Development of a Control and Monitoring System for Ballast Systems Based on Programmable Logic Controllers (PLC) and Human-Machine Interface (HMI)

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***Abstract*— The ballast control management system plays a vital role in maritime operations by ensuring vessel stability and safety while minimizing environmental risks associated with ballast water transfer. Effective ballast management regulates the filling and emptying of ballast tanks to maintain proper trim, draft, and balance during navigation and docking. With the enforcement of the Ballast Water Management (BWM) Convention by the International Maritime Organization (IMO), vessels must implement a Ballast Water Management Plan (BWMP) and maintain a Ballast Water Record Book to comply with international regulations. This study aims to develop a PLC- and HMI-based ballast control system that enhances monitoring and automation of ballast operations. The system is designed to improve control accuracy, diagnostic capabilities, and operational flexibility while ensuring compliance with IMO regulations. The research methodology involves system design, hardware integration, and software programming to create an automated control and monitoring solution. The PLC system utilizes digital inputs to operate pumps and valves, while analog sensors measure tank levels and pressure. The HMI interface displays real-time data, enabling seamless user interaction. The results demonstrate that the proposed system significantly enhances ballast operations by improving automation, control accuracy, and monitoring capabilities. The system ensures safe and efficient ballast management while facilitating regulatory compliance. These findings highlight the potential of PLC and HMI technologies in advancing maritime automation and control systems.**

Keywords—*Ballast control, Ballast monitoring, Programmable Logic Controller (PLC), and Human-Machine Interface (HMI)*

I. INTRODUCTION

The ballast system is a crucial component in maritime operations, enabling ships to regulate weight distribution and maintain optimal balance in water. By utilizing water as an adjustable load, the ballast system facilitates adjustments in sailing depth, stability, and trim. The system consists of several key components, including ballast tanks, ballast pumps, pipelines, control valves, level sensors, and a control system that manages the inflow and outflow of ballast water [1].

Efficient ballast control is essential for modern ship operations, ensuring vessel stability and safety under varying sea conditions. Traditionally, crew members have conducted ballast operations manually, which can be time-consuming and prone to human error. However, advancements in automation technology have significantly improved efficiency and safety. Automated ballast systems enable precise and consistent control of ballasting and deballasting processes, reducing human intervention and minimizing operational errors [2].

Despite these advancements, automated ballast control systems still face significant challenges. Failures in these systems can lead to severe consequences, including ineffective ballast pumping, complete loss of ballast distribution control, and potential compromises to vessel stability. Such malfunctions increase the risk of navigational accidents, environmental hazards, and regulatory non-compliance. Additionally, inefficient ballast operations contribute to higher fuel consumption and increased operational costs due to delays in loading and unloading processes [3]. Existing systems also often lack real-time monitoring capabilities and user-friendly interfaces, limiting operational efficiency and decision-making [4].

To address these challenges, this study focuses on designing and developing a novel PLC-based ballast control and monitoring system that integrates real-time automation, advanced monitoring capabilities, and user-friendly HMI interaction. The proposed system incorporates level sensors in ballast tanks, valve position indicators, and pump status monitoring to enhance automation and operational efficiency [5]. Operators can monitor fluid levels, control valve positions, and operate ballast pumps seamlessly through an interactive HMI.

The novelty of this study lies in the integration of real-time data acquisition, enhanced diagnostic capabilities, and adaptive control mechanisms within a PLC- and HMI-based ballast control system. By reducing manual workload, improving automation

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reliability, and enabling real-time monitoring, the system provides a more efficient, safer, and IMO-compliant solution for ballast management. This development represents a modern alternative to traditional ballast control methods, significantly enhancing vessel stability, operational safety, and environmental compliance

A. Previous Study

In recent years, significant advancements have been made in the automation of ballast water management systems (BWMS) to enhance the efficiency, safety, and environmental compliance of maritime operations. The integration of Programmable Logic Controllers (PLC) into these systems has been a key focus, improving automation, monitoring, and control mechanisms. Several studies have explored the role of PLCs in BWMS, demonstrating their effectiveness in optimizing system performance and ensuring compliance with international regulations.

Perrins et al. [6] conducted a study on the electrolytic sodium hypochlorite system for ballast water treatment, where PLCs were used to control the electrolytic generation of sodium hypochlorite for ballast water disinfection. The study demonstrated that PLC-based automation enhanced the precision and reliability of the treatment process, ensuring compliance with international discharge standards. The implementation of PLCs facilitated real-time monitoring and adjustment of the electrolysis process, improving the consistency and effectiveness of ballast water treatment.

Similarly, Matousek et al. [7] investigated the application of PLCs in ballast water treatment systems, emphasizing their role in integrating automated control mechanisms to optimize the disinfection process. Their findings highlighted the effectiveness of PLCs in managing complex treatment operations, leading to improved system efficiency and reliability. The research also pointed out that integrating PLCs with sensor-based feedback systems significantly enhances operational precision by adjusting treatment parameters in response to real-time water quality data.

Further research by Tsolaki and Diamadopoulos [8] reviewed various technologies for ballast water treatment, underscoring the significance of PLCs in automating processes such as filtration and disinfection. They concluded that PLC integration is essential for achieving the desired treatment standards while maintaining operational efficiency. This study also emphasized that PLC-based automation reduces the need for manual intervention, minimizing the risks of operational errors and ensuring consistent compliance with environmental regulations.

Park et al. [9] studied the implementation of PLC-controlled ozone-based ballast water treatment systems, demonstrating that PLCs effectively managed ozone generation and dosing. Their findings revealed that PLC-controlled automation improved the accuracy of ozone concentration regulation, resulting in efficient disinfection and compliance with international maritime regulations. The study also highlighted that PLC integration enables adaptive control strategies, allowing the system to dynamically adjust ozone levels based on real-time contamination levels in ballast water.

In addition, Wright and Dawson [10] conducted shipboard trials of primary and secondary ballast water treatment systems, highlighting the importance of PLCs in controlling and monitoring treatment processes. Their research indicated that PLC-based systems offer enhanced reliability and adaptability across various operational conditions. The trials demonstrated that PLC-based control systems reduce response times to changes in ballast water conditions and enhance system resilience to environmental variations.

Veldhuis et al. [11] contributed to this field by discussing the development of ballast water treatment systems with integrated PLC control. Their study emphasized that PLCs play a vital role in ensuring the effectiveness and compliance of BWMS with evolving international standards. The study also pointed out that the flexibility of PLC programming allows for easy adaptation to new regulatory requirements and technological advancements, making PLC-based systems a future-proof solution for ballast water management.

These studies collectively highlight the pivotal role of PLCs in modernizing ballast water management. The integration of PLCs enhances automation, monitoring, and control in BWMS, leading to increased operational efficiency, adherence to international regulations, and protection of marine ecosystems from invasive species. The findings from previous studies serve as a foundation for further advancements in automated ballast water management, reinforcing the importance of continued research and development in this field.

Meanwhile, in our study, PLC and Human-Machine Interface (HMI) are integrated to control and monitor ballast system pumps and valves, aiming for more efficient operation. The system optimizes real-time data visualization, automated diagnostics, and dynamic control, ensuring improved stability and reduced manual workload. By implementing PLC and HMI integration, the proposed system aims to enhance operational safety, reliability, and compliance with IMO regulations, thus contributing to the advancement of ballast water management technology.

B. Ballast System Overview

The ballast system is a critical component of a ship that ensures proper weight distribution, stability, and trim by controlling the intake and discharge of ballast water. This system is essential for maintaining a ship's structural integrity, reducing stress on the hull, and adapting to various loading conditions. A well-designed ballast system improves operational efficiency and enhances navigational safety [12].

A ballast system consists of multiple interconnected components as shown in **Figure 1** that work together to manage the ship’s stability effectively i.e., [13][14].

- Ballast tanks are defined as compartments distributed across the vessel that store ballast water.
- Control systems are defined as a combination of manual and automated control mechanisms that manage pump and valve operations.

- Pipelines and valves are defined as a control mechanism for directing water flow within the system.
- Level sensors are defined as devices used to monitor water levels in ballast tanks, ensuring accurate weight distribution.
- Ballast pumps are defined as equipment responsible for filling and emptying ballast tanks as needed.

Recent advancements in automation have led to the adoption of PLCs and HMIs for optimizing ballast operations [19][20]. PLC-based ballast control improves safety by minimizing human intervention, ensuring reliable operation, and enabling integration with ship-wide automation networks. The ability to automate ballast operations contributes to improved fuel efficiency and cost savings for ship operators [21][22].

