

ICSSIM – A Framework for Building Industrial Control Systems Security Simulation Testbeds

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Abstract

With the advent of smart industry, Industrial Control Systems (ICS) are increasingly using Cloud, IoT, and other services to meet Industry 4.0 targets. The connectivity inherent in these services exposes such systems to increased cybersecurity risks. To protect ICSs against cyberattacks, intrusion detection systems and intrusion prevention systems empowered by machine learning are used to detect abnormal behavior of the systems. Operational ICSs are not safe environments to research intrusion detection systems due to the possibility of catastrophic risks. Therefore, realistic ICS testbeds enable researchers to analyze and validate their intrusion detection algorithms in a controlled environment. Although various ICS testbeds have been developed, researchers' access to a low-cost, adaptable, and customizable testbed that can accurately simulate industrial control systems and suits security research is still an important issue.

In this paper, we present ICSSIM, a framework for simulating customized virtual ICS security testbeds where cyber threats and attacks can be investigated, and mitigations evaluated. ICSSIM aims to produce extendable, versatile, reproducible, low-cost, and comprehensive ICS testbeds with realistic details and high fidelity. ICSSIM is built on top of the Docker container technology, which provides realistic network emulation and runs ICS components on isolated pri-

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vate operating system kernels. ICSSIM reduces the time for developing ICS components and offers physical process modelling using software and hardware in the loop simulation. We demonstrated ICSSIM by creating a testbed and validating its functionality by showing how different cyberattacks can be applied.

Keywords: Cybersecurity, Software Simulation, Industrial Control System, Testbed, Network Emulation, Cyberattack

1. Introduction

Industrial Control Systems (ICS) emerged as a solution to monitor and control safety-critical industrial systems, such as powerplants, power grids, and railways. The term ICS has different realizations such as Supervisory Control and Data Acquisition (SCADA), Distributed Control System (DCS), or even Programmable Logic Controller (PLC) [1], but almost the same cyber threats can be considered for all of them. ICSs were traditionally isolated from the Internet to ensure overall system security. However, smart manufacturing targeted by industry 4.0 [2][3][4] has led corporations to use Cloud, Internet of Things (IoT), and other public network services as a key foundation [5]. Although connectivity has many advantages and potential, it exposes these systems to many security threats. To acknowledge the importance of cybersecurity risks, we could mention the Stuxnet malware attack on the Iranian Uranium enrichment facilities [6], the attack on the Ukrainian power grid [7], the Triton malware attack on the Saudi Arabian petrochemical plant [8], and the attack on U.S. natural gas pipeline companies [2], each of which endangered human lives and caused substantial financial loss. Moreover, according to Kaspersky ICS-CERT Report [9], 33.8% of ICS computers were attacked in the first half of 2021, which shows that cybersecurity is a severe concern to modern industry. Therefore, there is no doubt that ICS security has become an important topic for research in the past years [10], [11].

Due to confidentiality and safety issues, operational ICSs are not suitable for testing cyberattacks, analyzing their impacts, and developing defense sys-

tems. An alternative solution could be to use a miniaturized version of an ICS as a testbed. There are a few such real ICS testbeds, including the national SCADA testbed [12] and small-scale water treatment system (SWaT) [13]. However, these testbeds are not accessible by all researchers. Building such an environment is also time-consuming and expensive [14]. Besides, scientists using such testbeds must deal with a vast range of unrelated technical problems that require hardware knowledge. These barriers have led many security researchers, especially those who want to use Machine Learning (ML) methods for attack detection, to use available datasets for their experiments. However, intrusion detection using available datasets prevents researchers from defining customized test conditions or changing the type of attack on the industrial systems. Therefore, a tool to create a virtual industrial control system capable to perform cybersecurity research will be a great asset for researchers and practitioners.

This paper tries to fill this gap by providing ICSSIM framework, a tool to build a customized ICS simulation as a security testbed that enables researchers to research and experiment on cyber threats/attacks on their local testbed. In particular:

1. We surveyed the literature and analysed existing ICS testbeds to prepare a testbeds requirement list, which we used as the design objective for building testbeds. We believe that this list can also be used as a benchmark for comparing ICS testbeds.
2. We built ICSSIM, an open-source framework capable of building customized ICS testbeds based on the design objective list. We build ICSSIM configurable with versatile ICS architecture to cover a wide range of realistic ICS scenarios simulations.
3. We equipped ICSSIM with various attack scripts to facilitate security research on the testbed generated by ICSSIM.
4. We created a sample ICS testbed to prove ICSSIM functionalities. We also made this sample testbed publicly available to other researchers for

future researches.

