Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 5, October 2025, pp. 3439~3451
ISSN: 2302-9285, DOI: 10.11591/eei.v14i5.9516

Enabling SECS/GEM in legacy equipment: a proof of concept

Muhammad Syahir Kamal Fitri[1], Selvakumar Manickam[1], Shams Ul Arfeen Laghari[2], Siang Kok Chia[3], Mohamad Khairi Ishak[4], Shankar Karuppayah[1]
[1]Cybersecurity Research Centre (CYRES), Universiti Sains Malaysia, Pulau Pinang, Malaysia
[2]Sandisk Storage Malaysia Sdn. Bhd., Simpang Ampat, Pulau Pinang, Malaysia
[3]School of Information and Communication Technology, Faculty of Engineering Design Information Communications Technology (EDICT), Bahrain Polytechnic, Isa Town, Bahrain
[4]Department of Electrical and Computer Engineering, College of Engineering and Information Technology, Ajman University, Ajman, United Arab Emirates

Article Info

Article history:

Received Nov 6, 2024
Revised Aug 1, 2025
Accepted Sep 1, 2025

Keywords:

Industry
Manufacturing
Production
Protocols
SEMI equipment communication standard/generic equipment model

ABSTRACT

The rapid adoption of Industry 4.0 (I4.0) has driven the need for automated machine-to-machine (M2M) communication in manufacturing. However, legacy equipment remains a challenge due to its incompatibility with modern protocols like semiconductor equipment and materials international (SEMI) equipment communication standard/generic equipment model (SECS/GEM). Replacing these machines is costly, making retrofitting a more viable solution. This paper proposes a modular automation software framework that enables SECS/GEM integration for legacy machines without extensive hardware modifications. The system is implemented using Raspberry Pi and Arduino, acting as an intermediary between legacy equipment and modern factory networks. The framework facilitates real-time data exchange, remote monitoring, and enhanced automation while ensuring scalability and cost-effectiveness. Experimental evaluation demonstrates improved interoperability and reduced manual intervention. This solution provides a practical and adaptable approach to integrating legacy systems into (I4.0) environments.

Corresponding Author:

Shankar Karuppayah
Cybersecurity Research Centre (CYRES), Universiti Sains Malaysia
Gelugor, Pulau Pinang, 11800 Penang, Malaysia
Email: kshankar@usm.my

1. INTRODUCTION

Manufacturing industries are rapidly adopting automation to enhance productivity, efficiency, and quality, driven by advancements in Industry 4.0 (I4.0) and smart manufacturing (SM) [1]. Technologies such as the internet of things (IoT), sensors, robotics, and machine learning have significantly optimised production processes by enabling machine-to-machine (M2M) communication and reducing human intervention [2]. These advancements facilitate real-time data exchange, predictive maintenance, and autonomous operations, transforming modern industrial environments [3].

Despite the widespread adoption of automation, many manufacturing processes still rely on legacy equipment that lacks modern communication capabilities [4]. While semi-automated and fully automated workstations aim to minimise human involvement, legacy systems remain essential in semiconductor, automotive, and industrial production lines due to their durability, cost-effectiveness, and reliability [5], [6]. However, integrating these older machines into I4.0 frameworks presents a significant challenge due to their in-standard/generic equipment model [7].

Semiconductor equipment and materials international (SEMI) equipment communication standard/generic equipment model (SECS/GEM) is a widely adopted standardized communication protocol that enables automated data exchange between equipment and factory control systems. It plays a crucial role in real-time monitoring, production control, and process optimization in modern manufacturing. However, legacy machines typically operate on outdated communication interfaces, such as RS-232, which lack network connectivity, data synchronization, and machine-level automation required by I4.0 [8], [9]. Retrofitting these machines to support SECS/GEM is challenging due to the following:

- Hardware limitations–legacy machines lack network modules and require external interfaces for integration [10].
- Compatibility issues–existing solutions are often vendor-specific, requiring extensive customization for different machines [11].
- High implementation costs–direct replacement of older equipment with SECS/GEM-compliant machinery incurs significant financial investment [12], [13].

Several approaches have attempted to address legacy equipment integration into modern automation frameworks. Custom hardware adapters have been developed to bridge older communication protocols with SECS/GEM, but they are costly, difficult to scale, and require extensive modifications [14]. Modular software solutions enable partial compatibility, but they often suffer from latency issues, lack of modularity, and limited interoperability across different machine types [15]. Given these challenges, there is a pressing need for a scalable, vendor-independent, and cost-effective solution that enables seamless SECS/GEM integration for legacy manufacturing systems.

This paper proposes a modular automation software framework that enables legacy manufacturing equipment to communicate using SECS/GEM, thereby extending their usability and interoperability without requiring extensive hardware modifications or system overhauls. The proposed solution leverages:

- A low-cost, flexible architecture using Raspberry Pi and Arduino to act as a SECS/GEM communication bridge.
- A software-based approach that facilitates scalable integration across multiple machine types.
- A real-time monitoring system that enhances automation efficiency while maintaining compatibility with I4.0 standards.

This paper presents a novel approach to addressing these challenges by proposing a flexible, cost-effective solution for enabling SECS/GEM in legacy equipment. The remainder of this paper is structured as follows: section 2 provides an overview of the SECS/GEM protocol and its relevance to modern manufacturing. Section 3 reviews related works, highlighting existing solutions and their limitations. Section 4 details the design and implementation of the proposed modular automation software, followed by the expected outcome of this solution in section 5. The paper is concluded in section 6, which also outlines potential areas for future research.

2. BACKGROUND

With the manufacturing and semiconductor industry moving towards implementing I4.0 and industrial IoT (IIoT), legacy machines will need to co-exist with the newer ones [15]. However, newer machines have far more advanced functionalities that enable quick glance of information by users or factories to quickly glance at information that was not normally provided by legacy equipment, resulting in most of the legacy machines needing to be replaced with new ones [16]. This is due to the reason that newer technologies and infrastructure are needed to fulfil the requirements of I4.0 and IIoT [17], [18]. Since then, legacy equipment has been left behind. For many years, there have been so many efforts to ensure that legacy equipment can fit into the modern environment. This includes network interfaces, direct SECS/GEM implementation, network security, or even other ways of keeping up with the industry standard.

