DEVELOPMENT AND INTEGRATION OF A VESSEL MOORING DETECTION SYSTEM TO REMOTE OPERATION OF NAVIGATION LOCKS

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Abstract - The Douro River remains the only river in Portugal that allows navigation through dams, and since these represent a physical barrier to navigation, their construction was designed to include navigation lock operations. The navigation lock operations differ in terms of the type of equipment, how the gates work, and other technical details. As the Douro waterway was modernized, automation was implemented, which means the Bagaúste dam navigation lock is operated remotely and, as a result, the navigation lock operations are also operated remotely. However, although the navigation lock operations are remote, confirmation of the mooring of vessels to the mooring posts continues to be made verbally between the vessel's captain and the navigation lock operator. This work aims to fill an existing gap identified in the remote operation of a navigation lock, namely the monitoring of a vessel's mooring throughout the entire sluicing process. To this end, several adversities and restrictions were identified, including not only the external environment, permanent contact with water, and the forces exerted on the mooring posts. The development of this work has led to significant advances in remote navigation lock operations, such as safety, through continuous, real-time monitoring of mooring. The risk of human error associated with verbal communication has been reduced, enabling safer and more efficient operations due to the integration of the developed model with the navigation lock's automation systems. This work has contributed to the safety and efficiency of navigation lock operations, paving the way for more advanced automation and remote controls.

Keywords: Automation, Detection, Monitoring, Mooring, Mooring bollard, Navigation lock, Remote.

1. Introduction

The transition to remote and semi-autonomous operations in navigation lock operations presents significant challenges, especially regarding safety [1]. One of the critical procedures in these processes is the secure mooring of vessels to floating bollard [2], traditionally confirmed by verbal communication via radio between the operator and the vessel captain.

This problem becomes extremely difficult when the Douro has 208 km of navigable waters from the Douro bar (mouth of the Douro in Porto) to the Spanish border, at the port of Vega de Terron, with reference levels for dams ranging from 12 to 125.5 m [3]. *Figure 1* shows the Douro River Waterway and its 208 km length.

Figure 1: Douro River Waterway (Porto-Vega Torron), adapted from [4]

The Douro River is fully navigable (Portuguese Douro) and has five dams (Crestuma-Lever, Carrapatelo, Bagaúste, Valeira and Pocinho) and their respective navigation lock operations along its course. These date back to when the building was

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first constructed and was modernised over time. This modernisation involves the implementation of a remote-control system [5]. The first on the Douro is installed in the Bagaúste dam in Peso da Régua. This technological advance ensures remote monitoring of navigation lock operations using high-precision sensors and cameras. However, despite all the technology used in monitoring, the process of confirming the mooring of vessels to the mooring bollards continued to be done verbally between the vessel master and the remote operator, i.e. without automation.

This paper aims to present a project that seeks to develop an innovative system capable to verifying and monitoring the mooring of vessels throughout the entire sluicing process, eliminating the dependence on verbal communication and increasing safety. Mooring is monitored in real time, reducing human errors that occur during verbal communication, allowing for the optimisation of operations and, above all, their integration with navigation lock automation systems. The implementation and testing of the developed system consist of a prototype that allows the processing of sensor reading data, digital data, and an alert system capable of notifying the operator, via a wireless communication system, of both the operation performed and any failure thereof.

Thise paper is organised into five Sections. The first Section provides a brief introduction to the problem, offering some considerations on the matter. The second Section presents a reflection on the functioning of mooring bollards, highlighting the fundamental characteristics for the implementation of the system to be developed, while the third Section presents the methodology and the approaches to solve the problem. The fourth Section presents the solution implemented, while the fifth Section five concludes the paper.

2. Preamble

Sluicing is governed by a common procedure for both ascending and descending the river. This procedure, governed by Regulation 647/2019: Part G of DR 2nd series, requires that *"the navigators of all vessels are obliged to comply with the orders they receive from the lock operator when they are in the lock or its ante ports"* [3]. In addition to this requirement, other factors such as flow rate, elevation, etc. influence sluices, given that in situations of discharge [6] or energy production, levels may vary and access to the navigation lock can only be granted with authorisation. Once inside, vessels are moored to the eight bollards distributed on the two sides of the navigation lock, two upper and two lower (see *Figure 2*). Once moored, the vessel's master confirms the mooring by radio. The lockage process can then begin, either ascending or descending.