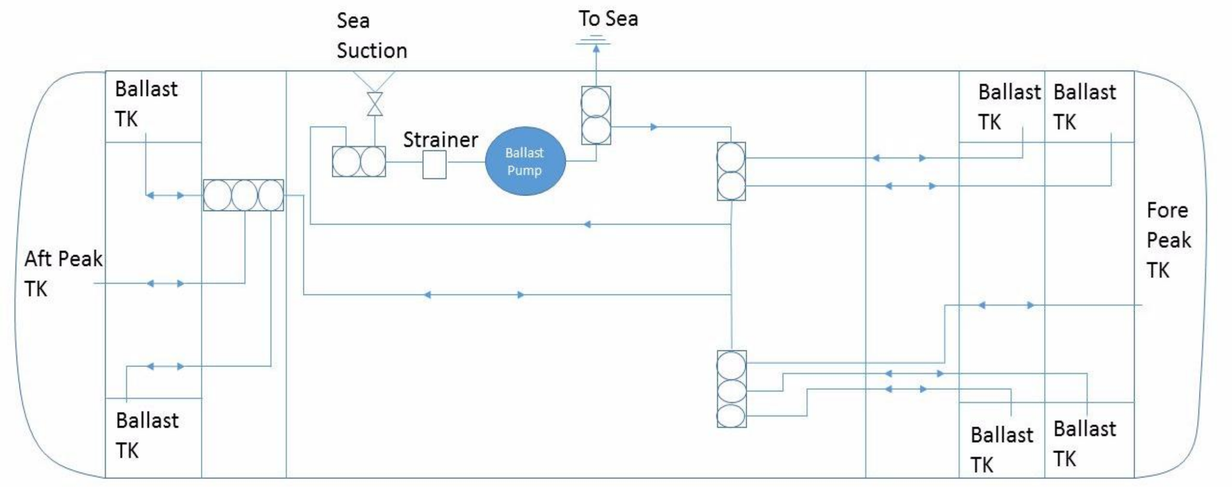


Figure 1. Ballast System Component

Traditionally, ballast systems required manual operation, with crew members physically opening and closing valves and activating pumps to manage stability. This method was prone to human errors and inefficiencies. Over time, automation has played a significant role in improving ballast operations by integrating advanced control systems [15].

Modern ballast systems utilize Programmable Logic Controllers (PLC) for precise operation of pumps and valves. PLCs provide better automation, minimize response times, and enhance control accuracy. The incorporation of Human-Machine Interface (HMI) further enhances system monitoring by displaying real-time data on tank levels, valve statuses, and pump conditions. These interfaces enable remote operation and provide alarms for critical failures, improving both safety and efficiency [16].

The improper discharge of ballast water poses a significant environmental threat by introducing invasive aquatic species into foreign ecosystems. To address this issue, the International Maritime Organization (IMO) introduced the Ballast Water Management (BWM) Convention, which mandates the adoption of approved ballast water management systems. Under this convention, ships must implement treatment methods such as filtration, chemical disinfection, and ultraviolet radiation to meet regulatory compliance [17].

Additionally, the implementation of automated ballast systems contributes to the enforcement of the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) by ensuring accurate water treatment and monitoring. Compliance with these regulations is essential for reducing ecological risks and avoiding penalties from maritime authorities [18].

C. Programmable Logic Controller (PLC)

A Programmable Logic Controller (PLC) is an industrial digital computer specifically designed to control manufacturing processes, such as assembly lines, robotic devices, and complex industrial automation systems. PLCs are widely recognized for their ability to withstand harsh industrial environments, offering high reliability, ease of programming, and robust fault diagnosis capabilities [23].

The architecture of a PLC consists of a central processing unit (CPU), a power supply unit, memory storage, input and output interfaces, and communication interfaces to interact with external devices and systems. The CPU interprets input signals, executes control logic based on a pre-programmed algorithm, and generates output signals to control actuators and other devices. The modular design of PLCs enables scalability and flexibility, making them suitable for a wide range of industrial applications, including maritime operations [24].

In the maritime industry, PLCs play a vital role in automating ballast systems, which are crucial for maintaining a ship's stability by regulating ballast water intake and discharge. The automation of ballast operations enhances operational efficiency, reduces human intervention, and ensures compliance with international maritime safety and environmental regulations. According to Kusuma [25], the development of an automatic ballast system using a PLC for a catamaran vessel resulted in improved stability during maneuvers. The study demonstrated that the PLC-based system could dynamically adjust ballast operations in response to real-time vessel tilt, enhancing safety and performance.

Furthermore, PLC integration in ballast control systems allows for precise monitoring and control of pumps and valves, significantly reducing the risk of manual errors. Automated ballast systems can dynamically respond to changes in water levels, vessel loading conditions, and environmental factors. Research conducted by Smith et al. [26] emphasizes that utilizing PLCs for ballast operations enhances accuracy, optimizes energy efficiency, and minimizes environmental impact by ensuring compliance with ballast water management standards established by the International Maritime Organization (IMO).

Recent advancements in PLC technology have also led to the integration of Human-Machine Interface (HMI) systems, enabling real-time visualization and user-friendly interaction with ballast control systems. According to a study by Wang and Liu [27], PLC-based ballast automation, combined with HMI visualization, improves diagnostic capabilities, allowing operators to identify faults, monitor performance trends, and implement predictive maintenance strategies. The incorporation of real-time data acquisition and remote monitoring functionalities further enhances the reliability of ballast operations.

Overall, PLC technology continues to evolve, offering enhanced automation, real-time monitoring, and improved safety measures for maritime applications. As the shipping industry moves towards digitalization and compliance with stricter environmental regulations, PLC-based ballast control systems play an essential role in ensuring optimal vessel stability and operational efficiency.

D. Human-Machine Interface (HMI

Human-machine interface (HMI) refers to the platforms and tools that facilitate interaction between humans and machines, enabling users to monitor, control, and manage systems effectively. The design and implementation of HMI are critical in various industries, including manufacturing, transportation, and healthcare, as they directly impact usability, efficiency, and safety [28]. HMIs are developed to enhance operator interaction with control systems, allowing real-time monitoring and operation of industrial processes.

In industrial automation, HMIs serve as the bridge between operators and machinery, providing real-time data visualization and control capabilities. Effective HMI design principles emphasize clarity, intuitiveness, and responsiveness to enhance user experience and reduce the likelihood of errors [29]. User-centered design is a fundamental approach in HMI development, ensuring that interfaces are tailored to the cognitive and physical capabilities of operators. For instance, a study presented at the IEEE International Conference on Mechatronics highlights the significance of ergonomic interface design in improving operational efficiency and reducing human errors in automated systems [30]. Research further suggests that graphical and touchscreen-based HMIs provide intuitive control mechanisms, thereby increasing productivity and reducing cognitive workload [31].

In maritime applications, particularly in ballast water management systems, HMIs play a crucial role in monitoring and controlling ballast operations. The integration of HMIs with Programmable Logic Controllers (PLCs) allows for real-time visualization of system parameters, such as tank levels, valve positions, and pump statuses, enabling operators to make informed decisions and respond promptly to changing conditions [32]. This integration enhances the overall efficiency and safety of ballast operations, ensuring compliance with environmental regulations such as the International Maritime Organization (IMO) Ballast Water Management Convention [33]. A well-designed HMI can assist ship operators in executing ballast operations efficiently by providing alerts, diagnostic insights, and automation features that reduce manual intervention while improving safety [34].

Furthermore, modern HMI solutions incorporate advanced technologies such as touchscreens, augmented reality (AR), and artificial intelligence (AI) to improve user experience and operational control. Recent advancements have shown that incorporating AI-driven predictive analytics into HMI systems can help in early fault detection and maintenance planning, thus reducing downtime in maritime systems [35]. Additionally, remote monitoring capabilities integrated into HMIs provide ship operators and fleet managers with access to real-time data, enabling centralized control and decision-making, which is essential for large-scale maritime operations [36].

In conclusion, HMIs are indispensable in industrial and maritime automation, significantly enhancing operational efficiency, safety, and regulatory compliance. As technology advances, the integration of AI, remote monitoring, and enhanced visualization techniques will further optimize HMI functionality, making them more adaptive and intelligent in responding to complex maritime operational needs.

II. METHOD

The structured research framework for developing a control and monitoring system for the ballast system using a Programmable Logic Controller (PLC) and Human-Machine Interface (HMI) as shown in **Figure 2** described as follows:

1. Literature Study
    - Conduct a comprehensive review of international journals and conference proceedings related to ballast system automation, PLC-based control systems, and HMI implementation in industrial applications.
    - Identify best practices, existing methodologies, and technological advancements in maritime automation.
2. Data Collection on Ballast System
    - Gather detailed information on the existing ballast system configuration, components, and operational parameters.
    - Identify key components such as ballast tanks, pumps, valves, sensors, and control panels.
    - Assess regulatory requirements, such as compliance with the IMO Ballast Water Management Convention.
3. Design of Ballast System

  - Develop a conceptual design for the ballast system, considering functional requirements, safety protocols, and automation objectives.
  - Define the interconnections between sensors, actuators, PLC, and HMI to ensure seamless operation.
4. PLC Design
  - Select an appropriate PLC model based on system complexity and operational requirements.
  - Develop ladder logic or functional block diagrams for automated ballast water intake, discharge, and monitoring.
  - Integrate safety interlocks and fault detection mechanisms to ensure system reliability.
5. HMI Design
  - Develop an interactive HMI interface for real-time monitoring and control of the ballast system.
  - Design graphical elements to display critical information such as tank levels, valve positions, pump statuses, and alarms.
  - Ensure user-friendly navigation and provide control functionalities such as manual override and system diagnostics.
6. Simulation and Testing
  - Simulate the PLC and HMI integration using software tools Schneider Vijeo Designer.
  - Test the system under different operating conditions to evaluate response time, accuracy, and fault tolerance.
  - If the simulation fails, return to the PLC design stage for modifications.
7. Data Analysis
  - Analyze system performance based on response time, operational efficiency, and stability control.
  - Compare manual vs. automated ballast operations to quantify improvements.
  - Identify potential areas to provide recommendations for real-world implementation.

