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Development and Performance Evaluation of Cyber-Physical Refrigeration System for Fishing Vessel

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Abstract

Technology development in the modern era encourages the utilization of efficient technologies, such as the Internet of Things (IoT) and Cyber-Physical Systems (CPS). This study focuses on developing a cyber-physical system using smartphones to control and monitor refrigeration systems in fishing vessels. Through performance testing, IoT and CPS technologies have been successfully implemented to monitor refrigeration system temperature in real-time, optimize performance, and take preventive actions as needed. The testing included the temperature control and monitoring of the primary sensor of the refrigeration machine. The accuracy of the application was evaluated by adding a reference sensor using the standard deviation as a measure between the primary and reference sensors. The test results consist of three data points. First, the test on data 1 shows the room temperature before activating the refrigeration machine, with an average difference of 2.6 and a standard deviation of 0.985. The second aspect involves a sudden pipe leakage, resulting in a difference of approximately 0.9 with a standard deviation exceeding 1.1. The third aspect includes the average difference in the measurements after activating the refrigeration machine, which indicates a higher consistency between the primary and reference sensors. The research findings indicate a minimal standard deviation, indicating a high level of measurement accuracy. Implementing this system is expected to enable the control and monitoring of refrigeration systems, assist fishermen in minimizing losses, and improve the quality of fishery products.

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1. Introduction

The rapid development of technology in the modern era has spurred individuals to consider efficient and fast technologies that have the potential to provide benefits for the future. These include the Internet of Things (IoT) and Cyber-Physical Systems (CPS). The IoT combines various areas such as control systems, automation, embedded systems, and wireless sensor networks (Kadhim et al., 2020). It forms a network of intelligent devices linked to the internet, enabling the exchange of data and information among these devices to facilitate processes related to tracking, management, and monitoring (Čolaković & Hadžialić, 2018). In contrast, CPS integrates computational, communication, and storage capabilities, ensuring physical systems' reliable, secure, efficient, and real-time utilization

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(Sanislav & Miclea, 2012). CPS integrates the physical processes using computational procedures (Matana et al. 2020). IoT plays a crucial role within the CPS framework by facilitating the connection of physical devices and providing solutions through the Internet network (Dibaji et al., 2019). Considering the role of IoT, this system has the potential to transform operations across various industries and establish infrastructure standards connecting physical objects, applications, machinery, and devices (Uslenghi et al., 2020).

IoT applications are structured into three distinct ecosystem layers: perception, networks, and applications (Talari et al. 2017). The perception layer consists of physical devices such as sensors and actuators. The network layer connects IoT devices to communication networks including Wi-Fi, 2G, 3G, and 4G (Talari et al., 2017). The application layer serves as an entry point for users and systems to access the data and functionalities provided by the IoT applications (Ramírez-Faz et al. 2020). IoT devices, including sensors, actuators, and controllers, can establish connections and communicate to collect real-time data and remotely monitor conditions, reducing time and cost. This control system can benefit the maritime and fishery sectors (Crowley et al., 2005). This sector often faces challenges overseeing and recording temperature controls to conserve fishery products.

This problem arises because fishermen must help determine and control the optimal temperature range for storing fishery products. Currently, the use of refrigeration to preserve the quality of fishery products is suboptimal because of its manual operation (Zuhri et al., 2023). Therefore, innovation is required in the form of remote control system technology for refrigeration machines. This innovation aims to enhance the machine's performance and efficiency to improve the quality of fishery products for fishermen.

This study aims to create a smartphone-based cyber-physical system for controlling and monitoring refrigeration machines in fishing vessels. This includes evaluating the performance of the system, developing an application to assist fishermen in minimizing losses, improving fishery product quality, and ensuring adaptability for real-time monitoring and preventive measures. Anticipated benefits include enhanced product quality, operational efficiency, and overall production outcomes in the fishery industry. Ultimately, the goal is to provide innovative solutions that enhance the performance and sustainability of the fisheries industry by integrating cyber-physical systems into fishing vessel refrigeration equipment.