With the automation of the navigation lock, using high-resolution cameras, radars, lidars and equipment with information sensors, the pilot navigation lock is now operated remotely, although communication between the masters and operators is maintained via radio with the locking held hostage by verbal confirmation between the master and the operators. This automation of locks is a process that provides improved operational safety, efficiency, reliability, and reduced operations and maintenance [7], and the waiting time [8].

2.1 Mooring system

On the Douro navigation route, the mooring bollards in each lock are floating and therefore follow the water level in the boiler chamber (inside the navigation lock), see *Figure 2*. The behaviour of the bollards and the vessels in the lock chamber are subject to unpredictable currents due to the inflow of water through the bottom of the lock chamber, i.e. due to the dynamics of underwater currents.

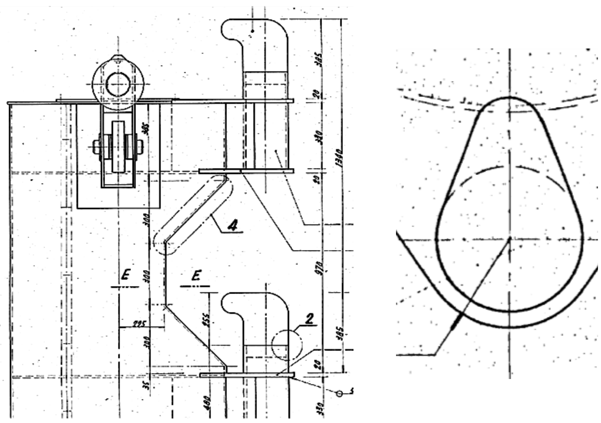

Figure 2: Detail of the lock mooring bollard

The buoyancy is an important feature for ascending and descending depending on the elevation level, but it poses a serious setback to the mooring automation process. This setback is related to the cabling, since the differences in accounts can be around 30 m, making it impractical to use a wired system. Therefore, to solve this problem, it was necessary to use sensors capable of communicating with the controller without the use of communication cables [9].

3. Methodology and Solutions Study

The implementation of a project of this nature, without reconstruction of the lock chamber [10], is subject to many structural and functional requirements that aim to ensure the reliability of the system and guarantee its efficiency. In this sense, factors external to the system, such as climatic and environmental conditions inherent to the navigation lock, as well as mechanical wear, prove to be predominant factors to defining the operational requirements of the mooring system. Therefore, in the initial phase, the methodologies to be adopted must be defined so that the development of the system can be successfully implemented and respond to all requirements:

- ***Wireless communication and power supply*** – necessary to avoid the use of cables and mechanical wear associated with the extensive vertical movement of approximately 30 m of the head structure. This requirement can be met by using wireless sensors, batteries, and transmission nodes that enable connection to the *gateway*.
- ***Ingress protection (IP) ratings*** – the degree of protection of the system must be defined in accordance with IEC 60529 [11]. This must ensure that the equipment can operate in aquatic environments subject to temporary immersion. This requirement can be guaranteed with a minimum IP rating of 67 (IP67, dust-tight and temporary immersion in water).
- ***Associated costs*** – the total costs associated with developing and implementing the system must be considered. In this situation, the type of sensor, the mode of communication, as well as the type of maintenance and frequency to be adopted are considered.

3.1 Mooring Bollard

The mooring bollards are made of carbon steel, offering durability and reliable performance in marine environments. Built according to a tubular topology, they have a diameter of 119 mm. The thickness of the carbon steel used is 13 mm, which allows it to withstand all tensile loads imposed during mooring manoeuvres. Each side has four sets of wheels, two above and two below (see *Figure 2*), which are installed centrally under the same vertical axis, but crossed in relation to each other.

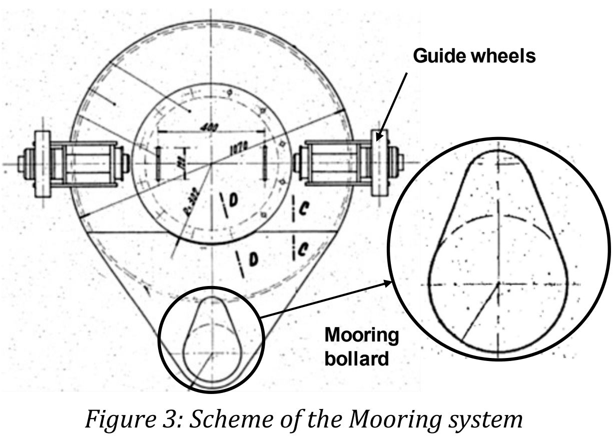

Figure 3: Scheme of the Mooring system

The bollards circulate in a groove on the side edges of the navigation lock structure, serving as a guide for the installed wheels. *Figure 3* shows a detail of the bollard as well as the guide wheels of the mooring system.