2.1. Overview of SEMI equipment communication standard/generic equipment model

The semiconductor and surface mount technology (SMT) industries are rapidly adopting automation, M2M communication, and real-time data analytics to enhance manufacturing efficiency [6]. The SEMI equipment communication standard/generic equipment model (SECS/GEM) protocol has been the industry standard for decades, enabling machine interoperability and automated process control [15].

SEMI is an organization that defines communication protocols to standardize data exchange between equipment from different manufacturers [19]. These standards improve interoperability, reduce downtime, and enhance production efficiency by ensuring seamless data transmission and system integration [20].

SECS/GEM includes four key protocols: SECS-I (E4), SECS-II (E5), GEM (E30), and high-speed SECS message service (HSMS) (E37), each serving different functions in automated manufacturing [21].

Since 1978, companies like Intel, Samsung, and IBM have widely adopted SECS/GEM for equipment communication and management [21]. The most recent protocol update was published in 2020.

2.2. SECS-I

SECS-I (SEMI E4), introduced in 1978, defines point-to-point communication between the host and equipment using the RS-232 standard. This protocol enables asynchronous message exchange, but it operates in half-duplex mode and lacks TCP/IP support, making it unsuitable for modern industrial applications [22]. SECS-I uses a block transfer protocol, where data is transmitted in 256-byte blocks containing a header, data bytes, and checksum. The message format supports single-block and multi-block transfers, ensuring structured data exchange between machines. Despite its role in early automation, SECS-I is now obsolete due to low transmission speeds, limited scalability, and poor noise immunity and is only found in older legacy equipment.

2.3. SECS-II

SECS-II (SEMI E5) is a communication protocol that establishes a general message layer for data exchange between hosts and manufacturing equipment [23]. It organizes messages into streams and functions, where streams group related messages, and functions specify message types. For instance, Stream 5 manages alarms, while Stream 7 handles recipe management.

Each SECS-II message follows a stream-function (SnFm) notation, where n represents the stream number and m represents the function number. Functions with odd numbers define requests (primary messages), while even numbers define responses (secondary messages). For example, S1F13 is a communication request, with S1F14 as its response. Transactions are uniquely identified, allowing multiple concurrent ex- changes. Figure 1 shows the stream and functions availability and Figure 2 shows the stream and functions message layout. SECS-II messages support various data types, including binary, ASCII strings, integers, floating points, and Boolean values. Data structures may be simple elements or nested lists, and all messages must be encoded before transmission using SECS-I.

Stream	Function	Availability
0	0 to 255	Reserved
1 to 63	0 to 63	Reserved
64 to 127	0	Reserved
1 to 63	64 to 255	User defined
64 to 127	1 to 255	User defined

Figure 1. Stream and functions availability

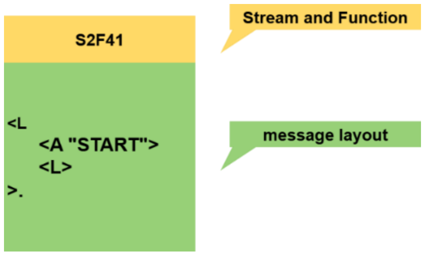

Figure 2. Stream and functions message layout

2.4. Generic equipment model

Generic equipment model (GEM), defined in SEMI E30, is a subset of SECS-II that standardizes equipment behaviour and communication in manufacturing automation. Developed in 1988 and officially published in 1993, GEM was created to ensure consistent messaging between factory control systems and equipment. However, its implementation posed challenges due to complex data management and real-time control requirements.

The GEM standard defines both fundamental requirements and additional capabilities for equipment compliance. To operate within a SECS/GEM environment, equipment must adhere to SEMI E30 specifications and support key functionalities such as alarm management, data collection, and remote control. GEM-compliant equipment communicates with a host system, typically part of a manufacturing execution system (MES), using either SECS-I (E4) or HSMS (E37).

For full compliance, equipment must implement all core GEM requirements, while additional capabilities can be selectively enabled as needed. Although the host system does not need to follow GEM hardware requirements, it must implement the host-side messaging protocols to facilitate communication.

2.5. High-speed SECS message service

High-speed SECS message service, SEMI E37 (HSMS), introduced in 1995, replaces SECS-I's RS-232 communication with TCP/IP for faster and more scalable message exchange [24]. It transports SECS-II messages over a network, ensuring seamless integration into modern industrial environments. HSMS follows RFC 793 with modifications for industrial automation. It supports active mode and passive mode connections, where the host (active) initiates communication, and the equipment (passive) responds. Once established, the connection remains open for continuous data exchange until it is terminated.

HSMS messages use a binary-encoded format, consisting of a 4-byte message length, a 10-byte header, and optional data payloads up to 4.3GB [6]. This structured approach enhances efficiency, reliability, and scalability in SECS/GEM communication. Figure 3 illustrates the HSMS message format, detailing its structure.

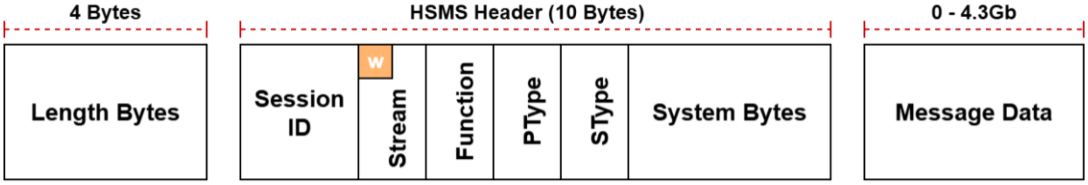

Figure 3. HSMS message format [21]

