Presenting the Secure Collapsible Makerspace with Biometric Authentication

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ABSTRACT

Traditional product design learning is inefficient, costly, and limited by safety concerns in physical and smaller-scale school workshops. The Secure Collapsible Makerspace is a mobile makerspace with smart sensors and an expandable work area facility. This study aims to develop a smart mobile makerspace platform using edge computing architecture and the biometric security model to compare real-time learners' engagement time and design performance. The developed platform consists of four blocks that provide service as a makerspace for the learners and monitor their utilization in a secure environment. The edge computing architecture allows real-time analysis of the users' makerspace utilization. A total of 750 learners were accessed for their product design outcome which presented a positive correlation of 0.72 between the engagement time and the design assessment with a corresponding p-value less than 0.001. This study concludes that makerspaces can be a platform that improves students' performance in hands-on activity-related learning.

Keywords-active learning; biometrics; Internet of things; intrusion detection; remote monitoring

I. INTRODUCTION

Combinations of robotics and Internet of Things (IoT) advancement provide excellent engineered systems that can be applied for monitoring and ensuring the security of autonomous learning platforms [1-2]. This study presents the Secure Collapsible Makerspace for remote learning monitoring. The proposed makerspace is an advanced, low-cost robot with a centralized and distributed security system equipped with time monitoring facilities. The robustness of the design makes this robot ideal for learning centers with limited space. The collapsible feature with centralized security control provides the robot with flexibility in offering wider learning options in STEM.

STEM learning is nowadays becoming costly and takes plenty of resources and manpower [3-4]. Efforts have been taken by the learning centers to improve knowledge delivery effectiveness through self-learning and automated monitoring systems [5-6]. Many such systems are currently software-based, limiting the learners' hands-on experience, especially in product design [7]. Traditional product design learning which operates in extensive physical workshops is highly inefficient in space management and costly. The existing smaller-scale workshops also proved ineffective in schools as learners are not allowed to be in the workshop without the supervision of the teachers or lab instructors to ensure the safety and security of the workshop and its equipment [8].

The role of mobility in learning became more crucial during the post-COVID-19 pandemic era which has created a knowledge gap in technology for product design learning [9-10]. Most learning centers are left behind in terms of infrastructure and equipment. The mobility aspect of the Secure Collapsible Makerspace is expected to close this gap by providing a powerful learning experience. Mobility in learning allows an individual to move away from his or her everyday context, such as the classroom, to take the experience of learning to the next step [11]. This approach is expected to be effective in addressing the knowledge gap in product design-related courses with a minimum investment.

Product design is a combination of different learning dimensions such as computer-aided 3D design sketching, product manufacturing, digital designing, and others [12]. As such, the learning process requires much more individual time and attention beyond formal classroom learning. In the traditional learning modality, the home has been a conducive environment for learners to practice beyond the formal classroom. Parents have played an important role in assessing or monitoring their children's engagement in extended learning. Nowadays, urbanization has created limited space in most homes, especially in high-rise living environments. This created a new need for a reliable learning monitoring system. As such, the design of the Secure Collapsible Makerspace embedded with biometrics security features serves a dual purpose by offering a secure working platform as well as usage monitoring.

The current study introduces a novel solution called the Secure Collapsible Makerspace, an advanced robot with integrated security systems. It addresses several pressing issues in STEM and product design education: the high cost and resource demands that hinder accessibility for diverse learners, the limited practical experience caused by software-based monitoring systems, the inefficient use of physical workshop space, and the amplified knowledge gap brought about by the COVID-19 pandemic. Additionally, it recognizes the changing dynamics of home learning environments due to space limitations. This innovative approach aims to provide an affordable, flexible, and secure learning platform, bridging these educational gaps.