III. RESULTS AND DISCUSSION

This section outlines the development process of the ballast system control and monitoring program, along with the results of the analysis conducted using the implemented system.

A. Design of Ballast System Model

To develop the ballast system program, information about the ballast system should be collected, i.e. the amount of ballast tank, the volume of each tank, etc. The tank information is shown in Table 1.

From sixteen (16) tanks, six (6) tanks will be taken as an example to create and simulate the program as shown in Table 1. The selected tanks are:

- Ballast tank number 3 B.S.W.BTK.P
- Ballast tank number 3 B.S.W.BTK.S
- Ballast tank number 4 B.S.W.BTK.P
- Ballast tank number 4 B.S.W.BTK.S
- Ballast tank number 5 B.S.W.BTK.P
- Ballast tank number 5 B.S.W.BTK.S

B.S.W.BTK.P indicates the Bottom Sea Water Ballast Tank Portside, and B.S.W.BTK.S indicates the Bottom Sea Water Ballast Tank Starboard Side. However, the information on the pressure tank is shown in Table 2. Based on the above information, a ballast system with 6 tanks is created, monitored by 14 valves controlled by 2 pumps, one for hydraulic valves and one for ballast pumps. The pipe layout design to be developed by PLC and HMI is shown in **Figure 3**.

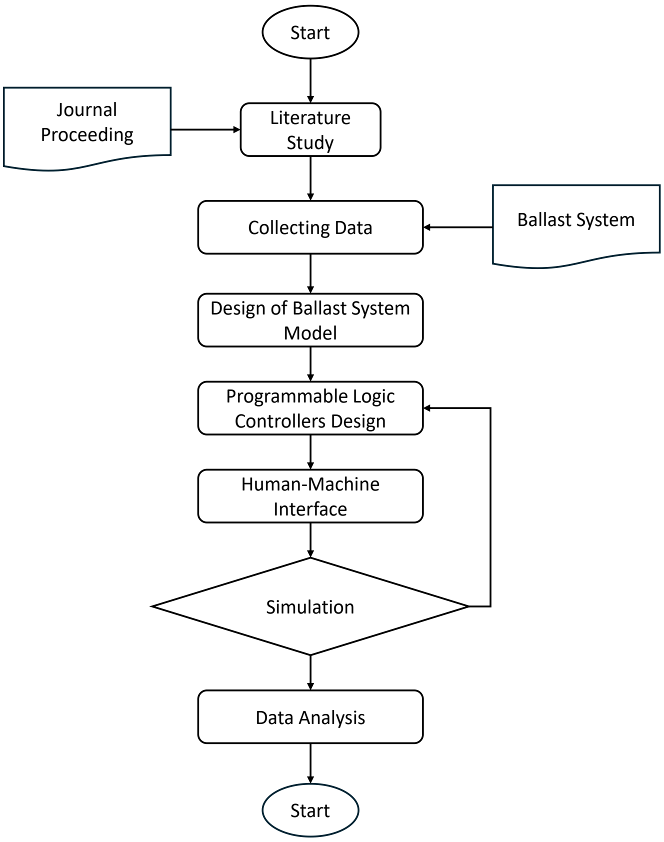


Figure 2. Ballast System Component

B. Development of Program Control

The development of the control program begins with creating the program using the EcoStruxure Machine

TABLE 1.
BALLAST TANK INFORMATION

NAME	FRMIN	FRMAX	FILL	VNET	WEIGHT	L.C.G	T.C.G	V.C.G
	#	#		m^3	t	m	m	m
Water Ballast: Density = 1.025 t/m^3								
F.P.T.K	217	FORE	1.00	2018.63	2069.10	179.500	0.000	7.947
No. 1 B.S.W.BTK.P	183	217	1.00	858.81	880.28	160.809	8.285	1.907
No. 1 B.S.W.BTK.S	183	217	1.00	858.81	880.28	160.809	-8.285	1.907
No. 1 T.S.W.BTK.P	183	217	1.00	481.95	494.00	160.175	13.0.93	16.716
No. 1 T.S.W.BTK.S	183	217	1.00	481.95	494.00	160.175	-13.093	16.716
No. 2 B.S.W.BTK.P	145	183	1.00	1047.30	1073.49	131.737	10.038	1.496
No. 2 B.S.W.BTK.S	145	183	1.00	1047.30	1073.49	131.737	-10.038	1.496
No. 2 T.S.W.BTK.P	145	183	1.00	601.70	616.74	131.841	13.378	16.569
No. 2 T.S.W.BTK.S	145	183	1.00	601.70	616.74	131.841	-13.378	16.569
No. 3 B.S.W.BTK.P	109	145	1.00	1001.00	1026.03	101.500	10.085	1.494
No. 3 B.S.W.BTK.S	109	145	1.00	1001.00	1026.03	101.500	-10.085	1.491
No. 3 T.S.W.BTK.P	109	145	1.00	570.01	584.26	101.500	13.378	16.569
No. 3 T.S.W.BTK.S	109	145	1.00	570.01	584.26	101.500	-13.378	16.569
No. 4 B.S.W.BTK.P	71	109	1.00	1039.46	1065.45	71.347	9.999	1.498
No. 4 B.S.W.BTK.S	71	109	1.00	1039.46	1065.45	71.347	-9.999	1.498
No. 5 B.S.W.BTK.P	35	71	1.00	998.28	1023.24	39.658	9.571	2.874
No. 5 B.S.W.BTK.S	35	71	1.00	998.28	1023.24	39.658	-9.571	2.874
A.P.TK.	AFT	13	1.00	1117.69	1145.63	2.075	0.018	12.698
SUBTOTAL				16333.35	16741.68			

TABLE 2.
HEIGHT AND TANK PRESSURE

Name Tank	H max m)	VNET (m^3)	Pres Max (bar)
NO.3 B.S.W.B.TK.P	6	1001	0.603
NO.3 B.S.W.B.TK.S	6	1001	0.603
NO.4 B.S.W.B.TK.P	6	1039.46	0.603
NO.4 B.S.W.B.TK.S	6	1039.46	0.603
NO.5 B.S.W.B.TK.P	11,51	998.28	1.157
NO.5 B.S.W.B.TK.S	11,51	998.28	1.157
Density	: 1.025 t/m^3		
Gravity	: 9.81 m/s^2		