3. RELATED WORKS

This section reviews existing solutions for enabling SECS/GEM in legacy equipment, highlighting the methodologies proposed by other researchers and identifying how they address the integration challenges in I4.0 environments. In the work by Terng *et al.* [25], the authors developed SECS/GEM communication software using C# and Windows Forms to facilitate communication between a host system and a reflow oven on the production line. This software allows for real-time monitoring and data retrieval from the oven, enabling users to configure parameters, set data collection intervals, and monitor the communication status between the host and the equipment. The system provides detailed event and alarm reports, which are crucial for analyzing machine performance. The data collected can be further analyzed using the integrated C# analytics tool, providing insights into equipment efficiency and operational trends. Similarly, Ma *et al.* [26] introduced the tool efficiency analysis (TEA) model, designed to monitor and evaluate production equipment performance based on the SEMI standards. The TEA model incorporates two main frameworks: automation data collection (ADC) and data analysis (DA). The ADC framework manages event triggers and state changes, while the DA framework filters data within specified time ranges and calculates key performance metrics. This model provides a comprehensive approach to understanding equipment efficiency, offering a structured method for performance analysis in automated production environments. Jónasdóttir *et al.* [27] proposed an innovative interfacing technology called BAUTA, aimed at upgrading legacy machines for compatibility with IIoT and I4.0 standards. BAUTA acts as a bridge, allowing legacy equipment to connect and communicate with other systems in a network with minimal modifications. This physical interface mimics human-machine interactions by remotely actuating control panel keys and collecting data for analysis. BAUTA enables remote maintenance and monitoring, ensuring that older machines can integrate into modern production environments without extensive overhauls. These studies demonstrate various approaches to integrating legacy equipment with SECS/GEM protocols and modern manufacturing standards. However, each approach has its limitations, particularly in terms of scalability and ease of implementation. Our research builds upon these foundations by proposing a more flexible and modular solution that addresses these gaps, offering a robust framework for seamless integration of legacy equipment in I4.0environments. Table 1 provides a summary of these solutions, highlighting their key features and limitations.

Table 1. Summary of existing solutions for enabling SECS/GEM in legacy equipment

Reference	eProposed solution	Key features	Limitations
[25]	SECS/GEM communication software using C# and Windows Forms	Real-time monitoring and data retrieval; provides event and alarm reports; includes C# analytics tool	Potential challenges in scalability and adaptation to different equipment
[26]	TEA model	Combines ADC and DA frameworks; monitors equipment performance based on SEMI standards	Complexity in implementation; restricted adaptability to various machines
[27]	BAUTA interface technology	Enables remote maintenance and integration of legacy machines into IIoT and I4.0; mimics human-machine interactions for control and data collection	Requires physical modifications; challenges in scaling across diverse equipment types
Proposed research	Modular and flexible automation software	Aims to provide a robust framework for integrating legacy equipment seamlessly in I4.0 environments	Still to be evaluated; potential challenges in ensuring broad compatibility

4. PROPOSED MODEL

The proposed model that will be used in this research is different from what has been done by other researchers. Modular automation software is software that can be used in many machines of different vendors and types. Automation software opens the chance for the machine to be operating with lesser human intervention. This allows a company to fully utilise legacy equipment on the manufacturing floor. Legacy elopements can vary, ranging from a machine that is designed to do one specific task using one sensor or motor to a machine that contains a lot of sensors and motors inside.

4.1. System overview

The proposed model is designed to enable SECS/GEM communication for legacy manufacturing equipment, allowing real-time data exchange, process automation, and remote monitoring. This integration eliminates the need for costly equipment replacements by retrofitting existing machines with a modular hardware-software solution. The system consists of two main components: hardware and software components. Hardware components are a combination of microcontrollers, sensors, and actuators that facilitate data acquisition and machine control. Software components include the implementation of SECS/GEM communication, data processing, and real-time monitoring to bridge the legacy equipment with modern industrial networks.

4.1.1. Hardware components

The success of the proposed SECS/GEM system depends a lot on its hardware setup. Each part has its own role but works together to collect data, control the machines, and connect with factory networks. By combining these components, the system makes it possible for older machines to work smoothly in a modern I4.0 environment.

a. Conveyor belt system: a motorized conveyor belt simulates a real-world production line, transporting objects through various validation and processing stations. Equipped with various sensors and controlled via Arduino Mega, which:
- Starts or stops the conveyor based on sensor feedback.
- Adjusts speed or triggers alerts for misaligned or defective products.

b. Raspberry Pi 4 (SECS/GEM communication bridge): the Raspberry Pi 4 serves as the primary SECS/GEM interface, handling data collection, processing, and transmission to the host system. It is responsible for:
- Establishing SECS/GEM connectivity with the host.
- Receiving raw data from sensors via serial communication with Arduino Mega.
- Encoded sensor data into SECS-II messages before transmitting them to the host.
- Logging and storing messages in a centralized database for further analysis.

c. Arduino Mega (sensor interface and conveyor control): The Arduino Mega manages low-level sensor inputs and actuator outputs, acting as an interface between legacy equipment and modern digital communication protocols. Its responsibilities include:
- Reading sensor data (photoelectric, colour, force, and camera sensors).
- Controlling the conveyor system to move objects through different processing stations.
- Sending processed data to Raspberry Pi for SECS/GEM message formatting.

4.1.2. Software components

The software handles communication, processes the data, and makes sure everything runs smoothly between the old machines and the modern factory systems. The software parts work together to share data, catch errors right away, and show the information on a dashboard that's easy to follow.

a. Python-based SECS/GEM protocol implementation: the SECS/GEM software layer is implemented in Python and runs on Raspberry Pi. It ensures:
- Establish SECS/GEM connection between the legacy system and the host.
- Encoding and decoding SECS-II messages for communications.
- Error handling and alarm triggering for real-time fault detection.

b. Serial communication with Arduino: to facilitate real-time data transfer, the Arduino and Raspberry Pi communicate using serial communication (UART).
- Arduino collects raw sensor data and transmits it as structured messages.
- Raspberry Pi parses, processes, and converts the data into SECS-II format before forwarding it to the host.

c. Database and live dashboard for real-time monitoring: all sensor readings, process logs, and alarm events are stored in a centralized database for:
- Live monitoring via a web-based dashboard.

– Historical DA to improve system performance.
– Triggering alerts when anomalies are detected (e.g., incorrect colour, excessive force, and misalignment).

4.2. System architecture

The system architecture is designed to enable the seamless integration of SECS/GEM communication with legacy manufacturing equipment. It consists of multiple components, including a host system, modular software running on Raspberry Pi, a database, and a real-time dashboard. Figure 4 illustrates the architecture design, highlighting the role of each component in facilitating communication and automation.