II. MATERIALS AND METHODS

A. A Framework of Biometrics Security-driven IoT Edge Learning Monitoring

Edge computing can be used to improve the performance, reliability, and security of applications that rely on real-time data processing and analysis. A unique capacity of IoT edge is connecting to both private and public networks such as the Internet with less than 1 ms latency capacity. The connecting device includes smart devices capable of processing data from mobile phones and basic surrounding sensors including security and usage time monitoring. The IoT edge computing data capturing method is selected considering its capacity to collect and process data at the edge of the network close to the data. This offers several advantages over traditional cloud-based IoT systems including lower latency, reduced bandwidth requirements, and improved data security. In this study, the edge computing capacity is applied to monitor learners' engagement time. Previous research has shown that monitoring equipment usage in skill-based learning can provide educators with the learners' competency level of achievement without the physical monitoring that is required in traditional skill-based learning assessment [13]. The designed platform features a dual-function security system that can ensure the safety of the platform while also recording user engagement time. A biometric sensor is integrated with electric linear actuators enabled by fingerprint data that optimize the platform performance, reduce energy consumption, and ensure safety. The operational capacity is further enhanced with an algorithm that can accurately control the mechanical movement of the platform based on the data received from the biometric system. The hardware is made of lightweight wooden panels and electric linear actuators embedded with a closed-loop control system with limit sensors that provide high-accuracy control and positioning with flexible processes and low operating costs.

The learning environment usage time monitoring technique refers to methods of tracking and analyzing the utilization of tools and resources among learners during their learning. This technique can provide valuable insight into learners' behavior and engagement, as well as inform instructional design and improve learning outcomes. There are various types of techniques and tools used for monitoring [14]. This study adapted learning engagement time tracking using a biometric fingerprint device and other forms of summative assessment to provide a comprehensive view of learners' learning engagement. The biometric fingerprint device was selected over other types of monitoring devices such as surveillance cameras and face recognition scanners, considering the cost sustainability factor in maintaining the system in remote locations as well as its reliability over a long period.

B. Hardware Modeling

The conventional laboratory is typically classified based on the subject matter, such as physics, chemistry, and computer laboratory. These laboratories are further divided into various types based on the learners' learning levels, resulting in up to four to five different types of laboratories in the school. This setting requires additional manpower for laboratory operation and maintenance which eventually increases cost. These well-equipped laboratories are often underutilized due to access security and time restrictions. This study offers a solution for the issue by proposing a mobile and collapsible platform driven by an IoT security model. To effectively utilize an interdisciplinary learning environment such as product design, a more robust laboratory is required. The Secure Collapsible Makerspace is designed to address a robust requirement of recent Industry 4.0 technology. Figure 1 illustrates a 3D model of the Secure Collapsible Makerspace modeled using the Sketchup 3D design and modeling software [15]. The user authentication module with two-factor authentication based on biometric technology provides access to authorized personnel such as teachers to activate the platform. The user access data are captured and sent to the edge through built-in Wi-Fi to reduce response time. Multiple heavy-duty wheels are installed to enable the physical mobility of the platform in serving the needs of different groups and locations. The portable front and side door panels are scalable to meet the learning environment setting for the product design course.

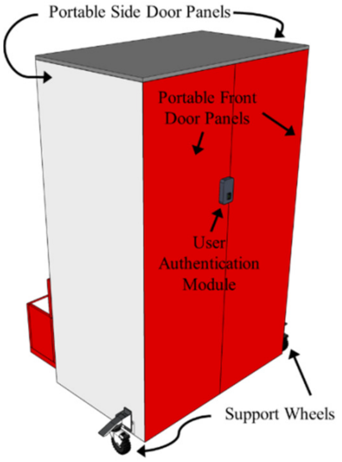

Fig. 1. 3D model of the proposed platform.

Figure 2 illustrates the expanded Secure Collapsible Makerspace. The platform is equipped with three collapsible tables which can be activated individually by the learners according to their needs. A fixed table equipped with six power outlets in addition to two power outlets at the back panel is rated at 240 V AC to hold the electrical equipment. To effectively control the expansion of the panels and the lifting of the tables, an automated actuator model is designed using biometric activation that commands a microcontroller to perform the panel activation operation.

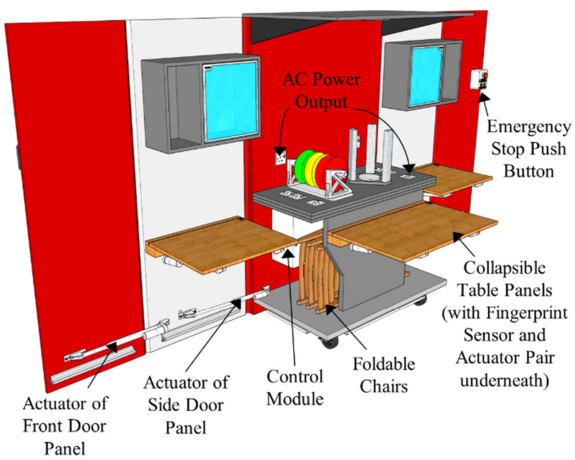

Fig. 2. 3D model of the expanded platform.