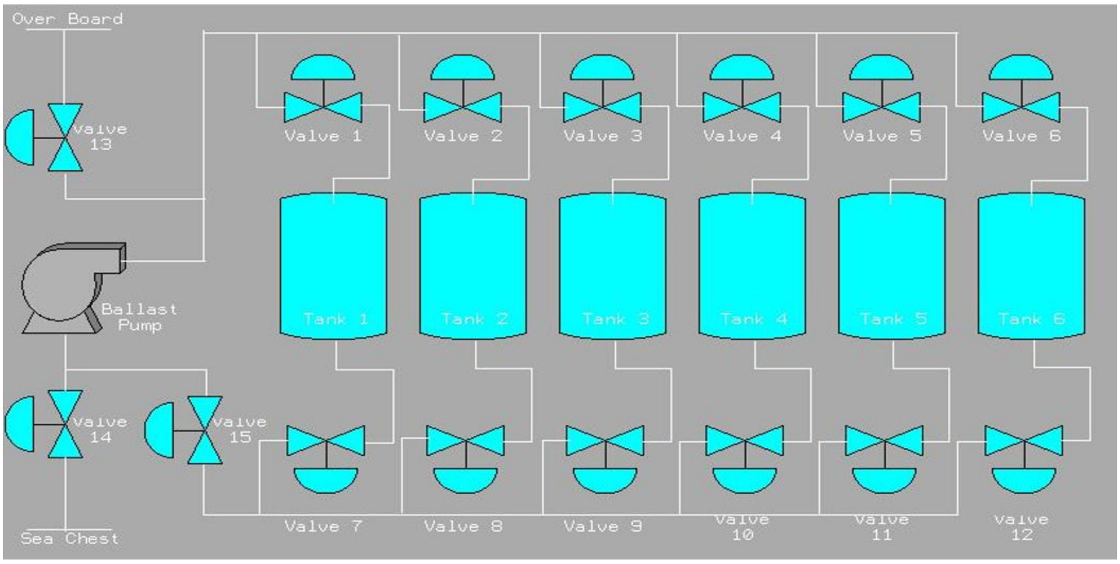
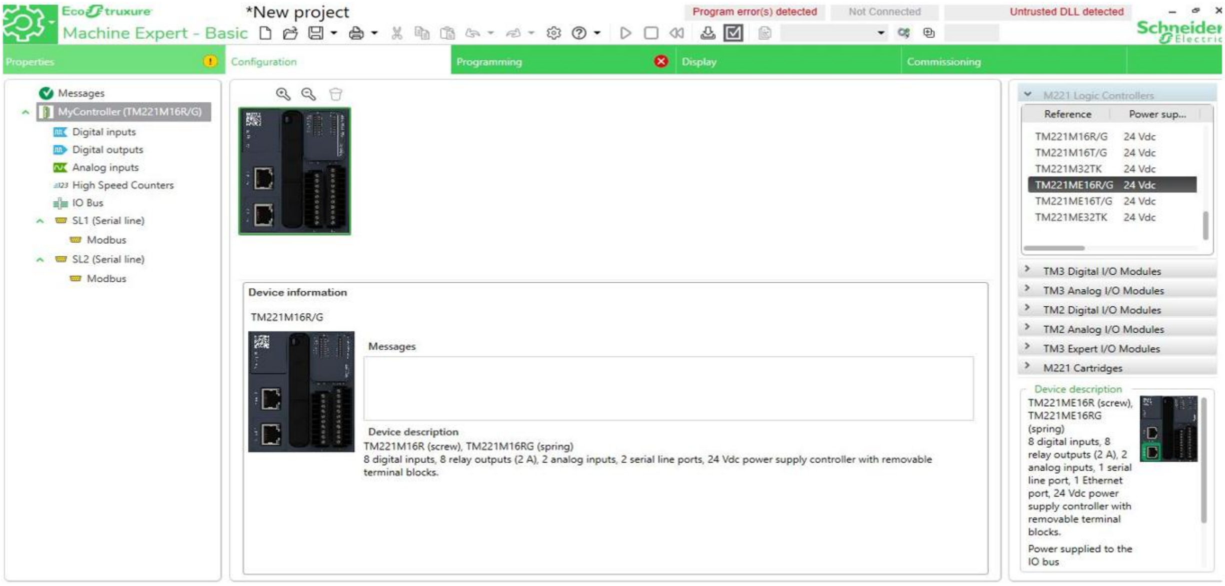


Figure 3. Ballast System Layout Design

Expert application. EcoStruxure Machine Expert is an engineering software developed by Schneider Electric for programming, configuring, and maintaining industrial automation systems, particularly for machine control applications. It is used to design, commission, and maintain controllers. The initial display of EcoStruxure Machine Expert is shown in **Figure 4**. The development of a control program for the ballast system in this study consists of the following steps:

1. Selecting a Controller
   The selection of the controller is used to choose the main controller to be used, along with the input module, output module, and analog module. This selection is adjusted according to the program's requirements and the number of items to be controlled and monitored. The type of controller used in this program is shown in **Figure 5**.
2. Developing a Hydraulic Pump Control Program
   The development of the hydraulic pump program is intended to program the hydraulic pump that will be used to operate the valve. The valve moves due to hydraulic pressure supplied by the hydraulic pump. Below is the hydraulic pump program as shown in **Figure 6**.



Reference	Power sup...
TM221M16R/G	24 Vdc
TM221M16T/G	24 Vdc
TM221M32TK	24 Vdc
TM221ME16R/G	24 Vdc
TM221ME16T/G	24 Vdc
TM221ME32TK	24 Vdc

Device information

TM221M16R/G

Messages

Device description
TM221M16R (screw), TM221M16RG (spring)
8 digital inputs, 8 relay outputs (2 A), 2 analog inputs, 2 serial line ports, 24 Vdc power supply controller with removable terminal blocks.

Device description
TM221ME16R (screw), TM221ME16RG (spring)
8 digital inputs, 8 relay outputs (2 A), 2 analog inputs, 1 serial line port, 1 Ethernet port, 24 Vdc power supply controller with removable terminal blocks.
Power supplied to the IO bus

Figure 4. Controller Selection

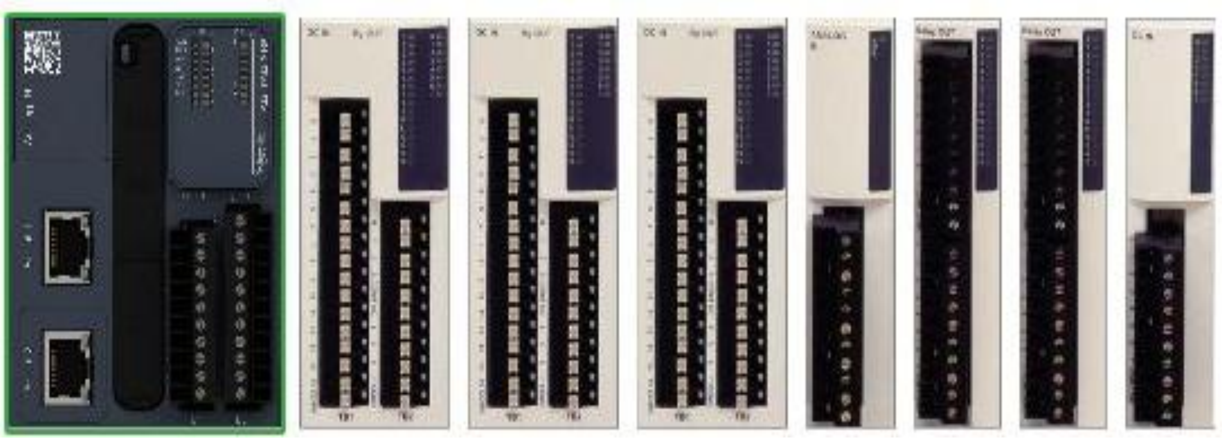
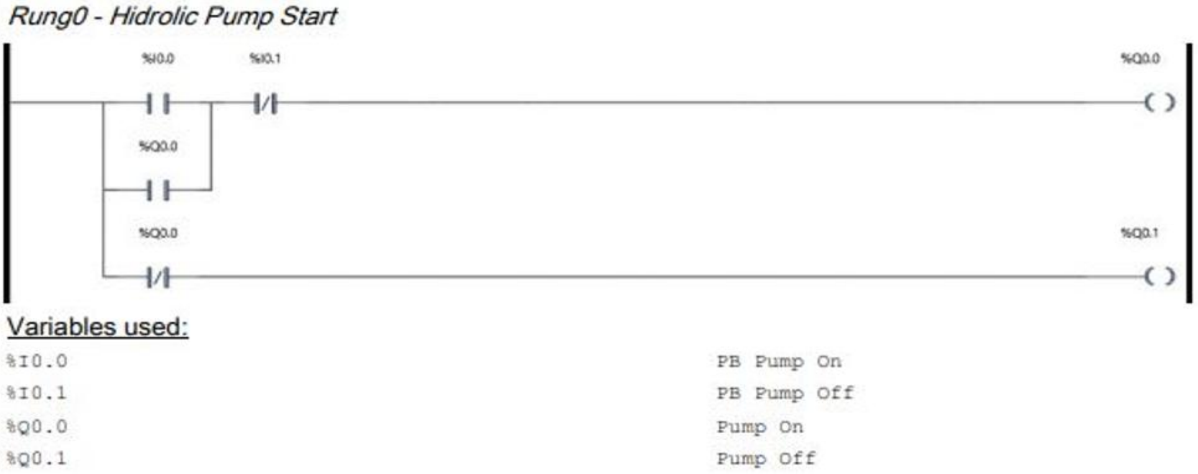