3.2 Solution Study

In accordance with the requirements presented above, a variety of solutions can be considered to meet the proposed objectives. Thus, any approach formulated will have to consider not only the cost of the equipment, but also the changes to the head structure that may result from its development. After considering all these points, several implementation hypotheses were raised, which resulted in the following:

Load Cell

A load cell or sensor is an electromechanical device capable of converting deformations resulting from applied forces into electrical signals. This is therefore the principle intended for our mooring verification system. Thus, if the idea is to quantify the force applied to the mooring bollard [9], it will be necessary to implement a load cell capable of measuring the force exerted by a kayak or a hotel ship with hundreds of passengers, i.e. a highly sensitive sensor. However, what is really needed in this operation is the reliable detection of the presence of a rope and the indication of the correct mooring of the vessel, regardless of the force exerted. On the other hand, and in constructive terms, the sensor would have to be housed in an internal cavity in the mooring bollard and, inside, ensure wireless communication with the receiver, in accordance with the appropriate environmental protections. *Figure 4(a)* shows a sketch of the load sensor implementation and how it works.

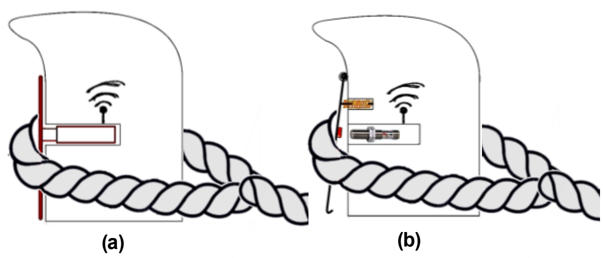

Figure 4: Implementation Scheme of the: (a) Load Cell; (b) spring Trigger

Spring Trigger

This solution consists of applying a retractable tab positioned by a spring. During the mooring action, the trigger approaches to the capacitive or inductive sensor, changing its logical state to high. Installed in a cavity, see *Figure 4(b)*, similar to the load cell implementation, it simply indicates whether it is active or inactive. This is the information we need to receive. Compared to the previous solution, this one is simpler, with the same requirements, as it simply indicates whether there is tension on the mooring head.

Sliding Actuator

This approach is similar to the previous one. In this case, the trigger was replaced by a vertical rail along the entire length of the bollard. This is kept away from the sensor by one or more springs which, when compressed by the mooring rope, bring it closer to the sensor installed inside the bollard structure. With this approach, it is necessary to open a vertical slit to accommodate the vertical rail, a machining operation that would have to be carried out on site or during maintenance operations. This is an expensive and time-consuming process.

As an alternative to machining, the possibility of applying a part that allows the sensor to operate without major structural changes was studied. The actuator would be manufactured as an extension of the headstock and fixed in the area of tension exerted by the strings at the moment of mooring, *Figure 5*.

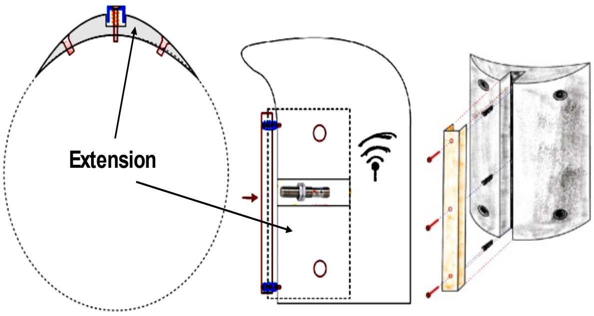

Figure 5: Scheme of the Mooring system

Other solutions using ultrasonic sensors could be adopted. However, this solution would be extremely complex to implement, not only because of the precision required of the sensor during mapping, but also because of the complexity of the control algorithm. Added to this are the high costs of an IP66 or higher category sensor, even though it does not require any modifications to the mooring bollard.

3.3 Choice Study

The choice of solution/study depends on the individual assessment of each proposal, considering the complexity, implementation and characteristics of the sensors to be used. Analysing what has been previously stated and, above all, the characteristics and complexity of the system, the most assertive choice is based on mechanical performance. This choice is supported by the simplicity and ease of detecting mooring using an industrial sensor, which leads to ease of installation and maintenance associated with reduced costs.