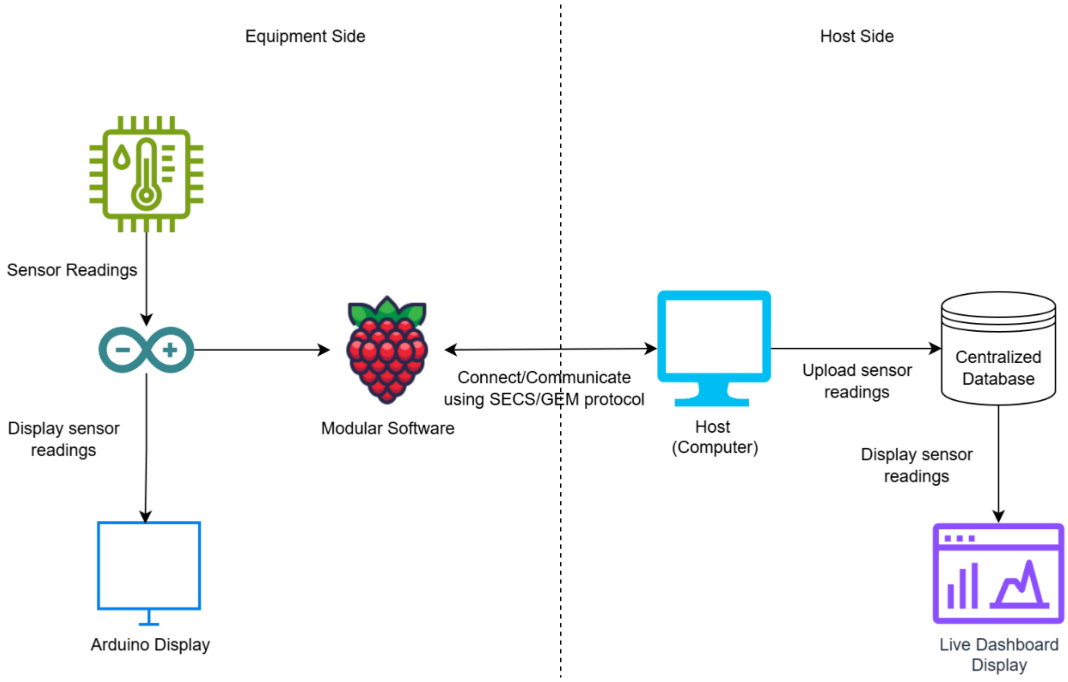

Figure 4. Architecture design

The architecture is split into two parts: the equipment side and the host side. The equipment side will consist of the demonstrator and the modular software. The host side consisted of the host, database and live dashboard display. At first, both the host and Raspberry Pi will be running the SECS/GEM host and equipment class. The host will be in active mode, where it will always find an active connection available, while the Raspberry Pi will be in passive mode, waiting for an incoming connection from the host. A SECS/GEM request for the connection function will be sent from the host to the Raspberry Pi to establish the connection. Once connected, the host will listen to the incoming messages or data from the equipment.

An Arduino Mega will be used to control the movement and action of the conveyor belt. Arduino Mega will collect data from all the sensors in the form of string and pass it to a Raspberry Pi, which is the modular software. The Arduino Mega will communicate with the Raspberry Pi through serial communication. Upon receiving the string of data, the Raspberry Pi will then break down the string and process the data from each sensor. Appropriate SECS/GEM messages and functions will be used between the host and the Raspberry Pi, allowing them to communicate and exchange data. Once the host receives the messages, it will upload all the sensors' readings into a centralised database. A live dashboard display is needed to display the current data detected by the sensors. The software will utilise the alarm functionalities defined in the SECS/GEM protocol. If the host detects an unexpected reading from a sensor, a respective alarm will be raised and will be sent to the Raspberry Pi. This will allow for a quick response to be taken. The proposed system consists of multiple components, including a host, modular software, sensors, and a live dashboard, all communicating using SECS/GEM.

4.3. Demonstrator design

The modular automation software will be developed for both the host and the equipment. The proposed system is implemented using a demonstrator setup that mimics an automated production line. This demonstrator integrates multiple sensors, a conveyor system, and SECS/GEM communication modules to simulate real-world manufacturing scenarios. Figure 5 illustrates the layout of the proposed demonstrator design and the functionality of each sensor and station.

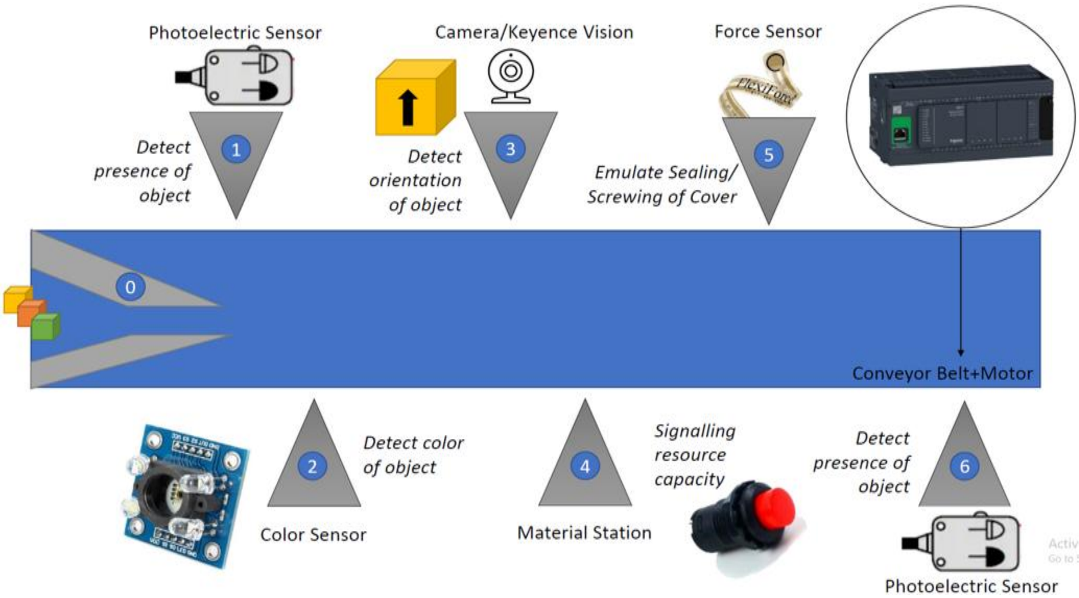

Figure 5. Proposed demonstrator design

The demonstrator will consist of a mini conveyor belt with a few sensors attached to the frame. These sensors are photoelectric sensors, cameras, colour sensors, and force sensors. Each sensor will have its respective task, representing a machine or station in the production line. A few wooden blocks will be used as the product that will go through all the sensors as it is in the real production line.

