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The Development Process of Human Machine Interface of Plant Protection System of a Small Modular Reactor

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A B S T R A C T

The Plant Protection System (PPS), which consists of Reactor Protection Systems (RPS) and Engineered Safety Actuated Systems (ESFAS), is one of the most important safety systems in nuclear reactors, including Small Modular Reactors (SMRs). The RPS generates a signal to trip the reactor if the measured reactor parameters exceed the trip setpoint, and then the ESFAS is actuated to mitigate the consequences of the accident by minimizing fuel damage and radioactivity release into the environment. Therefore, a comprehensive Human-Machine Interface (HMI) is essential for monitoring and controlling the PPS to ensure its reliability and enhance the operators' situational awareness. This study discusses the development process of the HMI for the digital PPS of an SMR. In this study, various standards, guidance, and design criteria for PPS and HMI are incorporated and applied to ensure that the proposed design meets the required level of reliability. In the first stage, the proposed design is intended for assessing the functionality and reliability of the PPS. Moreover, in the future, it will play an essential role in the design phase of the HMI for the PPS of an SMR in Indonesia.

1. INTRODUCTION

Due to the inherent flexibility and safety features of small and modular nuclear reactors, it is crucial to guarantee that the Human Machine Interface (HMI) of their Plant Protection System (PPS) is carefully designed. The PPS is essential for managing and monitoring the reactor, protecting it from potential mishaps, and guaranteeing the safety of the surrounding area. The usability, human factors, and integration of cutting-edge technologies are highlighted in this paper's early design of the HMI for the Plant Protection System of a Small Modular Reactor (SMR), which will improve operator performance and decision-making.

For SMRs to operate safely, dependably, and efficiently, the Plant Protection System (PPS) is essential [1]. It is important for protecting nuclear operations, preventing accidents, maintaining compliance with regulations, improving operational effectiveness, and assisting in the public acceptance of SMRs as a workable and long-lasting source of clean energy.

Effective Plant Protection Systems (PPS) are built on a foundation of the HMI [2]. It is crucial for

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improving safety, streamlining procedures, offering a user-friendly interface, allowing data analysis, enabling remote monitoring, guaranteeing compatibility, and assisting with regulatory compliance. An effective HMI enables users to take educated decisions and act quickly in response to changing circumstances, therefore enhancing the overall success and dependability of industrial processes where PPS is crucial.

The purpose of the study is to conduct development process of the HMI of the RPS by constructing the preliminary design of the HMI. This study was conducted based on system engineering consists of system requirements, system function, and system implementation to ensure that the HMI for the PPS in an SMR is successfully developed, meeting safety, operational, regulatory, and usability criteria while encouraging dependable and efficient reactor operation.

2. SMALL MODULAR REACTOR

Small modular reactors (SMRs) and their applications are gaining popularity. SMRs are newer generation reactors designed to generate up to 300 MW of electric power, with components and systems that can be factory-fabricated and then transported as modules to the sites for installation as needed [3]. SMRs offer a wide range of benefits that place them as a potential and alluring option in the field of nuclear energy production. These benefits include improved safety features, flexibility, scalability, and cost-effectiveness, making SMR a strong contender for safely and sustainably addressing future energy demands [4, 5].

SMRs are appealing because they can aid developing nations in their search for scalable, affordable electricity generation. SMRs open the door to sustainable development and energy security in areas where conventional large-scale reactors could be problematic by providing an energy option with positive environmental effect.

Additionally, SMRs promote ongoing developments in nuclear technology, materials, and safety measures. This continuing innovation benefits the whole nuclear business, raising operational effectiveness and safety standards everywhere.

3. PLANT PROTECTION SYSTEMS

The PPS, which acts as the last line of defense against mishaps and unexpected circumstances, is a crucial part of the safety infrastructure of a nuclear reactor. It is a crucial component of contemporary nuclear power generation due to its roles in detecting anomalies, responding to emergencies, providing crucial data, managing alarms, assisting operators, and ensuring regulatory compliance. These functions all contribute to the safe and reliable operation of nuclear reactors.

Reactor Protection Systems

RPS are crucial for maintaining the safety, dependability, and regulatory compliance of these cutting-edge nuclear reactors. Their main job is to spot unusual conditions, initiate automatic shutdowns, and establish a strong safety framework to stop accidents and reduce their impacts. To ensure that they are effective in protecting the reactor and the surrounding environment, these systems are built with redundancy, varied safety logic, and thorough testing [6, 7].