Communication system

The lack of electrical infrastructure near the bollards raises the problem of powering the sensors and transmitting the collected information. Therefore, the system must be equipped with sufficient autonomy to power the sensors and the communication system. This problem was solved by using a *WILSEN.node* unit from *Pepperl+Fuchs* [12], with an internal 13000 mAh lithium battery, two M12 socket inputs for two-wire NAMUR sensors, direct power supply capacity for the sensors, and remote configuration via Bluetooth 5.0 LE. This system can operate for several years (approximately 10 years) with efficient power supply (lithium battery) and ensure efficient transmissions based on the LoRaWAN class A device type as well as a GPS (Global Positioning System) sensor.

Proximity Sensor

The selected proximity sensors were of the NAMUR type, due to their characteristics [13], are in this application, as fundamental elements in the longevity of the system, since they operate with variations in the electrical current level of the circuit, allowing the control system to interpret the status of the sensor based on this current, keeping them in an inactive state with currents between 2.1 and 2.8 mA and voltages of 8 VDC, i.e., keeping them in standby.

The use of this type of equipment in the project, due to its simplicity and operational robustness in adverse environments, is a differentiating factor that will ensure, in the long-term, high-energy autonomy, with a consequent reduction in maintenance operations, and perfect integration with Industrial Internet of Things (IIoT) networks and, therefore, medium and large-scale industrial interoperability [14]. Interoperability was achieved using the IFM NE5001 sensor (M8, detection range 1.5-2.0 mm, 8V and IP67) which, in addition to meeting the project specifications, is very competitively priced compared to other similar alternatives. On the other hand, the combination of WILSEN.node and IFM NE5001 ensures robustness, energy efficiency, reliability of readings, maintenance, compatibility with the operating environment and, due to the need for replication of the other dams on the navigable Douro River, the scalability of the system in a simple and standardised way.

Figure 6 shows the variation in battery life in various operating scenarios, as provided by the manufacturer. This understanding of the system's behaviour in relation to the number of transmissions and information acquisition is vital for preventive/predictive maintenance operations [7][15]. Therefore, the MTBF (Mean Time Between Failures) maintenance interval will be closely linked to the average number of ascents and descents performed by the navigation lock.

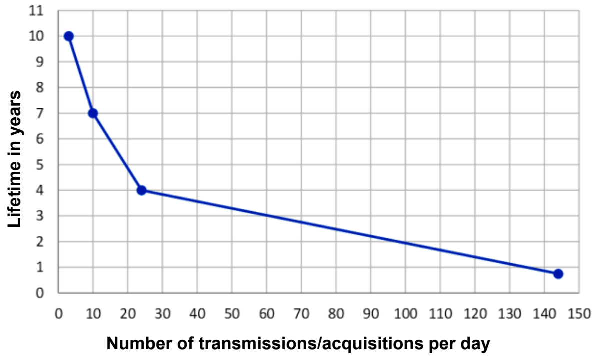

Figure 6: Battery life/cycles per day

3.4 Control Algorithm

The control algorithm was designed to receive information sent by each bollard to provide a reliable overview of ongoing operations. The information received from the eight bollards, four on each side of the navigation lock, allows the operator to act accordingly and in accordance with the signals received.

On the other hand, for this information to be accurate and enable sound decision-making, the system will have to carefully analyse the information received and use it intelligently. This assessment results from the oscillation of the vessels, the loosening of tension in the bollard and the consequent loss of signal. Then, the algorithm should not consider oscillations as an effective loss of signal, but rather as a temporary oscillation of the signal. In the eyes of the operator, the signal should remain active. It is natural that this phenomenon manifests itself in different ways for vessels that use only one mooring bollard or in the case of mooring with two bollards. In this situation, it is normal for one of the bollards to continue transmitting the signal.