4.4. Sensor functionalities

The demonstrator system incorporates four key sensors to detect object presence, colour, orientation, and applied force. These sensors ensure real-time validation, allowing automated intervention through SECS/GEM alarms and control signals. For every sensor, there will be a threshold or readings that are allowed. If the readings are out of the defined threshold or value, the conveyor will be stopped. For some sensors, an alarm will be raised. This is the same scenario as in the real production line, where the operators or the person in charge can check the product. This will ensure that it will not affect the later process in the production line and can minimise defects.

- The photoelectric sensor will be used at all six stations to detect whether the object has arrived at the stations or not. This will also help monitor the number of products that go through the stations on the conveyor.
- The colour sensor stops the conveyor if an incorrect colour is detected.
- If an object is misaligned, the camera sensor halts the process for correction.
- If force readings exceed the threshold, an alarm is triggered.

To enable real-time monitoring and automation, the proposed demonstrator incorporates various sensors to detect object presence, orientation, and colour while ensuring process quality.

4.5. Workflow description

The proposed system follows a sequential workflow, where objects move through different sensor-based stations, each performing a validation task. The workflow ensures proper data collection, processing, and decision-making before allowing objects to proceed. Figure 6 presents the flowchart of the demonstrator, detailing each step from object entry to final validation. Table 2 outlines the tasks performed at each station and their corresponding SECS/GEM messages for integration.

At the end of this workflow, the collected sensor data is processed and transmitted via serial to the Raspberry Pi, ensuring real-time monitoring and system automation. Each validation step is crucial in maintaining product quality and operational efficiency, as the system can detect anomalies early and trigger alarms when deviations occur. This structured workflow enhances process reliability, reduces manual intervention, and improves overall productivity in a manufacturing environment.

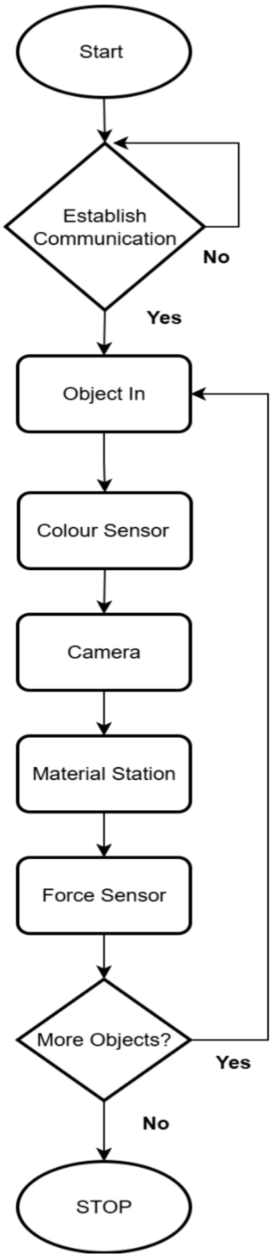

Figure 6. Flowchart of demonstrator

Table 2. Workflow description

Station No	Function
1 (Object entry)	Objects are placed on the conveyor belt and detected by a photoelectric sensor to ensure correct positioning.
2 (Colour detection)	Objects stop under a colour sensor that measures and records their RGB values, ensuring only correctly coloured objects proceed.
3 (Orientation check)	A camera checks the orientation of the objects, ensuring proper alignment for subsequent processes.
4 (Material station)	This station manages resource capacity and requires manual tasks by an operator. A stop/start button controls the conveyor if resources are low.
5 (Force check)	A force sensor measures the applied force on each object, triggering an alarm if the force is outside the acceptable range.
6 (Object exit)	Objects completed the process and the photoelectric sensor detects their presence.

5. RESULTS AND DISCUSSION

Although this proof of concept has not been implemented in a live production environment, the expected outcomes of integrating this modular software into legacy equipment are promising. Based on early testing and simulations with a demonstrator, few benefits can be anticipated if this software were to be implemented in the actual production environment.

This section presents the key findings of the proof of concept for enabling SECS/GEM in legacy manufacturing equipment. The results are discussed in terms of efficiency improvements, cost savings, scalability, and data analytics capabilities. The findings are compared with existing studies to highlight the significance of this approach.

5.1. Integration

The study was conducted using a demonstrator model, which is a conveyor system equipped with various sensors and a modular software interface that utilises SECS/GEM protocol as a communication protocol. The system successfully established real-time communication between the demonstrator and the modern manufacturing execution systems (MES) without the need to modify the existing hardware. The result shows that the legacy machines can be integrated into an I4.0 environment using the proposed SECS/GEM interface. Table 3 summarizes the key functional outcomes of the study.

Table 3. Functional outcomes of the proof of concept

No	Feature	Expected outcome	Observed outcome
1	SECS/GEM communication	Successful bidirectional communication	Achieved real-time data exchange between host and legacy machine
2	Data collection and transmission	Automated data logging in MES	Real-time sensor data successfully transmitted
3	Error handling and alarms	Integration of alarm system for abnormal conditions	SECS/GEM-based alarms triggered correctly during anomalies
4	Machine interoperability	Compatibility with other SECS/GEM-enabled equipment	Legacy machine successfully integrated with newer systems

5.2. Improved efficiency

The retrofitting of legacy equipment with SECS/GEM is expected to lead to significant improvements in overall system efficiency. By automating M2M communication, the need for manual intervention is reduced dramatically, allowing machines to interact directly with minimal human involvement. This change can help streamline the production process, reducing delays and increasing the accuracy of operations.

The integration of SECS/GEM enables real-time monitoring and data sharing between machines and the central control system, leading to more synchronized operations. As a result, companies can expect improved throughput as machines process tasks more efficiently without waiting for manual input or troubleshooting delays. Early tests with the demonstrator suggest a potential 40% increase in processing speed, which directly impacts overall productivity. Additionally, error rates are expected to decrease by as much as 60% due to improved accuracy in data transmission and reduced human error.

Moreover, enhanced machine performance and streamlined communication help minimize downtime. Predictive maintenance can be implemented more effectively since SECS/GEM enables real-time monitoring of machine performance. By identifying potential issues before they lead to equipment failure, maintenance can be scheduled proactively, reducing unexpected breakdowns and extending the operational life of machines.