The RPS' safety function stops the nuclear chain reaction and returns the NPP to a reliably controlled state. One of the most important criteria for digital RPS design is defense-in-depth protection. The first level of automatic protection is reactor trip, which inserts all control rods and stops the fission process. However, the core continues to generate heat, so the Engineered Safety Feature Actuation System (ESFAS) provides the next level of safety, rejecting decay heat that might cause catastrophic core damage. The final step of containment cooling prevents the containment structure from overpressurization. Failure of the RPS to execute its task causes hardware damage and major environmental consequences, hence the digital RPS must be extremely reliable [8].

Engineered Safety Features Actuation Systems

Built-in safety features facilities that must maintain a high level of safety, such as nuclear power plants, must have actuation systems [9]. Their main responsibility is to start and manage safety systems and operations, providing a safe sshutdown and accident or abnormal event mitigation. To ensure their effectiveness in defending the facility and its surroundings, ESFAS are constructed with redundancy, a variety of safety logic, and stringent testing. Functions provided by ESFAS comprises of emergency core cooling system (ECCS), emergency feedwater, containment isolation, containment spray (if needed) [8, 9].

4. HUMAN MACHINE INTERFACE OF MAIN CONTROL ROOM

Operators monitor and control the reactor in the main control room (MCR). Nowadays, the main control rooms are equipped with the digital system with a compact design [10, 11]. In general, the MCR includes visual display unit (VDU), computers console on the operators' workstation desks. Operators perform their function and tasks through HMI that consist of alarm, information display, and controls [12]. The purpose of modernization of main control room is to minimize human error [11].

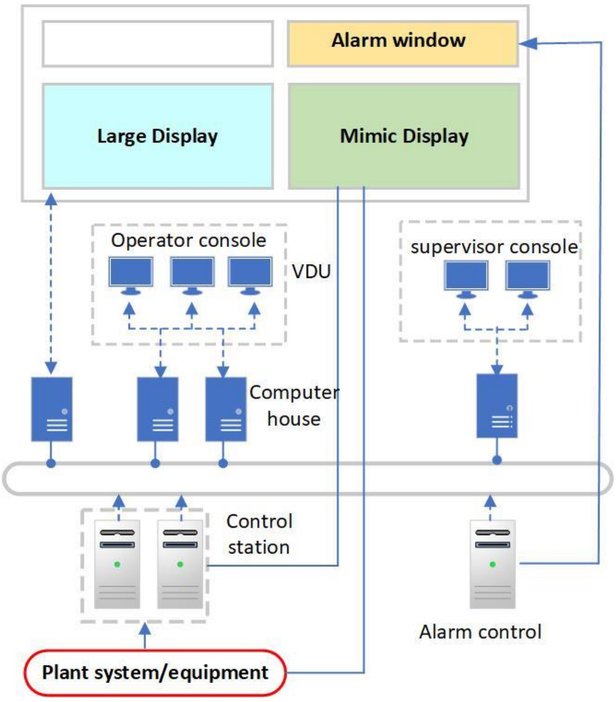

Fig. 1. HMI design of SMR main control room [13]

Fig. 1 shows the diagram of HMI in the main control room of nuclear power plant. Signals from plant system/equipments are processed in control station and computer house and then displayed in the VDU in the operator console and in the large screen display. Operator monitors the current status of the plants from the large screen display and mimic display and control the reactor through the computer on the console desks. In addition, the alarm control will actuate alarm system and send the information to the alarm window to inform operators there is anomaly in the plant.

5. METHODOLOGY

This study is conducted based on systems engineering principles, focusing on identifying standards and requirements related to the design of the HMI and PPS for SMRs. Additionally, the discussion addresses the information flow processed within the PPS and displayed on the HMI. The initial HMI design for the SMR's PPS was developed using this data. The human factors engineering was also considered in the design to ensure reliability and functionality.