Figure 5. Controller Selection

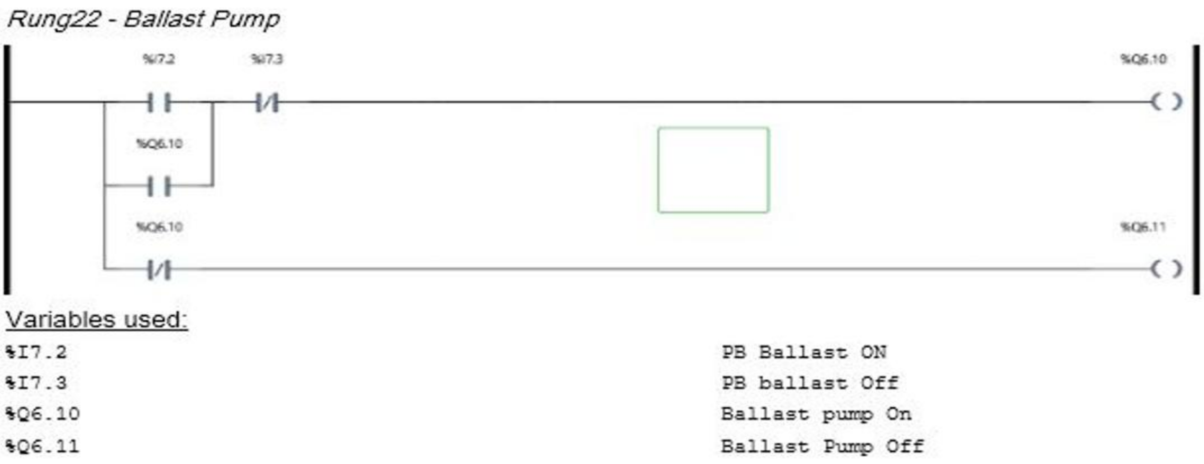
3. Developing a Ballast Pump Program
   The development of the ballast pump program is intended to program the ballast pump, which will be used to fill seawater from the sea chest into the tank and discharge seawater from the tank overboard. The developed program of the ballast pump is shown in **Figure 7**.
4. Developing a Control Valve Program
   The development of the control valve program is intended to open and close the valves used for filling and discharging water from the tank. The program controls a total of 14 valves. An example of the developed program is shown in **Figure 8**.
5. Developing a Pressure Pump Ballast Control Program
   The development of the pressure pump ballast program is intended to monitor the pressure generated by the ballast pump used for filling or discharging water from the tank. The development control program of pressure pump ballast is shown in **Figure 9**.
6. Developing a Ballast Tank Level Control Program
   The development of the ballast tank level program is intended to monitor the tank level. This monitoring uses a range of 0–100, representing the total volume of the tank being monitored. An example of the developed program is shown in **Figure 10**.


Rung0 - Hidrolic Pump Start

Variables used:

%I0.0	PB Pump On
%I0.1	PB Pump Off
%Q0.0	Pump On
%Q0.1	Pump Off

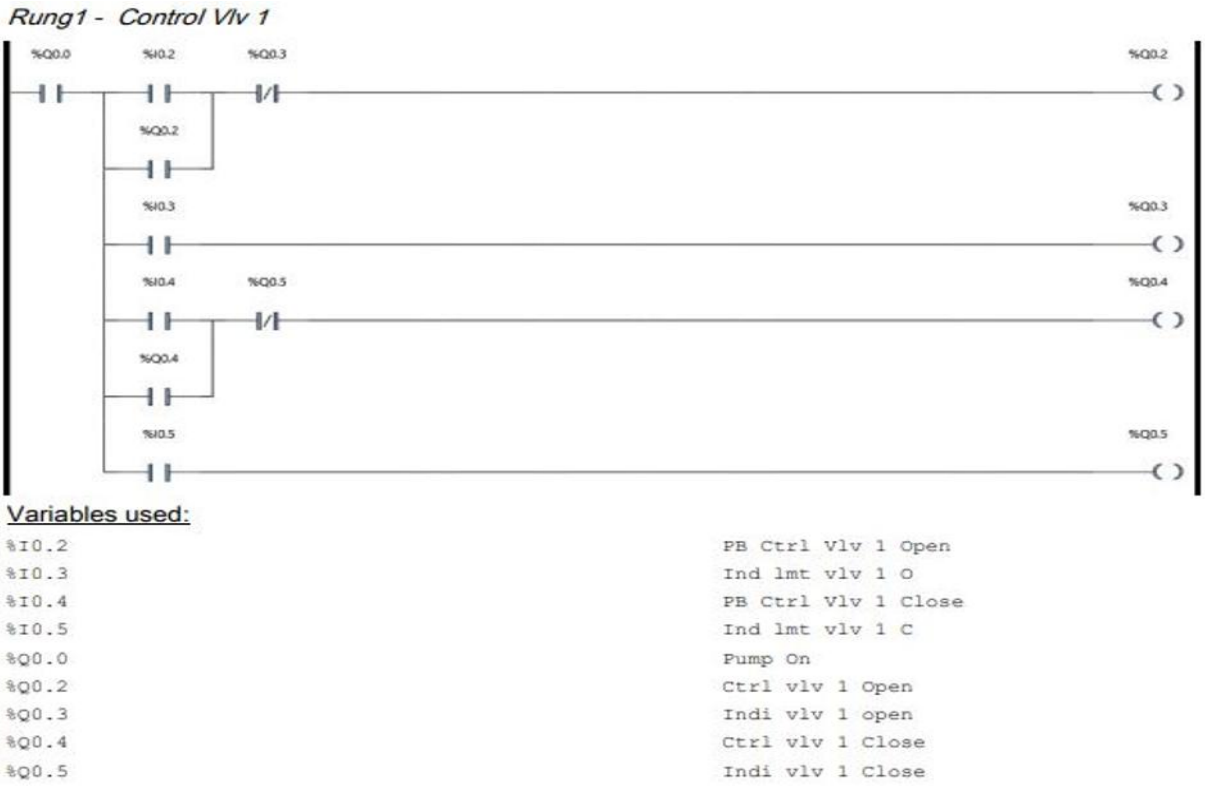
Figure 6. Hydraulic Pump Control Program


Rung22 - Ballast Pump

Variables used:

%I7.2	PB Ballast ON
%I7.3	PB ballast Off
%Q6.10	Ballast pump On
%Q6.11	Ballast Pump Off

Figure 7. Ballast Pump Program


Rung1 - Control Vlv 1

Variables used:

%I0.2	PB Ctrl Vlv 1 Open
%I0.3	Ind lmt vlv 1 O
%I0.4	PB Ctrl Vlv 1 Close
%I0.5	Ind lmt vlv 1 C
%Q0.0	Pump On
%Q0.2	Ctrl vlv 1 Open
%Q0.3	Indi vlv 1 open
%Q0.4	Ctrl vlv 1 Close
%Q0.5	Indi vlv 1 Close

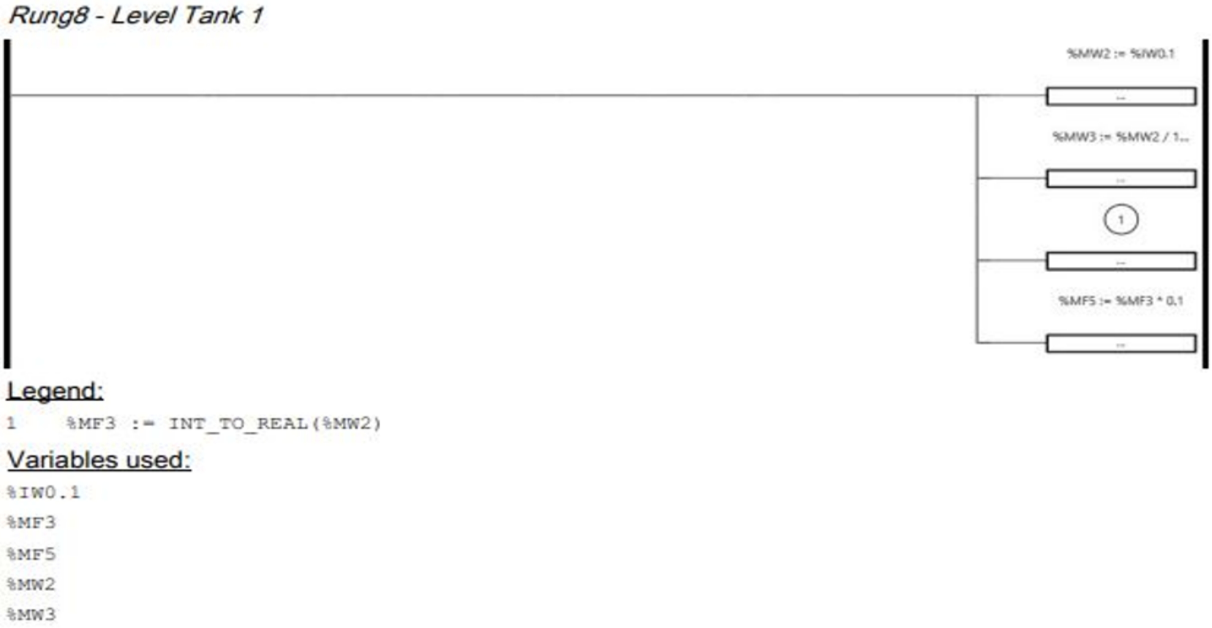
Figure 8. Control Valve Program

C. Development of Indicator Program to HMI

The development of the indicator program for the

```
Legend:
1    %MF2 := INT_TO_REAL(%MW0)
2    %MF4 := %MF2 * 0.006
Variables used:
%IW0.0
%MF2
%MF4
%MW0
%MW1
```

Figure 9. Pressure Pump Ballast Control Program



```
Legend:
1    %MF3 := INT_TO_REAL(%MW2)
Variables used:
%IW0.1
%MF3
%MF5
%MW2
%MW3
```

(a)

```
Legend:
1    %MW11 := %MW10 / 10
Variables used:
%IW4.1
%MW10
%MW11
```

(b)