The platform is also designed with compartments for books and component drawers, added with storage for foldable chairs. It is powered by a domestic voltage supply of 240 V AC supported by an extended power cable to cater to the movable nature of the platform. Considering the safety of the users and the platform, a turn-to-release emergency stop pushbutton is installed to halt the panel operation in the event of an emergency. The other safety aspect of the platform expansion is the appropriate selection of the actuator which will be discussed in the next section.

C. Automation Configuration

The two-factor biometric-based authentication is applied to provide more secure control by providing feedback and comparing the fingerprint input from the user and the passcode with the existing records. Three failed attempts in a row within five minutes will lock the platform for 20 minutes as a security measure. Upon successful verification, the system will initiate the panel movement sequence. An array of limit sensors is used as a feedback mechanism to stop the individual panel's motion at the predetermined limit for safety measures. The same motion control mechanism is used in activating the learners' tables. Figure 3 shows the block diagram of the Secure Collapsible Makerspace control mechanism.

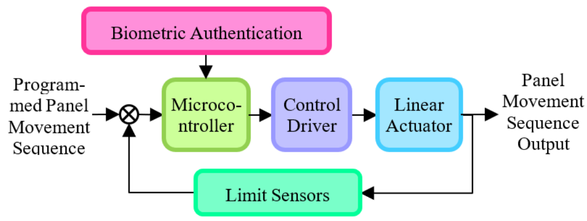

Fig. 3. Platform control mechanism.

D. Security Access Model

The platform access control is built on a two-factor authentication security access model that uses biometric fingerprint data with a passcode to identify and authenticate individuals attempting to gain access to the platform and its resources. Table I describes some key characteristics of the commonly used biometric security system [16-19]. According to Table I, the fingerprint biometric security model is the most optimal option in terms of usability, scalability, and cost. Since the purpose of the user authentication module is to allow authorized personnel to access the platform with fingerprint and passcode, the fingerprint images of registered users along with user ID and passcode are stored locally and backed up in the cloud storage. The system can be reset if there is a security breach or data corruption by restoring the factory settings from the cloud backup system.

User authentication based on the biometric technology approach is used during the activation of both the platform and tables for users. Minimizing the False Acceptance Rate (FAR) and False Rejection Rate (FRR) is a challenge for fingerprint biometric systems in multi-user and multi-level access settings. The system must be able to accurately distinguish between authorized and unauthorized users while minimizing false positives and false negatives. Error detection is caused by several factors, including the finger surface condition and the positioning of the finger. To address this issue, the authentication module is configured to capture images from any two fingers and two impressions per finger for memory optimization [20]. The proposed approach is expected to overcome the sensor's specific requirements on fingerprint images, which can limit flexibility and interoperability with other systems.

TABLE I. BIOMETRICS DATA CHARACTERISTICS

Characteristics	Fingerprint	Hand geometry	Iris	Facial	Voice
Ease of use	High	High	Medium	Medium	High
Accuracy	High	High	Very high	High	Medium
Verify time	< 3 s	3 s	< 5 s	3 s	5 s
Error incidence	Dryness, dirt, deep injury, age	Hand surface injury, age	Poor lighting, positioning	Lighting, glasses/ lens, hair	External noise, user health conditions
Security	High	Medium	Very high	Medium	Medium
Long term stability	High	Medium	High	Medium	Medium
Device user interface	Optical scanner	Hi-resolution camera	Illumination IR scanner	Hi-resolution camera	Hi-quality microphone
User age group suitability	Stable from 12-45 y.o. age	Stable from 21 y.o. age	Stable from 30 y.o. age	Affected by aging	Affected by aging

Collecting and storing biometric data raises concerns about privacy and security. While passwords can be changed, biometric data are unique to a user and may be permanently compromised if stolen or lost [21]. The biometric data of this platform are governed by a three-level security authorization by two different individuals to prevent data breaches or misuse. Another issue is system scalability, which requires the biometric system to be scalable to accommodate the increased number of users and access levels. The traditional approach requires the upgrading of hardware, software, and network infrastructure. To manage the growing number of users, this platform implements a unique usage-based optimization to move the least active user data to the archive every week. Considering all the preventive measures that have been considered in this design, the Secure Collapsible Makerspace is expected to serve the needs of the users efficiently and provide effective usage and data security.