6. RESULTS AND DISCUSSION

System Engineering-based HMI Development

The development of the HMI of the PPS is based on system engineering model. One of the recommended system engineering model by the IAEA, as mentioned in Specific Safety Guide No. 39 (SSG-39) is V-Model [14]. The system of engineering-based HMI design is shown in Fig. 2. The design is started with the system requirements and finalyzed with the system validation. In each step there is a verification to ensure that design is correct and meet the requirements. In this study, for the preliminary design of the HMI, the first three processes will be considered, which are system requirements, system function, and HMI system implementation.

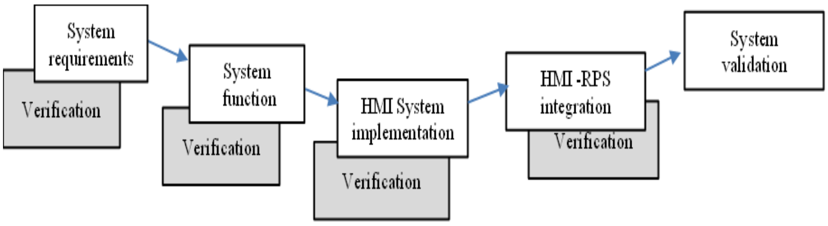

Fig. 2. System engineering-based HMI design

System Requirements of HMI and RPS

In the first stage of the design, some requirements and standards related to the HMI and PPS design were collected and the result of the requirements traceability is provided in Fig. 3. This picture depicts the requirements verification traceability process, beginning with the generic Design Criteria (GDC) for HMI in 10 CFR 50.55a. Control room, RPS, reliability and testability of the protection system, independence of the protection system, failure modes, and Divers Protection System are those connected to HMI. This specification was chosen because it is relevant to the HMI function that would be used in nuclear reactors, specifically the reactor protection system.

The Standard Review Plan (SRP) is a subset of the GDC that includes various subsystems that must also meet nuclear reactor design criteria. International and local rules will be referred to in this paper as industry standards that can be utilized as design references. It will be easier for design engineers to verify needs and requirements during the development process if they follow recommendations from regulators who already follow general design requirements and criteria, and the design validation process will be easier because they are following test methods for design feasibility properly.

In addition, the mandatory requirements for HMI and PPS of NPP is provided in Table 1. It can be seen in Table 1 that for HMI design, it should be designed to provide the operators with comprehensive but easily manageable information, which related to the IAEA SSG-51.