2. Materials and Methods

The research was conducted from February to September 2023, and experiments and data collection were conducted using refrigeration equipment at the Field Station Laboratory of Siswadhi Soepardjo, part of the Department of Mechanical & Biosystem Engineering, Leuwikopo, West Bogor. Data collection involved readings from the primary sensor, reference sensor, and pressure

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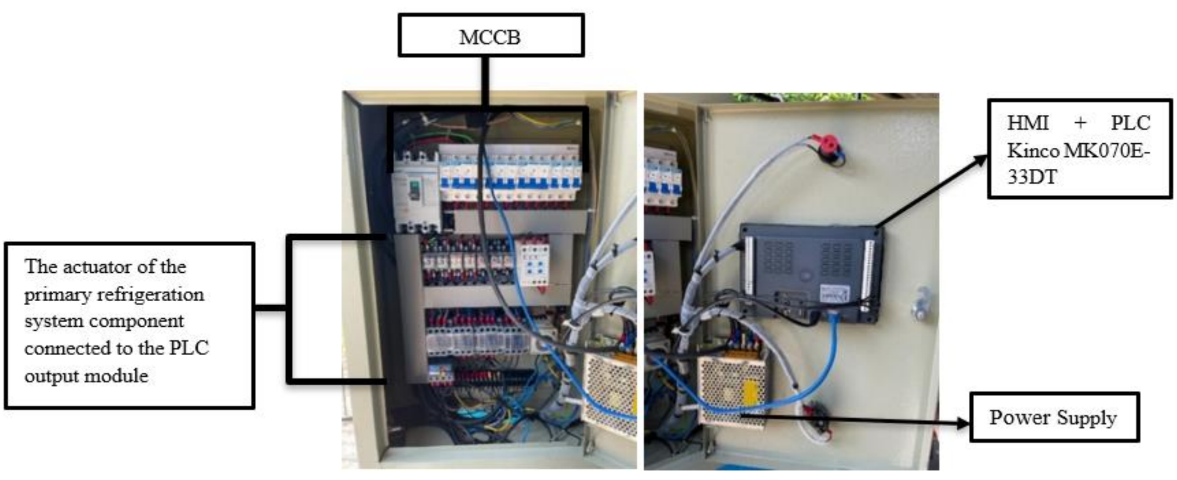
measurements of the refrigeration machine. This dataset facilitates the assessment of the integration of physical and cyber systems to monitor and control refrigeration processes.

The study employed various equipment, including a refrigeration machine, HMI, and Kinco PLC of the MK070E-33DT model. The primary temperature sensor was a PT100 (Platinum Resistance Temperature of 100 ohms), and the Negative Temperature Coefficient (NTC) functioned as a reference temperature sensor. Additionally, the research employed a pressure sensor (0–20 bar range), a temperature transmitter, a router, smartphones, and laptops equipped with software such as Kinco DTools, KincoBuilder, EdgeAccess Viewer, Matlab, and Microsoft Office. VNC mobile applications (Virtual Network Computing Mobile) on smartphones.

2.1 Control Panel and Connection Design

The control panel, measuring 40 cm × 60 cm, was assembled based on three main aspects. First, the output sweating configuration involves connecting devices such as the compressor actuator, condenser, evaporator, and defrost components to the PLC output module. This enables the PLC to command and control output devices and manage functions, such as compressor operation and defrosting, as per the programmed instructions. Second, the Input Wiring Configuration connects the sensors and input devices to the PLC input module, thereby enabling data collection from the temperature and pressure sensors for system monitoring. Third, the Distribution of Electrical Power ensures stable and adequate power for all panel components by supplying power from the MCCB and Power Supply Unit. This installation concept facilitates seamless information flow, allowing the PLC to effectively oversee and regulate the refrigeration systems.



(a) (b)

Figure 1. (a) The output wiring configuration; (b) The input wiring.

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2.2 Control System Architecture and Development of HMI and PLC Programing System Architecture

This research focuses on creating an IoT- and CPS-based control and monitoring system for supervising refrigeration systems in fishing vessels. The system comprises:

1. The primary and reference temperature sensors were placed approximately ±20 cm apart to monitor the temperature of the refrigeration system.
2. Pressure sensors were used to monitor the pressure levels within the refrigeration system.
3. The PLC microcontroller was used as the primary control device.
4. The VNC Mobile application establishes connections between users and the system, enabling smartphone-based monitoring and control of the refrigeration system.
5. An Internet connection connects all the system components, facilitating real-time data exchange and control.