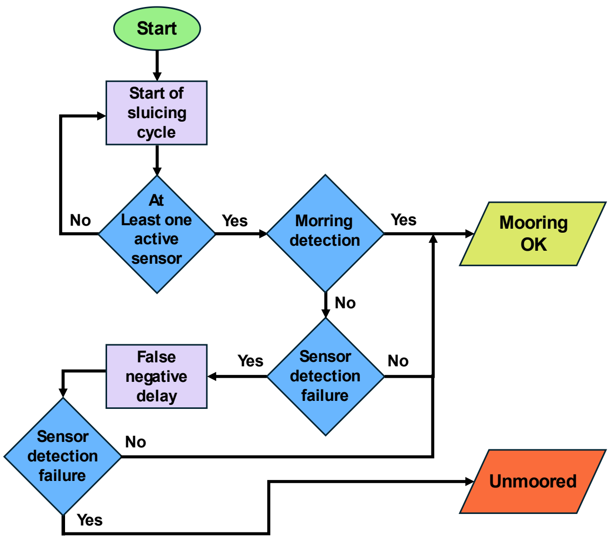

Figure 7: Flowchart of the mooring algorithm

Figure 7 shows the flowchart of the mooring control algorithm. This allows the information to be read and acted upon correctly, whereby information from one of the eight bollards will translate into mooring OK information. In the event of a signal failure or tension relief on the bollard, a delay begins to count down. If the tension is not restored by the end of the delay, the system automatically will assume that the vessel has inadvertently unmoored and will transmit this information to the operator in the form of an alert.

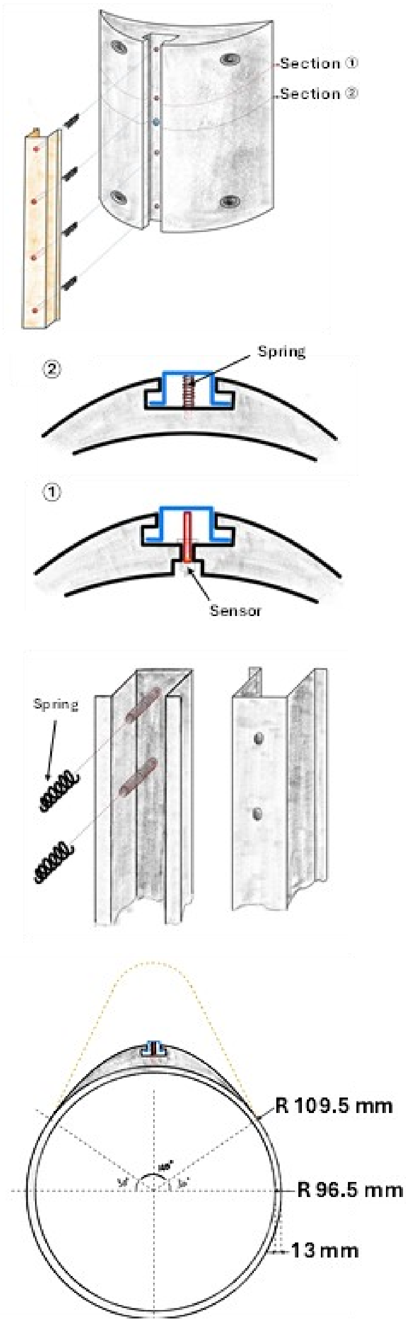

Figure 8: Details of the Mooring System Assembly

4. Solution Implementation

In the mooring process, the size of the vessel is fundamental. This difference in size is reflected in the angular position of the rope between the bollard and the vessel, which varies significantly with different sizes of the vessel. Ensuring that the sensor acts under the tension of the rope, regardless of the point of tension and its angle, is the main challenge at this stage of development. So, the most efficient way to deal with this variation is to place the sensor in a central position between the bollard and the actuator. A vertical rail moves perpendicular to the mooring bollard, penetrating the support structure by the pressure of the mooring rope. With this movement, the sensor will switch to the high logic level, indicating that the mooring is done correctly. This movement of the actuator in and out is performed by a spring-drive mechanical system that keeps the actuator vertically tensioned and in the rest position.

The final design of the actuator will be developed to accommodate the sensor at the rear, in the central area, and will be mounted on the mooring bollard. *Figure 8* details some of the operational characteristics of the system.

4.1 Communications Protocol

Communication between the floating bollards and the Siemens S7-1200 controller, used in the navigation lock automation, is based on a decentralised and completely wireless architecture, using LoRaWAN technology. Information is transmitted by radio frequency using the LoRaWAN protocol in the EU868 band and is received by a LoRaWAN gateway that acts as an access point between the wireless network and the facility's wired infrastructure. This gateway communicates with the Siemens S7-1200 PLC via an Ethernet network, using a compatible industrial protocol such as MQTT (Message Queuing Telemetry Transport) [16] or Modbus TCP/IP (Transmission Control Protocol/Internet Protocol) [17].