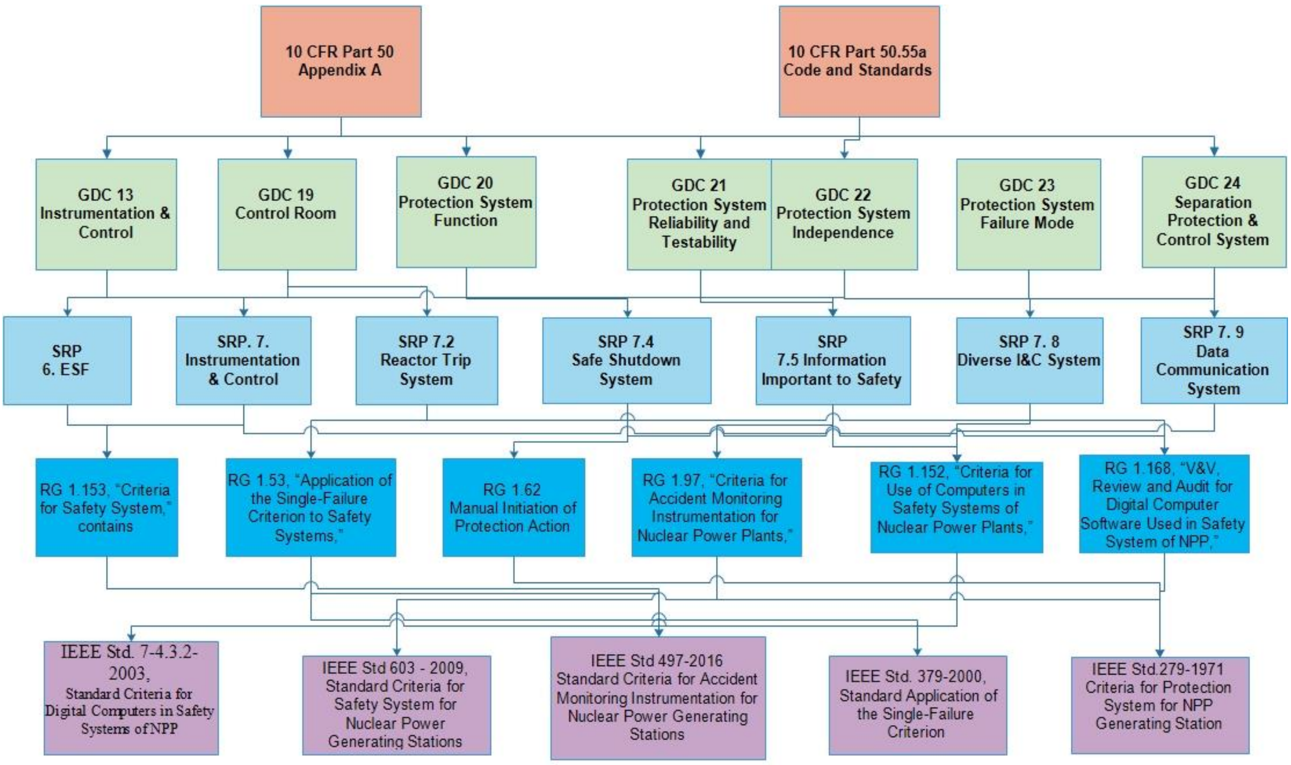

Fig. 3. Requirements traceability of HMI and RPS

Table 1. Mandatory requirement for Human Machine Interface and Plant Protection System of NPP

No.	Component	Statement	Document and guideline	Standard
1	Protection system	A protection system **shall** be provided at the nuclear power plant that has the capability to detect unsafe plant conditions and to initiate safety actions automatically	Req 61 of IAEA No.SSR-2/1 (Rev.1) [15]	
2	Protection system design:	• **Shall** prevent operator actions that could compromise the effectiveness of the protection system in operational states and in accident conditions • **Shall** automate various safety actions to actuate safety systems • **Shall** make relevant information available to the operator for monitoring the effects of automatic actions		
3	Separation of protection systems and control systems	Signal system **shall** be classified as part of the protection system.	Req 64 of IAEA No.SSR-2/1 (Rev.1) [15]	
4	Control Room	A control room **shall** be provided at the NPP from which the plant can be safely operated in all operational states, either automatically or manually	Req 65 of IAEA No.SSR-2/1 (Rev.1) [15]	IEC 60964, IEC 61772, IEC 62241, IEEE 576
5	Human Machine Interface	Systematic consideration of human factors, including the human–machine interface, **shall** be included at an early stage in the design process for a NPP and **shall** be continued throughout the entire design process.	Req 32 of IAEA SSR-2/1 (Rev. 1) [15]	
6	HMI design	HMI **shall** be designed to provide the operators with comprehensive but easily manageable information	IAEA SSG-51 [16]	

System Function

The next stage of the desin process based on the system engineering is the system function. In this stage, the design and the functionality of the HMI is described including system components, input and output systems, and interconnection between them. Fig. 4 represents the system function of the HMI of the RPS. In this study, the 2 out of 3 (2oo3)-type RPS is considered. The RPS has 3 redundancy channels (A, B, and C). Only channel A is shows in Fig. 4. Inputs from instrument sensors (reactor parameter values) are forwarded to the safety variable data module and presented on the display in the main control room. The safety variable data will be processed in the bistable processor to be compared with the pre-trip and trip setpoint, then set as trip initiation signal. The initiation signals from each channel are voted with mode 2oo3 to produce reactor trip signal and ESF signal in the local coincidence logic (LCL) processor. The value of the trip signal is also displayed on the HMI and alarm system to inform the anomaly to operators in the main control room.