5.3. Cost savings

Retrofitting legacy machines with SECS/GEM provides a cost-effective alternative to full equipment replacement, allowing businesses to extend the lifespan of existing machinery while benefiting from modern automation and communication protocols. This approach significantly reduces capital expenditures and minimizes downtime, as companies can continue operating without the disruptions associated with installing entirely new systems. Instead of investing in costly new equipment, businesses can gradually enhance their current infrastructure through software upgrades and protocol integration.

Beyond initial cost savings, operational efficiency improvements further contribute to reduced expenses. Enhanced M2M communication lowers error rates, minimizes waste and re-work, and improves throughput, leading to higher productivity. Additionally, predictive maintenance enabled by SECS/GEM reduces unexpected breakdowns and repair costs, further enhancing long-term savings. By integrating SECS/GEM, manufacturers can achieve greater efficiency, lower operational costs, and an improved return on investment (ROI). The estimated cost comparison is outlined in Table 4. These findings are supported by Ma *et al.* [26] who reported that upgrading legacy systems via automation software led to a 60% reduction in operational costs compared to complete equipment overhauls.

Table 4. Estimated cost comparison between retrofitting and replacement

No	Cost factor	Retrofitting with SECS/GEM	Full equipment replacement	Estimated cost saving (%)
1	Hardware investment	Low (software and adapters)	High (new equipment)	70-80
2	Installation and training	Minimal adaptation needed	Extensive setup and training	50-60
3	Operational downtime	Short, modular integration	Long, requires new infrastructure	40-50

5.4. Scalability

The modular software architecture developed for this proof of concept ensures that the SECS/GEM integration is highly scalable. As production demands evolve or new machines are introduced to the production line, the system can be expanded with minimal disruption to existing operations. Additional sensors, machines, or even entire production lines can be easily integrated into the system without requiring significant reconfiguration. This makes the solution highly adaptable to a wide range of manufacturing environments and equipment setups.

Scalability also allows for future-proofing. As technology evolves and production requirements change, businesses will be able to incorporate new features, devices, or sensors into the existing SECS/GEM frame- work. This flexibility reduces the risk of obsolescence, ensuring that companies can continue to use their legacy equipment well into the future while still staying competitive and keeping up with I4.0 demands.

Jónasdóttir *et al* [27] proposed the BAUTA interface for legacy system integration but noted limitations in physical modifications required. The proposed approach in this study eliminates such constraints by relying solely on software adaptation.

5.5. Enhanced data analytics and decision-making

Another significant benefit of SECS/GEM integration is the potential for enhanced data analytics. SECS/GEM enables real-time data collection from equipment across the production line, providing valuable insights into operational performance, machine health, and production trends. This data can be used to inform decision-making, helping managers optimize production schedules, identify bottlenecks, and improve overall efficiency.

With access to detailed machine data, companies can implement more advanced analytics, such as machine learning models, to further optimize operations. Predictive analytics can be used to forecast equipment failures or production delays, allowing businesses to act preemptively and avoid costly disruptions. These insights contribute to a more agile and responsive manufacturing environment. Table 5 illustrates an example of data collected during the study and the corresponding maintenance actions taken. Predictive maintenance reduces unplanned downtime and maintenance costs, a benefit also observed by Fischer *et al.* [7], who reported a 30-50% reduction in failure rates due to SECS/GEM-enabled monitoring.

Table 5. Example of real-time data analytics for predictive maintenance

No	Sensor data	Normal range	Observed value	Action taken
1	Colour sensor	Accepted colours (red/yellow)	White	Trigger alarm notification
2	Camera	Object orientation ($\pm 10^\circ$)	20°	Notified operator for adjustment
3	Force sensor	7-10 N	15 N	Notified operator for adjustment

6. CONCLUSION

In conclusion, this solution provides insight into solving the issue of using legacy equipment in the current automated production line to align with I4.0 needs. By retrofitting legacy equipment with the SECS/GEM protocol, the machines are able to communicate with newer machines, update and exchange data in real time, and allow for easier control. The Modular Software is designed to integrate seamlessly into any machine, regardless of vendor, model, or type. Although the modular software is not yet implemented in a real production line, the proof of concept has demonstrated promising results. Future implementations could explore optimizing communication speed and latency to further enhance interoperability and efficiency. Moreover, as this solution evolves, it holds the potential to contribute to sustainability by reducing the need to replace entire systems and extending the usable lifespan of legacy equipment. For future work, this modular software can be expanded to include additional sensors for diverse machine types and potentially commercialized as a comprehensive, adaptable solution for modern industrial automation.

FUNDING INFORMATION

This work is funded partly by Universiti Sains Malaysia's Matching Grant [R502-KR-ARU003-0008070031- K134] and supported by Ajman University Internal Research Grant No.2024-IRG-ENIT-15.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Muhammad Syahir Kamal Fitri	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Selvakumar Manickam	✓			✓						✓				
Shams Ul Arfeen Laghari	✓		✓	✓						✓				
Siang Kok Chia	✓	✓	✓	✓		✓	✓	✓		✓		✓	✓	✓
Mohamad Khairi Ishak				✓	✓					✓				✓
Shankar Karuppayah	✓	✓	✓	✓		✓	✓			✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] L. S. Goecks, A. F. Habekost, A. M. Coruzzolo, and M. A. Sellitto, "Industry 4.0 and Smart Systems in Manufacturing: Guidelines for the Implementation of a Smart Statistical Process Control," *Applied System Innovation*, vol. 7, no. 2, Apr. 2024, doi: 10.3390/asi7020024.

[2] J. Denning and K. Liyanage, "Systematic Literature Review of Industry 4.0 Implementation Frameworks Focusing on Applicability in Manufacturing SMEs," in *Advances in Transdisciplinary Engineering, IOS Press BV*, Nov. 2022, pp. 17–24, doi: 10.3233/ATDE220559.

[3] T. Kalsoom *et al.*, "Impact of IoT on manufacturing industry 4.0: A new triangular systematic review," *Sustainability*, vol. 13, no. 22, 2021, doi: 10.3390/su132212506.

[4] E. Matheson, R. Minto, E. G. G. Zampieri, M. Faccio, and G. Rosati, "Human-robot collaboration in manufacturing applications: A review," *Robotics*, vol. 8, no. 4, 2019, doi: 10.3390/robotics8040100.