E. Actuator Safety Modeling

Actuator safety modeling is an important aspect of the safe operation of actuators in both residential and industrial applications. Identifying potential hazards, evaluating risks, and integrating safety features to prevent accidents and protect users and equipment from harm produce safety-optimized equipment [22]. Safety optimization is an important element in the design of the Secure Collapsible Makerspace considering its nature to be used by learners with minimal or no supervision. The design team has considered the users' safety by carefully estimating the actuator selection and positioning. For high accuracy control as well as additional safety measures, limit sensors are positioned in selected locations as a feedback mechanism for panel operation. In the panel's collapsible operation, electric linear actuators are positioned between the two panels as a control mechanism. The actuator's rear end is mounted on the fixed panel, while the extension rod on the actuator's front end is mounted on the collapsible panel. Actuators are positioned to establish a triangular arrangement based on the fundamentals of Pythagoras' Theorem as shown in Figure 4 [23]. Determining the minimum stroke length is essential to increasing the efficiency of these actuators [24].

When a panel or table is said to be fully closed, the minimum retracted of the actuator is defined as:

$$L_R = \sqrt{(Y_2 - Y_1)^2 + X_1^2} \quad (1)$$

When a panel or table is said to be fully opened, the maximum extended length of the actuator is defined as:

$$L_E = \sqrt{(X_1 + Y_2)^2 + Y_1^2} \quad (2)$$

The minimum actuator stroke can be determined by the difference between (1) and (2):

$$S = L_E - L_R \quad (3)$$

Table II defines the acronyms used in (1)-(3).

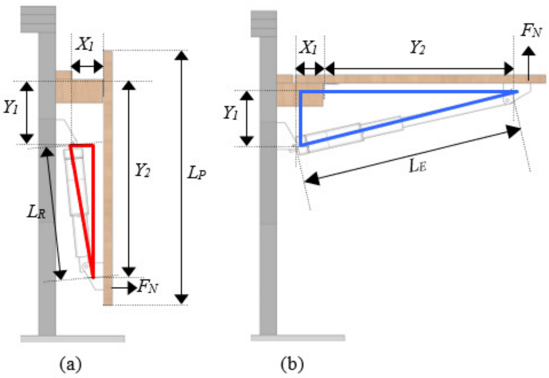

Fig. 4. Stroke calculation when fully (a) closed and (b) opened.

TABLE II. ACRONYM DEFINITIONS

Acronym	Definition
L_R	Maximum retracted length of the actuator when a panel or table is fully closed
L_E	Maximum extended length of the actuator when a panel or table is fully closed
Y_1	Distance (respective of the *y*-axis) between the actuator's rear-end mount and the panel hinge's axis of rotation
X_1	Distance (respective of the *x*-axis) between the actuator's rear-end mount and the panel hinge's axis of rotation
Y_2	Distance between the panel hinge's axis of rotation and the actuator's front-end mount
S	Actuator stroke, the distance of the extended length
L_P	Total length of the panel

The design of a linear actuator refers to the mechanism used to convert rotary motion into linear motion. The triangular arrangement is generally used particularly in linear applications where high accuracy and repeatability are required. The triangular calculation provides a high degree of rigidity and stability, which helps in preventing deflection and maintaining the accuracy of the linear motion. Additionally, the triangular arrangement allows for a compact and lightweight linear actuator which is particularly important in this application where space and weight are at a premium.

III. RESULTS

A. Functional Design

Figure 5 represents an overall functional block diagram, where the operational process of the platform is demonstrated. The control module and the security access block are communicated for user authentication instructions. Upon the user authentication process, the control module will instruct the sequential expansion of the door and side panels through the extension of the electric linear actuator. Each actuator's retraction and extension speeds are controlled by the dedicated driver. The panel expansion limit is triggered by the programmed limit sensor. The fully expanded panel allows the learners to engage in product design learning activities as in Figure 7. Each collapsible table is embedded with a fingerprint sensor that identifies the authorized user and monitors the usage time of the individual learners. Once the authorized user has been identified, the fingerprint sensor connected to the user authentication module will communicate with the control module to activate the desired table operation.