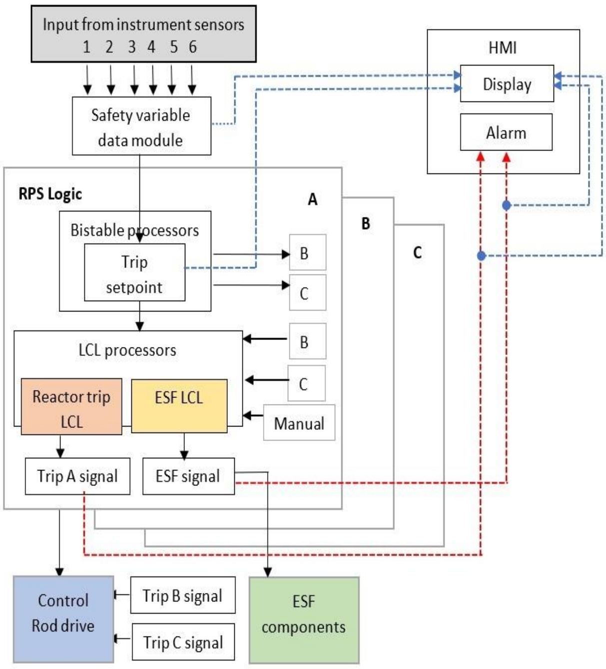

Fig. 4. System function of HMI

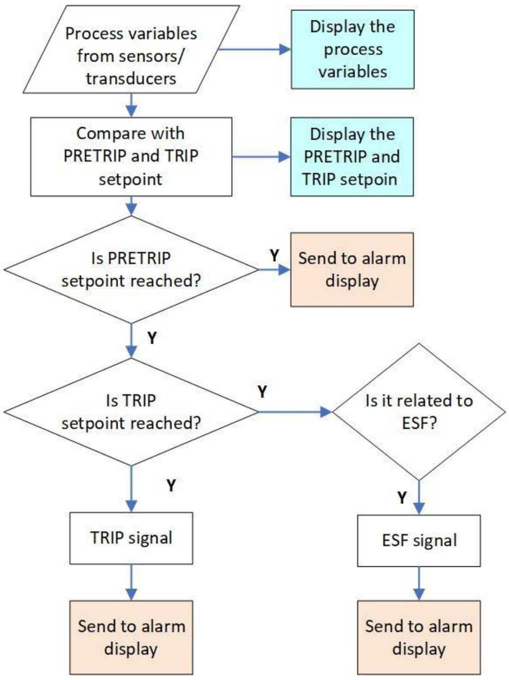

Fig. 5. Information flow of HMI of the PPS

Fig. 5. shows the flow of information in the HMI of the PPS. Related to above figure, the type of information and how it is presented on the HMI are summarized in Table 2.

Table 2. Type and presentation of information in HMI

No	Type	Presentation
1	Process variable	Display panel
2	Pre-trip and trip setpoint	Display panel
3	Pre-trip signal	Alarm display
4	Trip signal	Alarm display
5	ESF signal	Alarm signal

According to Table 2, if the process variable reach the pre-trip setpoint, the alarm on the HMI is ON to inform the operators there is anomaly in the plant an. If the anomaly happened continuously, the reactor will be tripped, indicated by the trip signal alarm and the ESF signal alarm. The ESF signal alarm also indicates the process variable causing the trip and the ESF will be activated to ensure the integrity of the reactor.

System Implementation

The last stage in this study is system implementation. It includes the preliminary design of the HMI using LabView. The preliminary design is constructed by considering standard and requirements such as IAEA SSG-51 [16] and NUREG-700 revision 3 [12]. The design considerably consists of some items as can be seen in Table 3.

Table 3. Considerably components and items in the HMI

No	Components	Items
1	Information display	
	• Display format	Continues text display, graphs, mimic and diagrams
	• Display elements	Labels; icons and symbols; numeric data; color; size, shape, and pattern coding
2	User interface interaction and management	
	• User input formats	Menus, direct manipulation,
	• Managing display	Display selection and navigation, display control
	• Managing information	Saving files
3	Alarm display	Display of alarm status, alarm contents

Referring to Table 3, the preliminary design of the HMI was built as can be seen in Fig. 6. Table 4 describes the components of the preliminary design.

Table 4. Components and functions of the preliminary design of HMI

No	Components	Functions
1	Alarm panel	Indicator there is an anomaly in the plan. The color of the panel turns to red and blinking when there is an anomaly
2	Input file	It is used for the simulation using automatic action
3	Action	Automatic: inputs from the excel file consists of process variable values (no 2 in Fig.6) Manual: inputs from rotary switchs that act as process variables (no 6 in Fig.6)
4	Pre-trip and trip indicator	The color will change to yellow (if it is pre-trip condition) and change to red (if it is trip condition)
5	Active channel	Indicator which channel is active.
6	Process variables	Represented by rotary switches are used as inputs for manual actions.