The adoption of this communication model aims to ensure not only reliability in the transmission of sensor data, but also to facilitate maintenance. It reduces installation costs and offers future scalability for other monitoring points. The proposed architecture integrates directly into the existing automation network, allowing the PLC to process the received data and make it available in real time in the Human Machine Interface (HMI). The communication model adopted was the Dragino LG308N Indoor gateway [18], for DIN rail (Deutsches Institut für Normung), given its balance of price, robustness, and functionality.

4.2 Integration with the Installed System

The added value of this project lies in the fact that the remote mooring control system can be directly integrated with equipment already installed and operational in the navigation lock, which currently supervises the various lock control systems as well as navigation water levels. On the other hand, this integration with the existing system will be considered by all operators as an additional task to their daily routine, so the learning curve for the procedure is negligible. This is a significant factor, as it significantly reduces development and learning costs, given that operators are already very familiar with the automation work environment in the HMIs.

The main objective of this integration adds a new tab to the touchscreen display, to the Siemens KTP 900, to the monitoring system, which can clearly display the status of sensors, alarms, and commands without compromising the procedure and experience of operators. Thus, to meet these operational requirements, the system will be developed to work discreetly and effectively in conjunction with all current lockage's operations. The control and integration logic will be developed considering the specific characteristics of the facility and its mode of operation. *Figure 9* shows the process of developing the control logic and its integration with the hardware system currently in use.

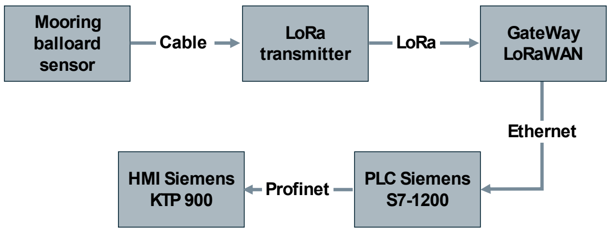

Figure 9: Communication Flow Integration

Therefore, considering all constraints and variables occurring inside the lock, vessel oscillations and momentary loss of tension in the mooring bollards, a control logic was developed capable of responding to these interruptions. To solve these issues, state variables were defined (0 to 4) for each sensor to reflect all these possibilities:

- ***State 0*** – indicates that the sensors are inactive. No tension is detected on the bollard. It is signalled by a red light.
- ***State 1*** – indicates that a lock cycle is in progress. The control variable "*Ecl_ON*" (lockage cycle) switches to high state, however without mooring detection. The mooring sensor light remains red.
- ***State 2*** – indicates that the "*Ecl_ON*" variable is active and that at least one of the bollard sensors has been activated. The light signal of the activated sensor turns green, indicating that the vessel is moored. In this state, if the sensor becomes inactive, the transition to state 3 occurs.
- ***State 3*** – indicates that the signal from a given sensor, previously active, has been lost, causing its light signal to turn orange. This state represents a transitional state due to the disappearance of tension in the bollard due to the

oscillation of the vessel. However, if after some time the signal reappears, it returns to state 2, otherwise it moves to state 4.

- ***State 4*** – indicates that, at the end of the preset timeout, the sensor has stopped detecting the vessel's mooring, so the light signal turns red. If the sensor does not return to the active state, the "Mooring Failure" alarm will appear highlighted on the HMI monitoring panel and the process will need to be restarted.

At the end of the locking process and departure of the vessel, the control variable "*Ecl_ON*" returns to the low state, indicating that there are no vessels inside the lock. *Figure 10* shows a simplified Grafcet that translates the four states mentioned above.

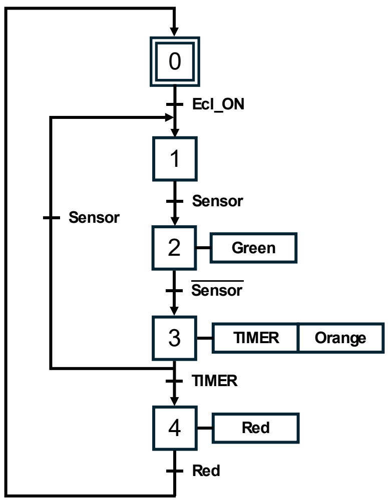

Figure 10: Simplified Grafcet of the Mooring States

4.3 Monitorisation

Monitoring process is fundamental to perceiving the operational status of the system. Thus, in addition to the monitoring signals already mentioned, the HMI should function as a process parameterization element. Therefore, parameterization, during the system commissioning phase, is vitally important in adjusting the delay used in the mooring failure detection logic. The perception of failure at the correct time is fundamental for the correct activation of the alarm, in the detriment of false alarms caused by momentary oscillations of the vessels, see *Figure 10*.