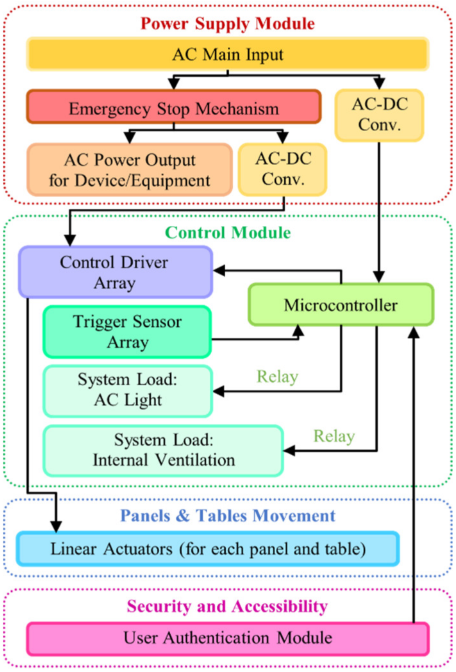

Fig. 5. Platform functional block diagram.

The operation of the user authentication module consists of two parts. The first part is the two-factor authentication module with integrated memory for storing fingerprint images, user ID, and passcode. The second part is the usage time data storage managed by the local SD card embedded with Wi-Fi facilities as shown in Figure 6, which adapts edge computing architecture. The edge computing architecture enables user data to be analyzed in real-time at the edge device, as in this case the biometric-integrated user authentication module, before being transmitted to the central location [25]. This enables the system to identify and respond to security threats much faster than if all the data had to be transmitted to a central location first [26].

Edge computing provides solutions to reduce costs associated with data storage and transmission. By processing and analyzing data locally, only relevant data needs to be transmitted to a central location for storage, which can significantly reduce the amount of data that needs to be transmitted especially in suburban and rural areas with limited communication infrastructure.

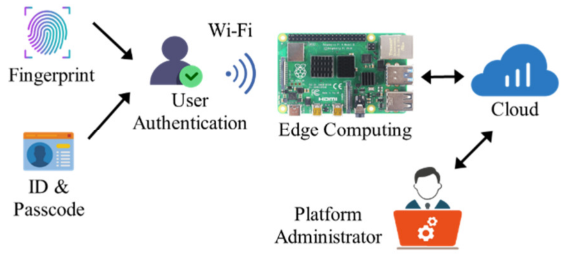

Fig. 6. Hardware communication with an edge computing architecture.

B. Platform Prototype and Application

The developed Secure Collapsible Makerspace was recently placed in a local school facility (Figure 7). Considering the requirement for product design learning skills, the prototype was installed in front of the existing product design workshop. In August 2022, the platform started operating and accommodated a total of 750 learners by December 2022. Engagement with the newly developed platform has significantly increased the learners' learning capacity. Figure 8 represents the pre- and post-assessment outcomes of 750 learners.

Fig. 7. Platform prototype.

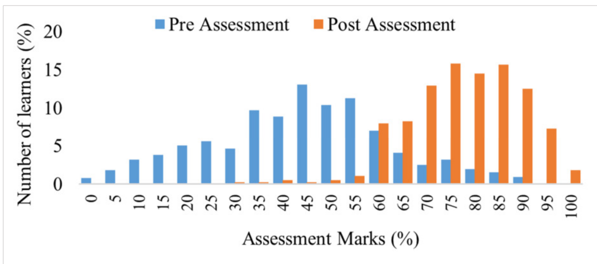

Fig. 8. Learners' pre- and post-assessments.

The Pearson correlation coefficient was computed to assess the linear relationship between learners' engagement time in the Secure Collapsible Makerspace and assessment outcome.