Figure 10. Pressure Pump Ballast Control Program (a) Level Tank 1; (b) Level Tank 2

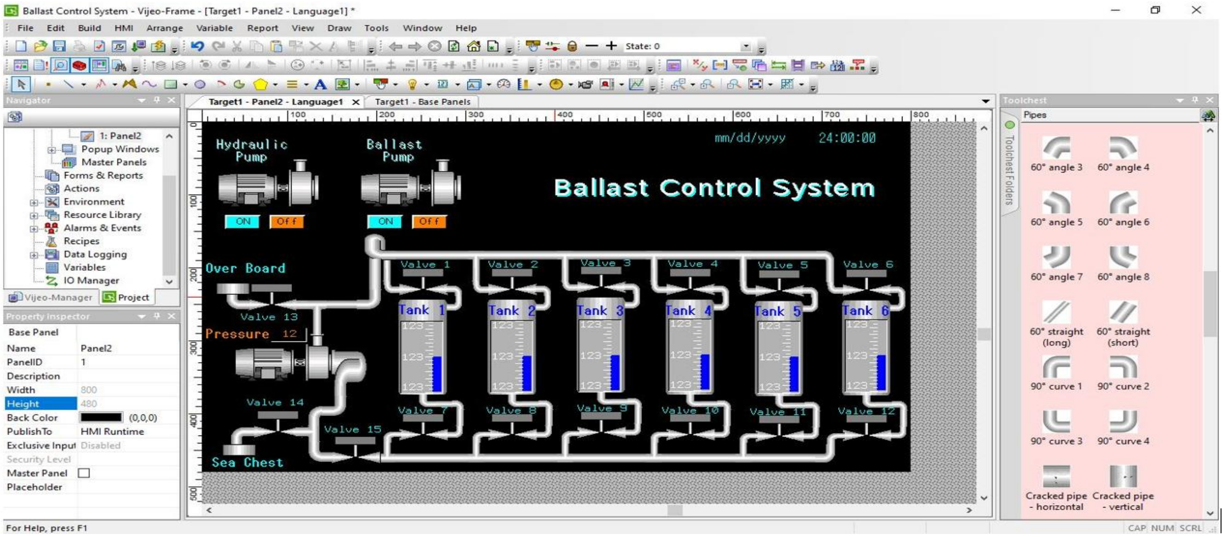
HMI is used to send signal bits to the HMI as an indicator of equipment operation. Signal bits are binary signals (0 or 1) used in automation and control systems to represent the status of a device or process.

- Bit 1 (High/On) → Indicates that the equipment is active, or a condition is met.
- Bit 0 (Low/Off) → Indicates that the equipment is inactive, or a condition is not met.

In HMI systems, signal bits are used for status indicators, alarms, and control commands to provide real-time monitoring and feedback. The integration of the indicator program into HMI is conducted by the following steps:

1. Program Interface Development
   The development of the program interface aims to facilitate the use and supervision of the system, as well as to function for controlling and monitoring the planned ballast system. The interface is created using Vijeo Designer software.
2. HMI Template Design Development
   The design is adjusted according to the required information to be displayed, as well as the elements that need to be controlled and monitored. Below is the HMI design that will be used. The HMI design visualization is shown in **Figure 11**.
3. Program Address Input
   The input of program addresses for each image functions to ensure that each image operates according to the program created in EcoStruxure, as well as to display the data obtained from the EcoStruxure program. The program address input is adjusted based on the memory bits, digital I/O, and analog signals used in the EcoStruxure program. Below is the program that has been input into Vijeo Designer, which has been adjusted to match the EcoStruxure program as shown in **Figure 12** to **Figure 15**.
4. Program Execution/Running
   The program executes using two software applications simultaneously. The software running together are Vijeo Designer, which is used as the HMI, and EcoStruxure, which serves as the main program. Below are the displays of the EcoStruxure program and Vijeo Designer when executed as shown in **Figure 16-17**.

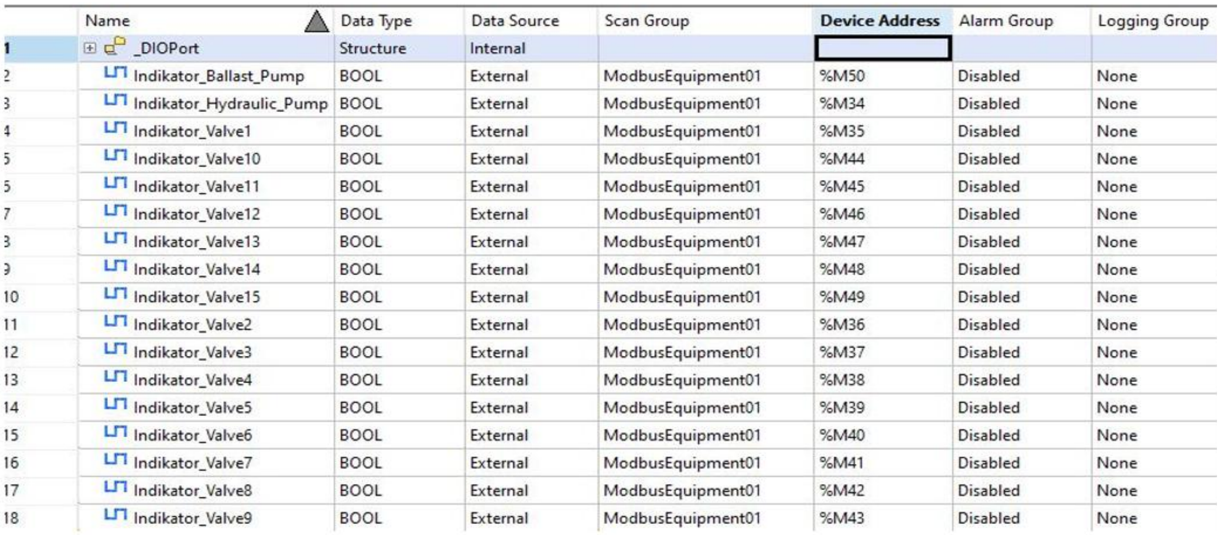
Based on the running program the following results can be obtained as shown in **Table 3**.



Property Inspector

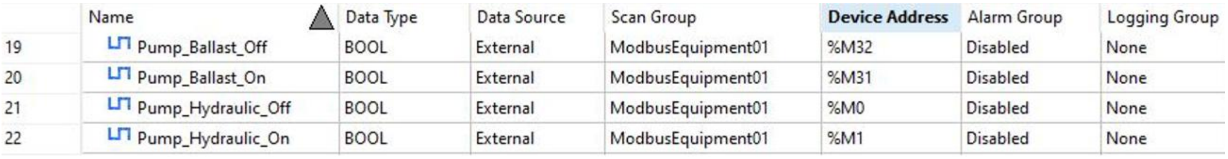
Base Panel	
Name	Panel2
PanelID	1
Description	
Width	800
Height	480
Back Color	(0,0,0)
PublishTo	HMI Runtime
Exclusive Input	Disabled
Security Level	
Master Panel	☐
Placeholder	