[5] O. Haffner, E. Kučera, and D. Rosinova, "Applications of Machine Learning and Computer Vision in Industry 4.0," *Applied Sciences*, vo. 14, no. 6, 2024, doi: 10.3390/app14062431.

[6] S. A. Laghari, S. Manickam, and S. Karuppayah, "A Review on SECS/GEM: A Machine-to-Machine (M2M) Communication Protocol for Industry 4.0," *International Journal of Electrical and Electronic Engineering and Telecommunications*, vol. 10, no. 2, pp. 105–114, Mar. 2021, doi: 10.18178/ijeetc.10.2.105-114.

[7] D. Fischer, P. Moder, and H. Ehm, "Investigation of Predictive Maintenance for Semiconductor Manufacturing and its Impacts on the Supply Chain," in *Proceedings of the IEEE International Conference on Industrial Technology*, Mar. 2021, pp. 1409–1416, doi: 10.1109/ICIT46573.2021.9453481.

[8] N. Thakkar, "Plug-n-Play SECS/GEM for Legacy Equipment," *CS Mantech*, 2022.

[9] A. Alqoud, D. Schaefer, and J. Milisavljevic-Syed, "Industry 4.0: A systematic review of legacy manufacturing system digital retrofitting," *Manufacturing Review*, vol. 9, no. 32, 2022, doi: 10.1051/mfreview/2022031.

[10] L. Tarjan, I. Šenk, J. E. Obućina, S. Stankovski, and G. Ostojić, "Extending legacy industrial machines by a low-cost easy-to-use IoT module for data acquisition," *Symmetry (Basel)*, vol. 12, no. 9, Sep. 2020, doi: 10.3390/sym12091486.

[11] A. Alqoud, D. Schaefer, and J. Milisavljevic-Syed, "Industry 4.0: A Review of Digital Retrofitting Solutions for Legacy Manufacturing Systems," in *Advances in Transdisciplinary Engineering*, Nov. 2022, pp. 3–9, doi: 10.3233/ATDE220557.

[12] A. Fattouh, K. Chirumalla, M. Ahlskog, M. Behnam, L. Hatvani, and J. Bruch, "Remote integration of advanced manufacturing technologies into production systems: integration processes, key challenges and mitigation actions," *Journal of Manufacturing Technology Management*, vol. 34, no. 4, pp. 557–579, May 2023, doi: 10.1108/JMTM-02-2022-0087.

[13] S. Kumar, A. Abu-Siada, N. Das, and S. Islam, "Review of the Legacy and Future of IEC 61850 Protocols Encompassing Substation Automation System," *Electronics*, vo. 12, no. 15, 2023, doi: 10.3390/electronics12153345.

[14] A. E. H. Gabsi, "Integrating artificial intelligence in industry 4.0: insights, challenges, and future prospects–a literature review," *Annals of Operations Research*, Aug. 2024, doi: 10.1007/s10479-024-06012-6.

[15] A. Korodi *et al.*, "Integration of Legacy Industrial Equipment in a Building-Management System Industry 5.0 Scenario," *Electronics (Switzerland)*, vol. 13, no. 16, Aug. 2024, doi: 10.3390/electronics13163229.

[16] J. Cunha, N. Batista, C. Cardeira, and R. Melicio, "Upgrading a legacy manufacturing cell to IoT," *Journal of Sensor and Actuator Networks*, vol. 10, no. 4, Dec. 2021, doi: 10.3390/jsan10040065.

[17] M. Alabadi, A. Habbal, and X. Wei, "Industrial Internet of Things: Requirements, Architecture, Challenges, and Future Research Directions," *IEEE Access*, vol. 10, pp. 66374-66400, 2022, doi: 10.1109/ACCESS.2022.3185049.

[18] M. A. O. Pessoa, M. A. Pisching, L. Yao, F. Junqueira, P. E. Miyagi, and B. Benatallah, "Industry 4.0, How to Integrate Legacy Devices: A Cloud IoT Approach," in *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2020, pp. 2902–2907, doi: 10.1109/IECON.2018.8592774.

[19] F. R. Golra, S. Azaiez, and M. Engel, "Multi-level modeling to OPC UA for migrating to Industry 4.0 in semiconductor manufacturing," in *Proceedings - 2020 IEEE Conference on Industrial Cyberphysical Systems, ICPS 2020*, Jun. 2020, pp. 589–595, doi: 10.1109/ICPS48405.2020.9274791.

[20] P. Visconti, G. Rausa, C. Del-Valle-Soto, R. Vela´zquez, D. Cafagna, and R. De Fazio, "Machine Learning and IoT-Based Solutions in Industrial Applications for Smart Manufacturing: A Critical Review," *Future Internet*, vol. 16, no. 11, p. 394, Oct. 2024, doi: 10.3390/fi16110394.

[21] S. A. Laghari, S. Manickam, S. Karuppayah, A. Al-Ani, and S. U. Rehman, "Cyberattacks and Vociferous Implications on SECS/GEM Communications in Industry 4.0 Ecosystem," *International Journal of Advanced Computer Science and Applications (IJACSA)*, vol. 12, no. 7, 2021, doi: 10.14569/IJACSA.2021.0120737.

[22] A. Jaisan, S. Manickam, S. A. Laghari, S. U. Rehman, and S. Karuppayah, "Secured Secs/Gem: A Security Mechanism For M2m Communication in Industry 4.0 Ecosystem," *International Journal of Advanced Computer Science and Applications*, vol. 12, no. 8, pp. 241–250, 2021, doi: 10.14569/IJACSA.2021.0120828.

[23] S. U. A. Laghari, S. Manickam, A. K. Al-Ani, M. A. Al-Shareeda, and S. Karuppayah, "ES-SECS/GEM: An Efficient Security Mechanism for SECS/GEM Communications," *IEEE Access*, vol. 11, pp. 31813-31828, 2023, doi: 10.1109/ACCESS.2023.3262310.

[24] S. U. A. Laghari, S. Manickam, A. K. Al-Ani, S. U. Rehman, and S. Karuppayah, "SECS/GEMsec: A Mechanism for Detection and Prevention of Cyber-Attacks on SECS/GEM Communications in Industry 4.0 Landscape," *IEEE Access*, vol. 9, pp. 154380–154394, 2021, doi: 10.1109/ACCESS.2021.3127515.