On the other hand, considering the entire system already developed and operational at the lock, the integration of a new graphic separator, dedicated exclusively to the mooring system, must maintain the aesthetic standard so as not to compromise the operator's familiarity with the system. In this new separator, each bollard is represented visually, reflecting its status in real time: moored, awaiting confirmation, or detection failure.

Figure 11 shows the configuration of the separator for monitoring the mooring status of vessels in the lock. In addition to displaying the LEDs associated with each mooring bollard. It also offers two buttons that allow you to check the settings in (PARÂMETROS) and the events that have occurred in (EVENTOS).

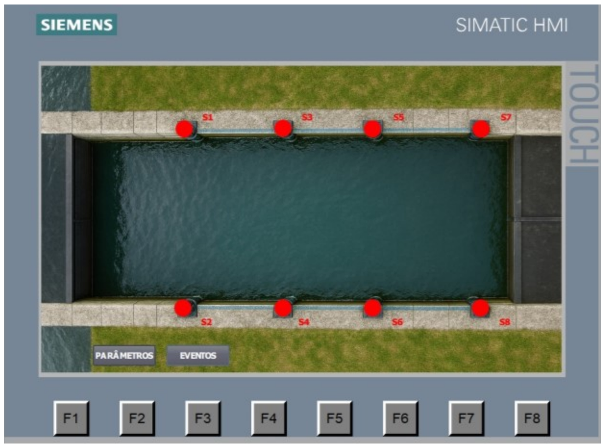

Figure 11: Monitorisation of the Mooring State

On this page, each mooring bollard is visually represented, reflecting its status in real time: moored (*Figure 12*), awaiting confirmation of mooring (*Figure 13*), or detection failure (*Figure 14*).

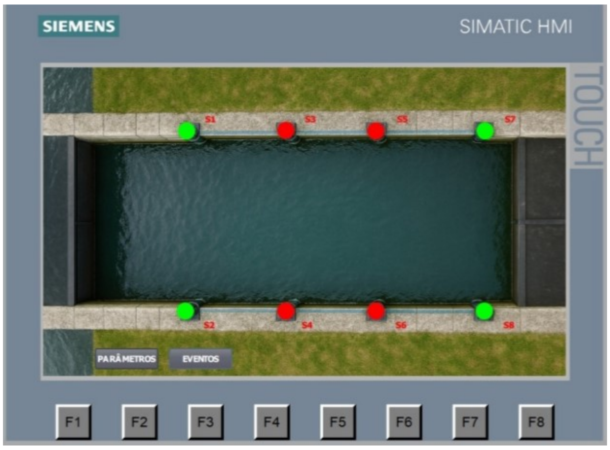

Figure 12: Lock Monitoring, 4 Active Mooring Points

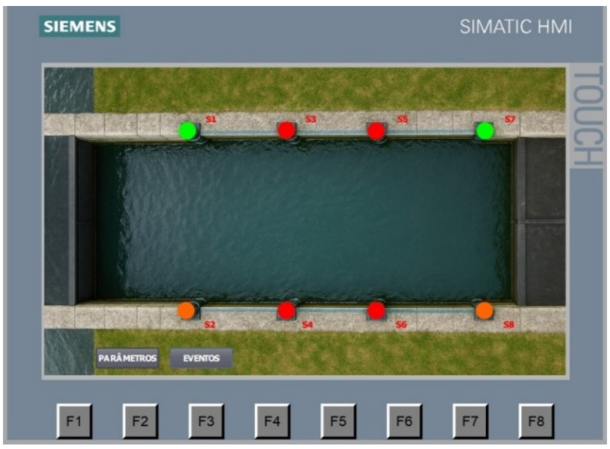

Figure 13: Lock Monitoring, 2 Oscillating Mooring Points

Sensors S2 and S8 momentarily turn orange, corresponding to the vessel's oscillations. Temporary loss of tension in the mooring bollard.