2.3 HMI Programming

Programming the HMI is a critical aspect of user-system interaction in this study. Figure 2 (a) shows the HMI interface within the VNC mobile application, whereas Figure 2 (b) shows the HMI interface installed on the control panel circuit.

(a) **(b)**

Figure 2. (a) The HMI display is shown in the VNC mobile application; (b) The HMI + PLC Kinco MK070E-33DT is on the control panel.

The functions developed in the HMI programming are as follows:

1. User interface design focuses on creating an operator-friendly HMI interface that considers elements, such as color, font, icons, and layouts. Screen organization involves structuring information across multiple screens for easy access.
2. Interaction with the system incorporates controls, buttons, and data input features for the system operation and parameter settings.

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3. Integration aspects encompass establishing seamless functionality between the HMI and PLC for control processes and integrating the HMI program with the VNC mobile app for remote control on smartphones.
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2.4. PLC Programming

The PLC program oversees system operations by connecting sensors, actuators, and HMI; performing tasks such as configuring I/O; creating a programming language for temperature and pressure control; establishing data communication protocols with HMI; implementing security login controls; and integrating redundancy mechanisms for system reliability. The VNC Mobile application allows remote monitoring and control of refrigeration systems for fishing vessels, offering visual sensor data representation for enhanced flexibility and efficiency. Integration with the VNC Mobile app was seamlessly achieved through Kinco's edge access viewer, utilizing a mandatory login process for exclusive control. Similar login protocols apply to the HMI display on the control panel, requiring a login for control operations but not for monitoring purposes.

2.5 Sensor Data Acquisition, Analysis, and Standard Deviation

2.5.1 Sensor Data Acquistion

The research comprised three data collection sessions involving temperature measurements from the primary and reference sensors within a temperature range of 5°C. MATLAB was employed to analyze the simultaneous measurements of both sensor types, and the results were graphically presented for a clearer insight into the system performance

2.5.2 Sensor Data Analysis and Standard Deviation

The initial sensor data analysis involves calculating the average for each sensor test and identifying the differences between the primary and reference sensor measurements. This process assesses the potential variations between the two sensors and provides insights into reading disparities. The program then determined the average difference and calculated the standard deviation using these results. The outcomes, including variance and standard deviation, were visually presented to facilitate interpretation and effective comparisons between the primary and reference sensors. This analysis is essential for understanding the temperature measurement accuracy and variation within refrigeration systems, offering valuable insights for evaluating the system's performance and reliability.
The purpose of the standard deviation is to analyze the variability or deviation from the collected data (Xie et al., 2021). The standard deviation describes the extent to which temperature measurements

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vary from the mean value of the difference data. A low standard deviation indicates a higher level of consistency around the mean, whereas a high standard deviation indicates broader dispersion from the mean (Lee et al., 2015).

The formula used for deviation calculation is as follows:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\bar{x}-x_i)^2}{n-1}} \quad (1)$$

Note: s = Standard deviation, x = The average of the middle sample values, n = Sample or population size.

3. Results and Discussion

This research involves analyzing data by comparing direct measurements from a refrigeration machine with the data recorded in the VNC application. Temperature readings from the reference sensor were incorporated to evaluate the consistency of the temperature measurement of the primary sensor. The testing, conducted in three repetitions, presents the average results from the initial two repetitions in Table 1, starting at room temperature before activating the refrigeration machine.

