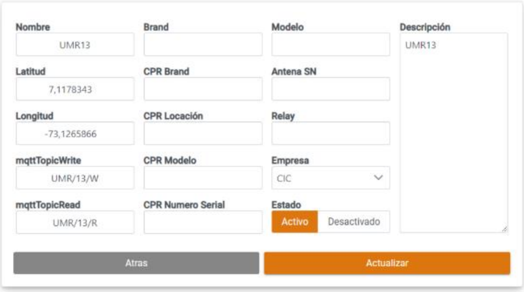

Nombre: UMR13
Brand:
Modelo:
Descripción: UMR13
Latitud: 7,1178343
CPR Brand:
Antena SN:
Longitud: -73,1265866
CPR Locación:
Relay:
mqttTopicWrite: UMR/13/W
CPR Modelo:
Empresa: CIC
mqttTopicRead: UMR/13/R
CPR Numero Serial:
Estado: Activo / Desactivado

Fig. 9. *Configuration of RMU connected to a CPRU in the platform.*
Source: *Authors' own creation.*

5.6. Field Implementation

Finally, the equipment is implemented in a real-world environment, where a complete connection is established with the cathodic protection rectifier, and the data is transmitted via GPRS and/or LTE network to the Mapled platform. An example of this implementation can be seen in Fig. 10.

Fig. 10. *RMU implemented on cathodic protection rectifier*
Source: *Authors' own creation.*

6. CONCLUSIONS

This work encompasses various stages of developing a technological solution focused on SPC monitoring, culminating in the implementation of a product tailored for industrial applications. It includes requirements gathering supported by area specialists, evaluation and proposal of Hardware, Firmware, and Software designs, as well as implementation, integration, and validation at both laboratory and industrial environment levels. Additionally, it's important to highlight that the data collected by the monitoring equipment is presented on a platform specifically designed for this purpose. This platform offers an intuitive interface and analysis tools, enabling users to effectively visualize and understand the collected information. It facilitates informed decision-making in industrial environments, as well as the control of cycling and UMR alarms.

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