Figure 11. HMI Indicator Program



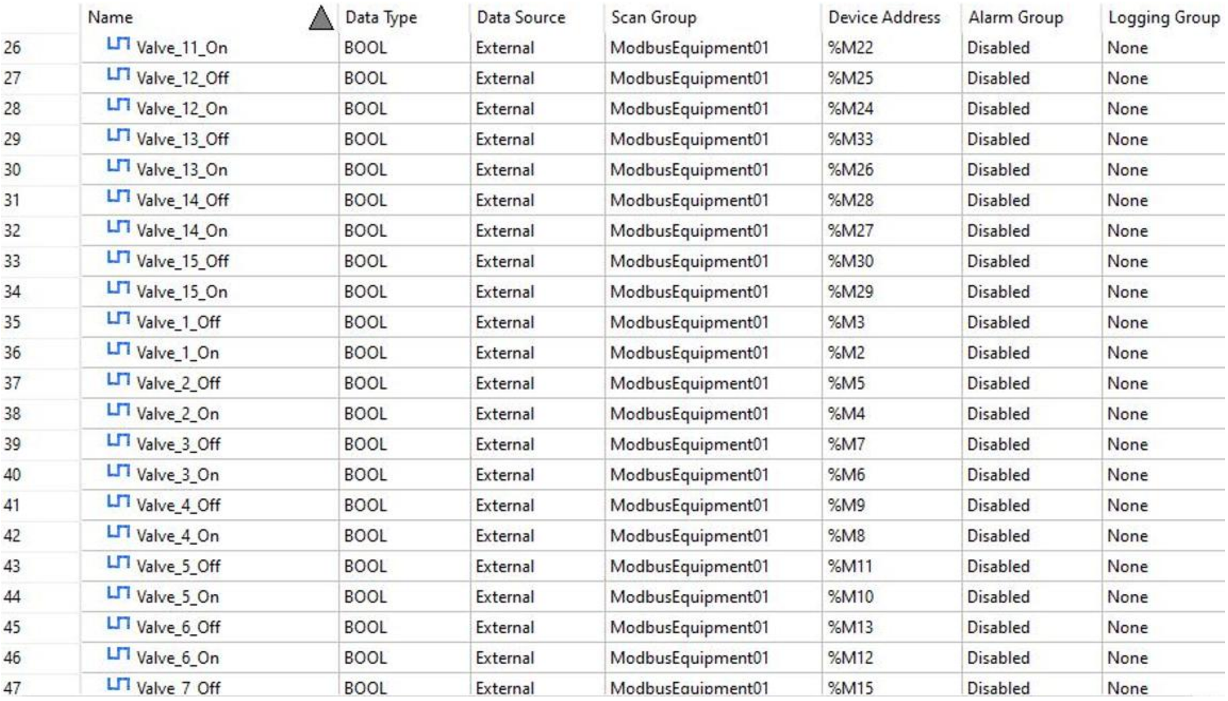
	Name	Data Type	Data Source	Scan Group	Device Address	Alarm Group	Logging Group
1	_DIOPort	Structure	Internal				
2	Indikator_Ballast_Pump	BOOL	External	ModbusEquipment01	%M50	Disabled	None
3	Indikator_Hydraulic_Pump	BOOL	External	ModbusEquipment01	%M34	Disabled	None
4	Indikator_Valve1	BOOL	External	ModbusEquipment01	%M35	Disabled	None
5	Indikator_Valve10	BOOL	External	ModbusEquipment01	%M44	Disabled	None
5	Indikator_Valve11	BOOL	External	ModbusEquipment01	%M45	Disabled	None
7	Indikator_Valve12	BOOL	External	ModbusEquipment01	%M46	Disabled	None
3	Indikator_Valve13	BOOL	External	ModbusEquipment01	%M47	Disabled	None
9	Indikator_Valve14	BOOL	External	ModbusEquipment01	%M48	Disabled	None
10	Indikator_Valve15	BOOL	External	ModbusEquipment01	%M49	Disabled	None
11	Indikator_Valve2	BOOL	External	ModbusEquipment01	%M36	Disabled	None
12	Indikator_Valve3	BOOL	External	ModbusEquipment01	%M37	Disabled	None
13	Indikator_Valve4	BOOL	External	ModbusEquipment01	%M38	Disabled	None
14	Indikator_Valve5	BOOL	External	ModbusEquipment01	%M39	Disabled	None
15	Indikator_Valve6	BOOL	External	ModbusEquipment01	%M40	Disabled	None
16	Indikator_Valve7	BOOL	External	ModbusEquipment01	%M41	Disabled	None
17	Indikator_Valve8	BOOL	External	ModbusEquipment01	%M42	Disabled	None
18	Indikator_Valve9	BOOL	External	ModbusEquipment01	%M43	Disabled	None

Figure 12. HMI Pump Control Program



	Name	Data Type	Data Source	Scan Group	Device Address	Alarm Group	Logging Group
19	Pump_Ballast_Off	BOOL	External	ModbusEquipment01	%M32	Disabled	None
20	Pump_Ballast_On	BOOL	External	ModbusEquipment01	%M31	Disabled	None
21	Pump_Hydraulic_Off	BOOL	External	ModbusEquipment01	%M0	Disabled	None
22	Pump_Hydraulic_On	BOOL	External	ModbusEquipment01	%M1	Disabled	None

Figure 13. HMI Pump Control Program

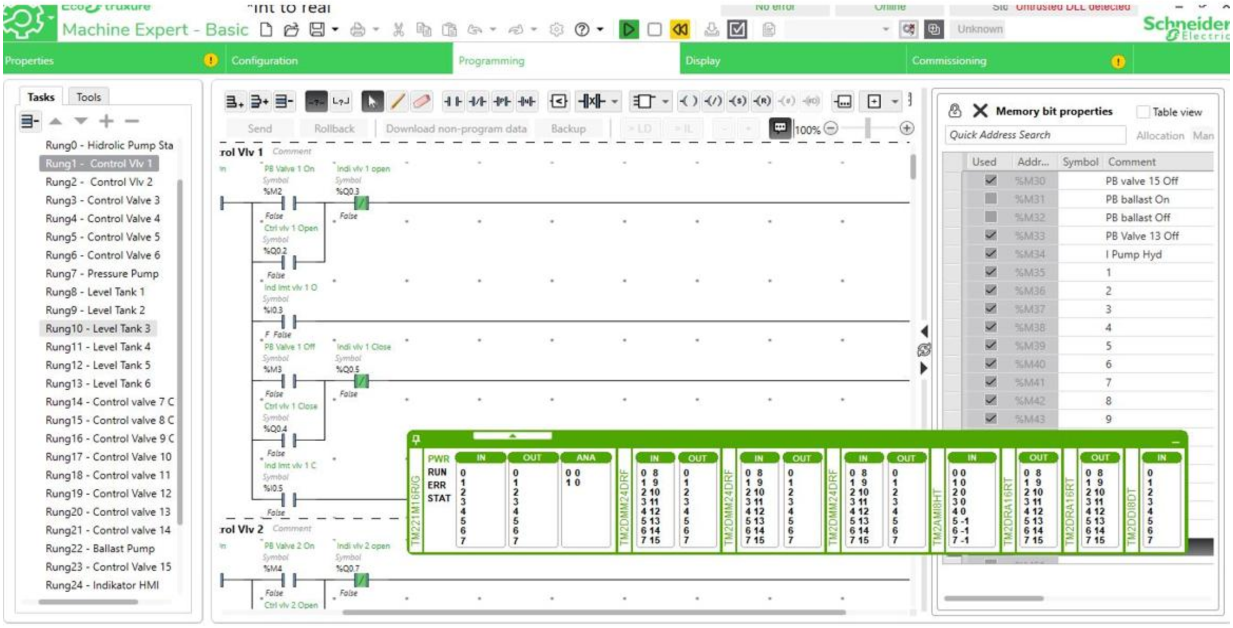


	Name	Data Type	Data Source	Scan Group	Device Address	Alarm Group	Logging Group
26	Valve_11_On	BOOL	External	ModbusEquipment01	%M22	Disabled	None
27	Valve_12_Off	BOOL	External	ModbusEquipment01	%M25	Disabled	None
28	Valve_12_On	BOOL	External	ModbusEquipment01	%M24	Disabled	None
29	Valve_13_Off	BOOL	External	ModbusEquipment01	%M33	Disabled	None
30	Valve_13_On	BOOL	External	ModbusEquipment01	%M26	Disabled	None
31	Valve_14_Off	BOOL	External	ModbusEquipment01	%M28	Disabled	None
32	Valve_14_On	BOOL	External	ModbusEquipment01	%M27	Disabled	None
33	Valve_15_Off	BOOL	External	ModbusEquipment01	%M30	Disabled	None
34	Valve_15_On	BOOL	External	ModbusEquipment01	%M29	Disabled	None
35	Valve_1_Off	BOOL	External	ModbusEquipment01	%M3	Disabled	None
36	Valve_1_On	BOOL	External	ModbusEquipment01	%M2	Disabled	None
37	Valve_2_Off	BOOL	External	ModbusEquipment01	%M5	Disabled	None
38	Valve_2_On	BOOL	External	ModbusEquipment01	%M4	Disabled	None
39	Valve_3_Off	BOOL	External	ModbusEquipment01	%M7	Disabled	None
40	Valve_3_On	BOOL	External	ModbusEquipment01	%M6	Disabled	None
41	Valve_4_Off	BOOL	External	ModbusEquipment01	%M9	Disabled	None
42	Valve_4_On	BOOL	External	ModbusEquipment01	%M8	Disabled	None
43	Valve_5_Off	BOOL	External	ModbusEquipment01	%M11	Disabled	None
44	Valve_5_On	BOOL	External	ModbusEquipment01	%M10	Disabled	None
45	Valve_6_Off	BOOL	External	ModbusEquipment01	%M13	Disabled	None
46	Valve_6_On	BOOL	External	ModbusEquipment01	%M12	Disabled	None
47	Valve_7_Off	BOOL	External	ModbusEquipment01	%M15	Disabled	None

Figure 14. HMI Valve Control Program

	Name	Data Type	Data Source	Scan Group	Device Address	Alarm Group	Logging Group
1	Pressure	REAL	Internal			Disabled	None
2	Tank_1	REAL	Internal			Disabled	None
3	Tank_2	REAL	Internal			Disabled	None
4	Tank_3	REAL	Internal			Disabled	None
5	Tank_4	REAL	Internal			Disabled	None
6	Tank_5	REAL	Internal			Disabled	None
7	Tank_6	REAL	Internal			Disabled	None