[25] E. F. Terng, S. C. Yeoh, K. C. Tong, and K. S. Yeo, "Data Analysis on SMT Reflow Oven with SECS/GEM Communication Protocol," in *2020 IEEE 10th Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, Malaysia, 2020, pp. 118-124, doi: 10.1109/ISCAIE47305.2020.9108797.

[26] L. Ma, N. Zhang, and Z. Zhang, "Tool Efficiency Analysis model research in SEMI industry," in *2018 4th International Conference on Energy Materials and Environment Engineering (ICEMEE 2018)*, Jun. 2018, vol. 38, doi: 10.1051/e3sconf/20183802027.

[27] H. Jónasdóttir, K. Dhanani, K. Mcrae, and J. Mehnen, "Upgrading Legacy Equipment to Industry 4.0 Through a Cyber-Physical Interface," in *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0 (APMS 2018)*, 2018, pp. 3–10, doi: 10.1007/978-3-319-99707-0_1.

BIOGRAPHIES OF AUTHORS

Muhammad Syahir Kamal Fitri is currently pursuing his Master's degree at the prestigious Cybersecurity Research Centre (CYRES), Universiti Sains Malaysia, where he builds upon a strong foundation laid during his Bachelor's in Computer Science at the School of Computer Science at the same institution. His academic journey reflects a profound dedication to the field, marked by exceptional achievements and a relentless pursuit of knowledge. His research interests are diverse, encompassing cybersecurity, machine learning, deep learning, and software development. In addition to his studies, he actively participates in collaborative research projects and contributes to the university's initiatives aimed at advancing digital security and innovation. His work often explores the integration of AI-driven approaches to enhance security frameworks, particularly in network environments, reflecting a commitment to bridging theory with practical solutions that address contemporary challenges in cybersecurity. He can be contacted at email: syahirkamal@student.usm.my.

Selvakumar Manickam is currently the Director of the Cybersecurity Research Centre (CYRES) and an Associate Professor specializing in cyber-security, the internet of things, Industry 4.0, cloud computing, big data, and machine learning. Previously, he was with Intel Corporation and a few start-ups working in related areas before moving to academia. He has authored or coauthored more than 220 papers in journals, conference proceedings, and book reviews. He has graduated with 18 Ph.D. students in addition to bachelor's and master's students. He has given several keynote speeches and dozens of invited lectures and workshops at conferences, international universities, and industry. He has given talks and training on internet security, the internet of things, industry 4.0, IPv6, machine learning, software development, and embedded and OS kernel technologies at various organizations and seminars. He also lectures in various computer science and IT courses, including developing new course-ware in tandem with current technology trends. He is involved in various organizations and forums locally and globally. While building his profile academically, he is still very involved in industrial projects involving industrial communication protocol, robotic process automation, machine learning, and data analytics using open-source platforms. He also has experience in building the IoT, embedded, server, mobile, and web-based applications. He can be contacted at email: selva@usm.my.

Shams Ul Arfeen Laghari is a seasoned computer scientist with over 24 years of experience, is passionate about advancing cybersecurity and network security. Currently serving as an Assistant Professor at the School of ICT, Bahrain Polytechnic, He is committed to nurturing the next generation of cybersecurity experts. He earned his Ph.D. in Cybersecurity from Universiti Sains Malaysia (USM), where he delved into the intricacies of safeguarding digital systems. His academic journey was further enriched by a postdoctoral research position at the National Advanced IPv6 Centre (NAv6) within USM, where he contributed to cutting-edge research in network security. Beyond academia, he has honed his skills through collaborations with leading technology companies, gaining invaluable insights into the practical challenges and opportunities in the field. His industry experience has equipped him with a deep understanding of real-world cybersecurity threats and mitigation strategies. His research interests span a wide range of topics, including cybersecurity, the internet of things (IoT), Industry 4.0, distributed systems, cloud computing, and mobile cloud computing. His contributions to the field are evident in his numerous publications in top-tier international journals. He can be contacted at email: shams.ularfeen@polytechnic.bh.

Siang Kok Chia earned his first degree in Mechanical Engineering from the Universiti Sains Malaysia (USM), Malaysia, in 2006. Currently, he serves as Principle Engineer in the Department of Automation Development Engineering, Sandisk Storage Malaysia Sdn. Bhd. He can be contacted at email: Siang.Kok.Chia@sandisk.com.

Mohamad Khairi Ishak holds a B.Eng. in Electrical and Electronics Engineering from the International Islamic University Malaysia (IIUM), an M.Sc. in Embedded Systems from the University of Essex, and a Ph.D. from the University of Bristol. He is a member of IEEE and a registered graduate engineer with the Board of Engineers Malaysia (BEM). Currently, he serves as an Associate Professor and Lecturer in Computer Engineering at the Department of Electrical and Computer Engineering, Ajman University, United Arab Emirates. His research interests include embedded systems, real-time control communications, artificial intelligence, and the internet of things (IoT). His work focuses on both the development of theoretical frameworks and the application of practical methodologies, with a strong emphasis on real-world impact. He can be contacted at email: m.ishak@ajman.ac.ae.

Shankar Karuppayah is currently the Deputy Director and Senior Lecturer in the Cybersecurity Research Centre (CYRES), Universiti Sains Malaysia. He obtained his B.Sc. (HONS) Computer Science from Universiti Sains Malaysia in 2009 and his M.Sc. Software Systems Engineering from King Mongkut's University of Technology North Bangkok (KMUTNB) in 2011. In 2016, He obtained his Ph.D. degree. He is currently working actively on several cybersecurity projects and working groups. Till date, he has published in more than 30 articles in cybersecurity journals and conferences. He has been a Senior Lecturer with the Cybersecurity Research Centre (CYRES) (formerly National Advanced IPv6 Centre (NAv6)), Universiti Sains Malaysia, since 2016. He has also been a Senior Researcher/Postdoctoral Researcher with the Telecooperation Group, TU Darmstadt, since July 2019. He is currently working on several cyber-security projects and groups, such as the National Research Center for Applied Cybersecurity (ATHENE), formerly known as the Center for Research in Security and Privacy (CRISP). He can be contacted at email: kshankar@usm.my.