Table 1. Average Primary Temperature, Reference Temperature, and System Pressure

Data	Temperature Sensor (°C)		System Pressure
	Primary Temperature	Reference Temperature	
1	25	27.3	17.4
2	20	21.0	21.5
3	15	15.3	22.3
4	10	9.8	22.1
5	5	5.8	22.2
6	0	0.6	22.1
7	-5	-5.9	22.4
8	-10	-11.0	22.7
9	-15	-15.4	22.3

In the pre-activation room temperature, a 2.3°C difference in sensor readings occurs because each sensor registers the ambient temperature. Upon activation of the refrigeration

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machine, temperature measurements were performed at specific intervals, ranging from the initial room temperature to -15°C. This dataset includes readings from the primary sensor, reference sensor, and system pressure, offering a comprehensive overview of temperature changes during testing. These outcomes are vital for assessing the accuracy and consistency of refrigeration machine temperature measurements.

Figure 3 shows a temperature comparison between the primary, reference, average primary, and average reference sensors. The graph includes a linear trend line that illustrates the relationship between the average temperatures of the primary and the reference sensors. Although some data points exhibited slight differences from the average test values, the temperature difference between the two sensor types remained relatively low. This suggests that despite variations in the sensor readings during each experiment, there was a high consistency between the primary and reference sensors. Consequently, the temperature readings in this application can be deemed accurate and consistent with direct measurements from both sensors.

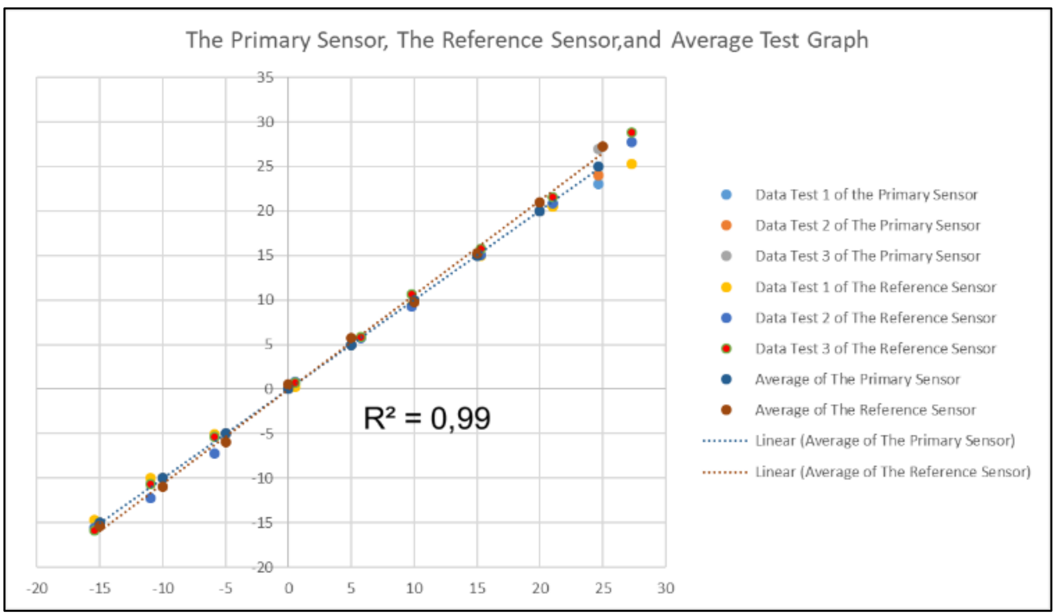

Figure 3. The primary sensor, the reference sensor, and the average test graph

The temperature difference between the readings from the primary and reference sensors was calculated for each test based on the collected data. The average difference between the two types of sensors is computed, and the standard deviations of the calculation results are presented in Table 2. A graph illustrating the average temperature difference calculation for both sensors, as well as the calculation of the standard deviation for each data point, is shown in Figure 4.

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Table 2. Test Differences for Tests 1 to 3, Average Difference, and Standard Deviation

Data	Test 1	Test 2	Test 3	Average Difference	Standard Deviation
1	2.3	3.7	1.8	2.6	2.6
2	0.5	0.9	1.6	1.0	1.0
3	0.0	0.1	0.8	0.3	0.3
4	0.6	0.7	0.7	0.7	0.7
5	0.8	0.7	0.8	0.8	0.8
6	0.2	0.8	0.7	0.6	0.6
7	0.1	2.2	0.4	0.9	0.9
8	0.0	2.2	0.7	1.0	1.0
9	0.3	0.6	0.9	0.6	0.6