There was a positive correlation between the two variables of 0.72 with a corresponding *p*-value less than 0.001. The learners' monitoring system was triggered and successfully recorded the biometrics log-in and log-out of individual users as well as the usage time. Some recorded raw data during the event can be seen in Figure 9.

```
DATE: 01.12.2022; LOG IN TIME: 14:56:16; Teacher ID: 003;
DATE: 01.12.2022; TABLE 1 START: 15:01:05; Learner ID: 221;
DATE: 01.12.2022; TABLE 2 START: 15:02:25; Learner ID: 256;
DATE: 01.12.2022; TABLE 2 END: 17:04:51; Learner ID: 256;
DATE: 01.12.2022; TABLE 1 END: 17:06:02; Learner ID: 221;
DATE: 01.12.2022; LOG OUT TIME: 17:10:39; Teacher ID: 003;

DATE: 02.12.2022; LOG IN TIME: 14:42:31; Teacher ID: 007;
DATE: 02.12.2022; TABLE 3 START: 14:48:11; Learner ID: 703;
DATE: 02.12.2022; TABLE 1 START: 14:48:16; Learner ID: 015;
DATE: 02.12.2022; TABLE 2 START: 14:51:32; Learner ID: 038;
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Fig. 9. Learners' platform usage record sample.

IV. DISCUSSION

A. *Learning Enhancement with Secure Collapsible Makerspace*

Currently, there are various monitoring devices and platforms used to empower STEM learning among learners [27]. The Google Classroom application is one of the most used platforms for monitoring learners' self-learning time in the product design course, especially during the pandemic [10]. Before the pandemic, the learners' independent learning time was not included in the learning assessment [28-29]. When compared to the existing product design workshop, the developed Secure Collapsible Makerspace has more flexibility to be applied to different assignments for learners due to its security and monitoring features. The platform monitoring feature has added significant value to the learners' self-learning time to be included in the assessment. The impact of self-learning time monitoring on the product design course will be determined by how it is integrated into the overall curriculum.

Balancing self-learning time with guided instructions and collaborative activities can help to maximize the benefit of both approaches and promote more effective learning outcomes. Factors that influence the outcome of the self-learning component in the product design course are flexibility, depth of learning, skill development, and time management. The Secure Collapsible Makerspace directly supports flexibility and time management by allowing learners to work at their own pace on their schedule. This flexibility was found to be beneficial for learners who have limitations in scheduling their learning time due to other commitments, especially in the post-pandemic era [30]. The depth of learning was indirectly benefited from the platform where learners had sufficient time at their comfort to delve deeper into topics that interest them and explore different design techniques and methodologies in greater detail [31].

Skill development is another factor that benefits from self-learning time, which allows learners to practice and develop their skills and helps them become more proficient in software design, prototyping, and product testing. However, there are several drawbacks to self-learning time in the product design course, including the lack of guidance, isolation, and the lack of motivation to engage in self-learning activities [32]. During five months of intervention, it has been significantly recognized that the self-operative, secure, embedded with user monitoring, Secure Collapsible Makerspace encourages a significant increase in self-learning time against the assessment. As a result, the developed platform can help both learners and teachers improve the learning efficiency and productivity of the product design course. As a real-world application system, the developed monitoring platform has been applied for a patent that improves the self-learning practice among learners and brings a significant increase in knowledge and skills in the product design course. Unlike other monitoring platforms on the market, this platform can be used as a mobile multi-purpose monitoring platform at schools and community learning centers.

V. CONCLUSION

The Secure Collapsible Makerspace has been developed to assist learners in hands-on activity-related learning. The platform is driven by a control module that integrates electric linear actuators, limit sensors, and a biometric security system to ensure an expandable and secure environment. The platform is further empowered with edge computing and biometric security technology to facilitate real-time analysis of the users' makerspace utilization. The design has the option to transfer the recorded data to the cloud instantly or store it locally and transfer it when a reliable connection is available. The compact Secure Collapsible Makerspace provides learners with easy, yet secure access control without time constraints. At the same time, the teachers can remotely access the data on the cloud for learners' monitoring and assessment purposes. During the five months of the school intervention study, the platform successfully recorded learners' utilization information for the teachers to evaluate learners' performance in product design against self-learning time. The study observation concluded that the learners' productivity in the product design course can be increased with freely available and secure learning space. Self-learning monitoring Secure Collapsible Makerspace revolutionizes education by offering dynamic, personalized, and accessible learning experiences compared to conventional static learning spaces.

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