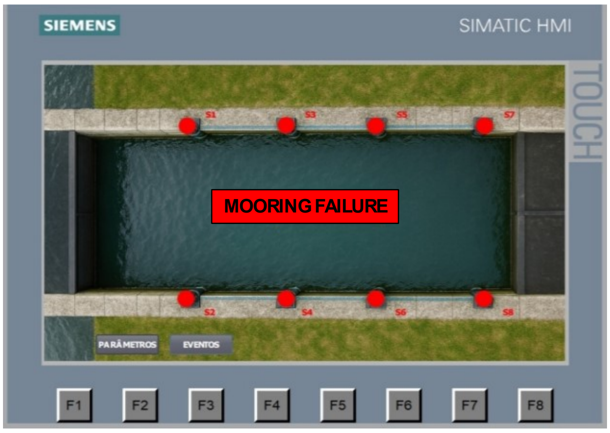

Figure 14: Lock monitoring, "Mooring Failure" Alarm

In addition, a new page/tab has been developed that allows users to view event logs and consult the history of relevant faults, alarms and interventions, thereby improving traceability and future analysis of system performance, *Figure 15*. Whenever a relevant state transition occurs, such as a prolonged loss of the mooring signal, a visual and audible alert is generated, accompanied by the recording of the event in the system history, which is essential for incident analysis, contributing to continuous improvement and good operational practices.

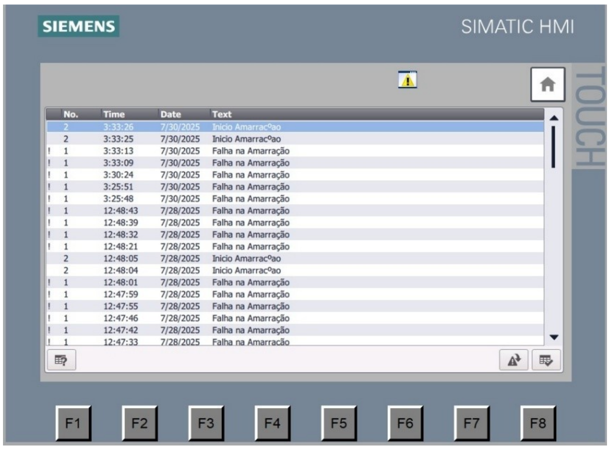

Figure 15: Monitorisation of Events Page

To complement all these lock control and monitoring features, the system also provides another tab ("Parameters" >> Setpoint delay) that allows you to adjust the time applied to the fault detection logic. This feature allows the operator to dynamically configure the tolerance time between the loss of tension signal and the activation of the alarm, adapting the system to the type of vessel present or the lock conditions. The timing value is adjusted in real time, ensuring operational flexibility and avoiding false alarms caused by momentary rope oscillations. All information displayed on the HMI is obtained directly from the data processed by the PLC, which ensures total consistency between the control logic and the information presented.

4.4 Solution Validation

The logic control for detecting vessel mooring was designed to respond consistently to different operational scenarios, with a particular focus on situations that could compromise the safety of the lockage operation. Although it was not possible to physically implement the sensors and equipment, the solution was fully validated through simulations in the TIA Portal environment [19].

During the simulation phase, the system's response to different types of faults was verified, namely the momentary or permanent loss of the tension signal from a bollard, the total absence of signal from all bollards, and the cyclic variation of the logical state of the sensors. The control logic behaved consistently in all cases, maintaining the integrity of the system and ensuring that alarms were only activated in duly sustained critical conditions. The values used for timing were defined based on realistic estimates of the behaviour of vessels during the lockage process, considering the natural oscillations caused by currents inside the lock chamber.

Despite the lack of real-world testing, the simulation carried out in a digital environment confirmed that the solution met the main logical and functional requirements.

5. Conclusions

The proposal presented proved to be technically feasible and flexible, capable of integrating with existing systems in the lock infrastructure. The system's ability to adapt to different operational realities stands out, namely through the parameterisation of times directly on the HMI and the inclusion of an events page that records all occurrences, which contributes to improving traceability, maintenance, and operational safety.

The detection logic is based on a clear and replicable criterion, which can be easily implemented in a physical environment in the future, maintaining compatibility with existing Siemens equipment in the infrastructure of any of the locks on the Douro River. The modularity of the logic also allows it to be adapted to different bollards configurations or sensor models, giving it flexibility for different operational contexts.

Future work will involve moving on to the physical prototyping and real-world testing phase, where the parameters can be refined and the expected advantages in terms of safety, efficiency, and reliability can be confirmed in practice. The scalability of the system to other locks on the Douro River is an interesting challenge, given that along the

Douro River and its five locks, the challenges are different and conditioned by the characteristics and dimensions of each lockage's.

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