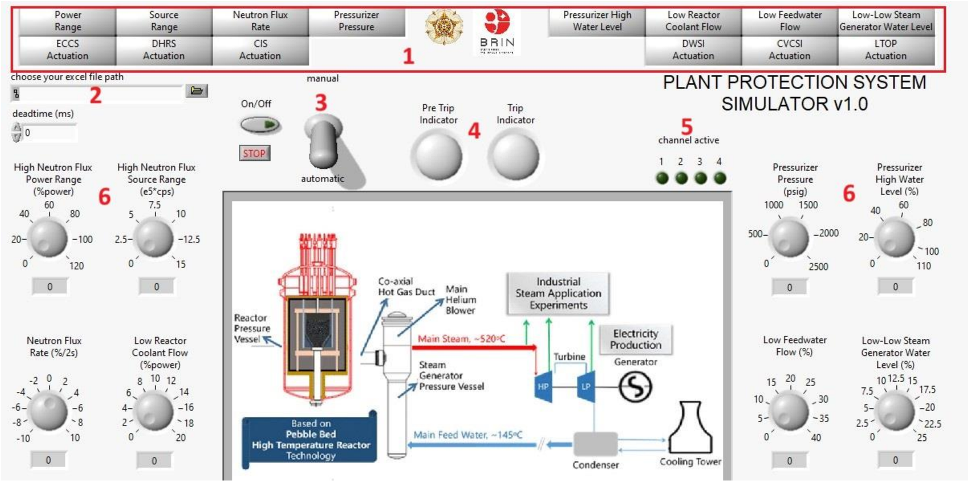

Fig. 6. Initial condition of RPS

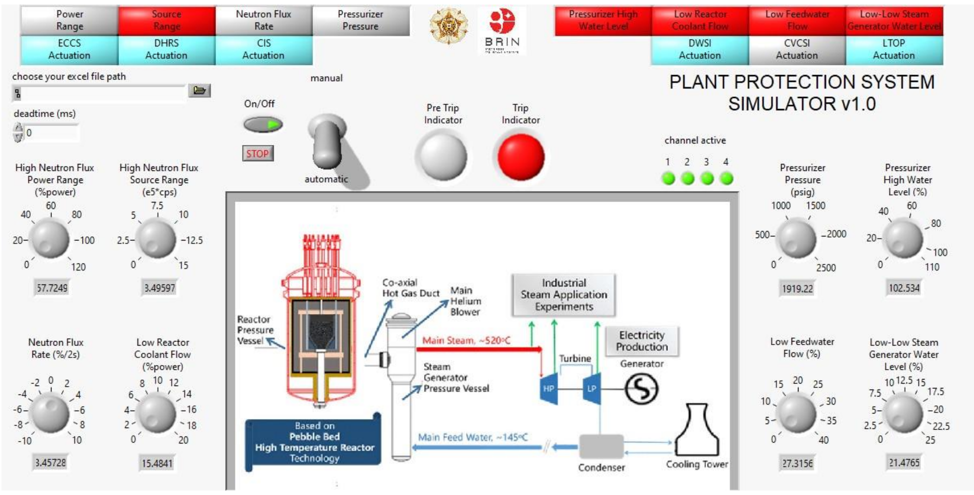

Fig. 7. Trip condition of RPS

In order to verify the design, a few experiments were conducted both for automatic and manual actions. For the automatic action, the file was uploaded to the design. After several times, the alarm panels were activated, indicated by the red colors as well as the trip indicator, as can be seen in Fig. 7. It is also happened when the rotary switch was rotated into some values, some alarm panels turned into red color, pre-trip panel became yellow and then the trip panel turned to red. In general, the preliminary design of the HMI can demonstrate the functionality of the RPS.

7. CONCLUSION

The preliminary design of the HMI for the RPS for an SMR was created to simulate the functionality of the RPS. This design can also be adapted for other types of NPPs. It was constructed based on the relevant standards and requirements. Through several experiments, the design has been able to demonstrate the functionality of the RPS.

In the future, the design will be further developed by incorporating additional features such as a mimic diagram of the plant and trend graphs displaying the current values of process variables. Further experiments will also be conducted to verify the functionality and reliability of the design.

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AUTHOR CONTRIBUTION

Tulis Jojok Suryono, Sigit Santoso, Restu Maerani, Sudarno, Pandhu Ardita Dharma Pratama equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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