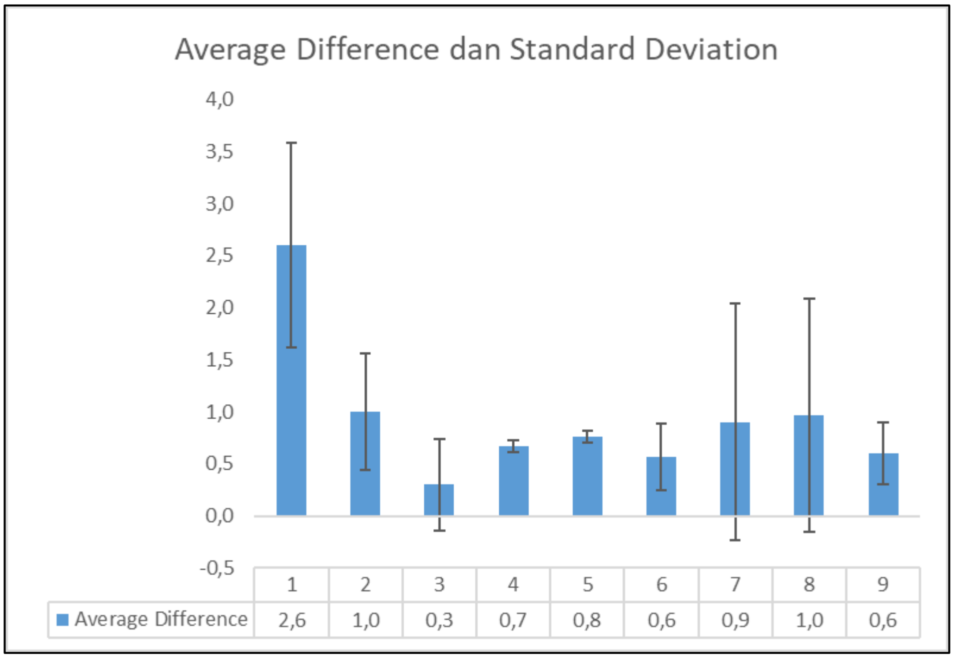

Figure 4. Calculation of mean and standard deviation

In Table 2, the data from the first test, representing the temperature readings when the refrigeration machine was inactive, exhibited more significant differences than the other data points. Specifically, in Test 1, the difference was 2.3, in Test 2, it was 3.7, and in Test 3, it was 1.8. The average temperature difference across all tests was 2.6, with a standard deviation of 0.985. These variations may be influenced by the ambient temperature around the different sensors and the distance between the primary and the reference sensors.

Upon activation of the refrigeration machine, the temperature difference from the average measurements and the standard deviation decreased. This decrease indicates higher consistency between the primary and reference sensors, as illustrated in Figure 4. However, a significant spike occurred at data points 7 and 8, coinciding with a sudden pipe leakage. This event resulted in temperature differences ranging from 0.9 to 1.0, with a standard deviation exceeding 1.1. This condition suggests that pipe leaks can significantly affect the temperature readings.

4. Conclusion

In summary, this study successfully developed a smartphone-based cyber-physical system for monitoring and controlling refrigeration machines in fishing boats. The system was evaluated in three repetitions, demonstrating its ability to oversee temperatures in real-time, enhance performance, and enforce preventive measures. This presents potential advantages in minimizing losses and enhancing the quality of fish products. The cyber-physical system introduces flexibility in managing refrigeration machines, positively impacting operational efficiency, fish product quality, and overall production outcomes in the fishing industry, thereby contributing to its performance and sustainability.

Data analysis, comparing direct measurements and VNC application records, revealed variations in the sensor readings at room temperature before activating the refrigeration machine. Despite the slight differences in the individual data points, the overall temperature difference between the primary and reference sensors remained low, indicating a high level of consistency. Activating the refrigeration machine further reduced the temperature differences and standard deviations, signifying heightened consistency between the sensors. However, sudden pipe leakage incidents resulted in spikes in temperature differences, exceeding 1.1 in standard deviation, emphasizing the significant impact of pipe leaks on temperature readings.

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