Figure 15. HMI Valve Control Program



Rung0 - Hidrolic Pump Sta
Rung1 - Control Vlv 1
Rung2 - Control Vlv 2
Rung3 - Control Valve 3
Rung4 - Control Valve 4
Rung5 - Control Valve 5
Rung6 - Control Valve 6
Rung7 - Pressure Pump
Rung8 - Level Tank 1
Rung9 - Level Tank 2
Rung10 - Level Tank 3
Rung11 - Level Tank 4
Rung12 - Level Tank 5
Rung13 - Level Tank 6
Rung14 - Control valve 7 C
Rung15 - Control valve 8 C
Rung16 - Control Valve 9 C
Rung17 - Control Valve 10
Rung18 - Control valve 11
Rung19 - Control Valve 12
Rung20 - Control valve 13
Rung21 - Control valve 14
Rung22 - Ballast Pump
Rung23 - Control Valve 15
Rung24 - Indikator HMI

Memory bit properties

Used	Addr...	Symbol	Comment
☑	%M30		PB valve 15 Off
☐	%M31		PB ballast On
☐	%M32		PB ballast Off
☑	%M33		PB Valve 13 Off
☑	%M34		I Pump Hyd
☑	%M35		1
☑	%M36		2
☑	%M37		3
☑	%M38		4
☑	%M39		5
☑	%M40		6
☑	%M41		7
☑	%M42		8
☑	%M43		9

Figure 16. Program Running EcoStruxture

Based on the above results, it can be realized that the

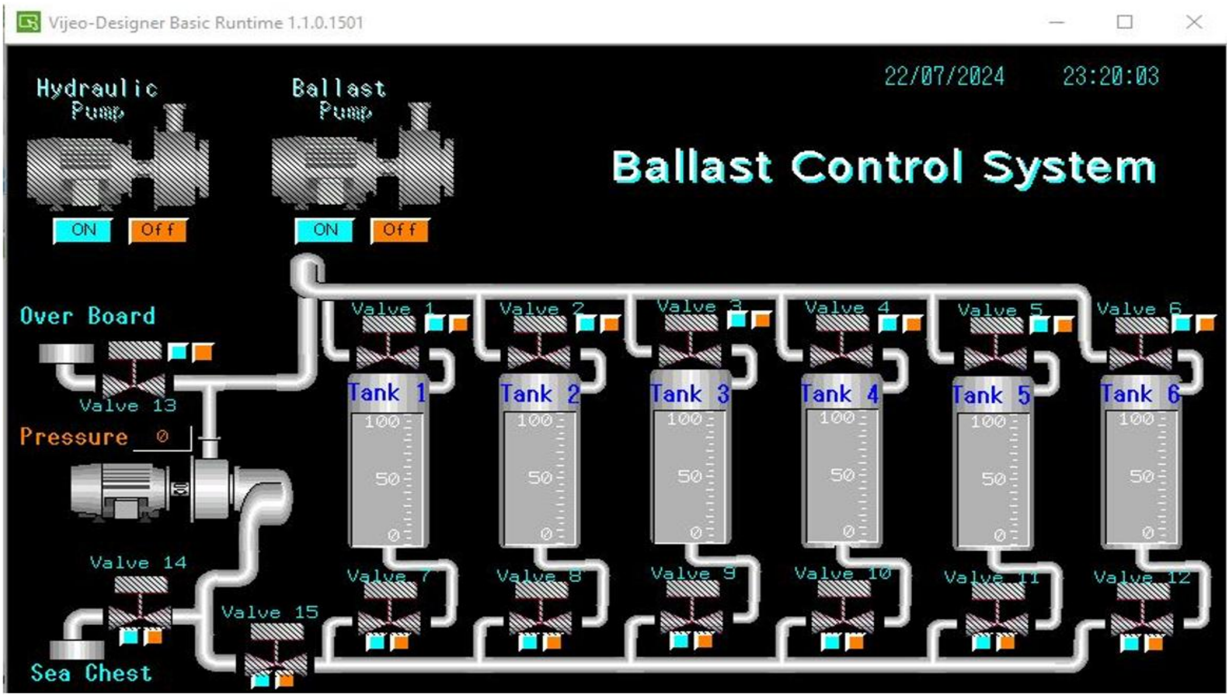


Figure 17. Program Running Vijeo and EcoStruxture

TABLE 3.
RUNNING PROGRAM RESULTS

DIGITAL SIGNAL		
ITEM	SIGNAL 1	SIGNAL 0
Pompa Hydraulic	Active	Inactive
Pompa Ballast	Active	Inactive
Valve 1	Active	Inactive
Valve 2	Active	Inactive
Valve 3	Active	Inactive
Valve 4	Active	Inactive
Valve 5	Active	Inactive
Valve 6	Active	Inactive
Valve 7	Active	Inactive
Valve 8	Active	Inactive
Valve 9	Active	Inactive
Valve 10	Active	Inactive
Valve 11	Active	Inactive
Valve 12	Active	Inactive
Valve 13	Active	Inactive
Valve 14	Active	Inactive
Valve 15	Active	Inactive
ANALOG SIGNAL		
ITEM	ANALOG INPUT	MEASUREMENT
Pressure Ballast Pump	0 - 10 V	0 - 6 Bar
Tank 1	0 - 10 V	0 -100%
Tank 2	0 - 10 V	0 -100%
Tank 3	0 - 10 V	0 -100%
Tank 4	0 - 10 V	0 -100%
Tank 5	0 - 10 V	0 -100%
Tank 6	0 - 10 V	0 -100%

research presents a significant advancement in ballast control systems by integrating Programmable Logic Controllers (PLC) and Human-Machine Interfaces (HMI). Unlike traditional ballast control systems that rely on manual operations or relay-based logic, the developed system enables real-time automation and monitoring. This transition from conventional to PLC-HMI-based control enhances system reliability, reduces human error, and streamlines ballast operations.

One of the key findings is that the proposed system enhances control accuracy through digital signal processing. The PLC processes inputs and executes logic-based commands to operate pumps and valves with precision. The activation and deactivation of these components through binary signal logic (1 = ON, 0 = OFF) ensure a deterministic and error-free operation, reducing the likelihood of incorrect ballasting or de-ballasting actions. Additionally, the system improves diagnostic capabilities by continuously monitoring valve and pump status, enabling operators to detect anomalies such as valve failures, pump malfunctions, or unexpected changes in tank levels before they escalate into safety hazards.

The study also highlights the effective utilization of digital and analog signal inputs for controlling and monitoring ballast operations. Digital signals provide on/off control for pumps and valves, ensuring reliable and immediate actuation, while analog signals (e.g., from level and pressure sensors) are processed within the PLC, converted into meaningful values, and displayed on the HMI for real-time monitoring. This dual-signal integration optimizes the accuracy of tank level measurements and pressure monitoring, improving situational awareness for operators and ensuring precise ballast control.

Another key contribution of the research is the flexibility offered by the PLC-HMI framework in making operational adjustments. Operators can dynamically adjust ballast operations via the HMI, reconfigure logic settings without extensive hardware modifications, and respond quickly to emergencies by overriding automation if necessary. This flexibility ensures that the system can adapt to different loading conditions and comply with changing regulatory requirements, making it a robust solution for modern maritime applications.

The study further demonstrates that the proposed PLC-HMI system aligns with International Maritime Organization (IMO) regulations, which mandate stringent ballast water management practices to prevent marine pollution and enhance vessel safety. The system automates ballast operations, reducing human intervention and errors, provides real-time monitoring to ensure proper ballast distribution, and logs operational data to aid in compliance documentation and audits required by regulatory authorities.

Beyond compliance, the automation of ballast control also minimizes operational risks and costs by reducing the need for manual intervention. This lowers the risk of human-induced errors, enhances crew safety by eliminating hazardous manual ballasting procedures, and improves overall efficiency, leading to cost savings over time. These factors contribute to the economic feasibility and long-term sustainability of the system in maritime applications.

In other words, the key to this research lies in its practical implementation of PLC-HMI integration for ballast operations. The study demonstrates how this system enhances control accuracy, diagnostic capabilities, and digital-analog signal integration, while also ensuring flexibility, compliance with IMO standards, and operational efficiency. The findings highlight that PLC-HMI-based ballast control is a transformative approach that modernizes ballast water management, ensuring regulatory compliance, safety, and cost-effectiveness in the maritime industry.

IV. CONCLUSION

The development of a PLC- and HMI-based ballast control system effectively enhances the monitoring and automation of ballast operations, addressing the need for improved accuracy, diagnostics, and operational flexibility. By integrating digital and analog signal processing, the system ensures precise control of pumps and valves while providing real-time monitoring of tank levels and pressure. This seamless interaction between PLC automation and HMI visualization optimizes ballast management, reducing human errors and enabling quick operational adjustments as needed. Furthermore, the system aligns with International Maritime Organization (IMO) regulations by automating ballast operations, minimizing environmental risks, and ensuring compliance through accurate record-keeping. The reduction of manual intervention enhances crew safety and operational efficiency while lowering long-term maintenance costs. These findings highlight the potential of PLC and HMI technologies in transforming ballast water management, paving the way for more advanced, reliable, and sustainable ship automation solutions in the maritime industry.

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