The remainder of this paper is organized as follows. Section II discusses the current state of the art for virtual ICS testbeds. Section III identifies design goals and desired characteristics for ICS testbeds. Section IV provides detail on the proposed framework. Section V presents a bottle filling factory process control problem as a sample ICS testbed created by ICSSIM. Section VI implements various attacks on the candidate problem to evaluate the framework's ability to simulate cyberattacks. Finally, Section VII gives a conclusion and a vision for extending the testbed in the future.

2. RELATED WORK

Several publications in this field have provided different testbeds and tools for ICS simulation, while their strengths and weaknesses have been discussed. We used the same categorization for literature classification as the authors in [15, 16] proposed: 1) Physical testbeds. 2) Semi-physical testbeds. 3) Virtual testbeds.

2.1. Physical Testbeds

Several articles have reported the construction of physical control systems testbeds to provide a cyber threats research platform [3, 13, 17, 18, 19, 20, 21, 22, 12]. To the best of our knowledge, two comprehensive surveys [15, 16] provide an extensive analysis of various testbeds for ICS. This paper focuses more on presenting our testbed, and readers can check the mentioned papers to find more information about testbeds. Here, we only refer to a few articles to highlight the main obstacles with physical testbeds.

According to [23, 14], physical testbed implementations require substantial time, effort, and costs. For example, Mathur and Tippenhauer [13] created a small-scale water treatment system (SWaT) testbed for security research. The footprint of this testbed is approximately 90 square meters, and still, it is a miniature version of an operational water treatment system. The SCADA

testbed presented in [12] implements a 61-mile of 138kV power grid distribution network to create a testbed.

Meanwhile, some implementations target this gap by introducing low-scale physical implementations. Thiago Alves et al. [22] presented OpenPLC, which provides PLC Logic software along with modular and simplified architecture to create low-cost open-source PLCs. Sauer et al. [21] created the LICSTER open-source low-cost (500 Euros) ICS testbed for researchers and students. Although it takes relatively less time and cost to build such minimal testbeds, having hardware knowledge is still a challenge for using these testbeds. It is also impossible to share these testbeds without replicating the hardware part of the testbeds, and unfortunately, the availability of recommended hardware in the market decreases over time.

We studied physical testbeds to learn their requirements and constraints. However, using physical testbeds is not a feasible solution in most cases due to time, cost, and access constraints. Although publishing physical testbed datasets are helpful for Artificial Intelligence (AI) research, access to these physical testbeds for experiencing customized experiments is not feasible for most researchers. Therefore, in the following, we will examine virtual and semi-physical testbeds.

2.2. Semi-Physical Testbeds

In semi-physical testbeds, some essential testbed components, such as networking infrastructure, controlling components, or Hardware in a Loop (HIL), are replaced by software simulations. Gao and Peng [4] designed and implemented the EPS-ICS testbed according to an ICS layered architecture to facilitate the development of security standards. They used Matlab/Simulink to simulate mathematical models of HIL, while the control system of the testbed was implemented using real PLCs. They also used Emulab, DETERlab, and PlanetLab to emulate the network infrastructure. Unfortunately, this testbed uses hardware for controllers, which increases cost and implementation time, and forces researchers to dig into the hardwired implementation details. More-

over, this testbed was not built explicitly for attack detection, which means they did not implement any cyberattacks on the proposed testbed nor generate any dataset for AI/ML-based Intrusion Detection System (IDS).

Koganti et al. [24] created a testbed with a simulated HIL, emulated PLC with Matlab/Simulink and real network implementation. The HIL was a power grid distribution substation simulated in a virtual machine (VM). SCADA simulator and attack simulator were two other VMs connected through a Modbus connection on a real network. The lack of proper implementation of the control system components, such as commanding Human Machine Interface (HMI), has prevented them from simulating a wide range of attacks. They only simulate reconnaissance attacks and Distributed Denial of Service (D-DoS) while lacking cyberattacks such as Man-in-the-Middle (MitM) and false data injection attacks.

Kaouk et al. [25] presented a GSCOP testbed architecture for an ICS in an IoT environment that is easily configurable with simulated HIL or hardwired HIL. They also demonstrated its applicability through two case studies. The physical processes in these case studies were simulated while they used real ICS components with wired connections. The main shortcoming of their simulation is that implementations of industrial protocols such as Modbus, DNP3, or Ethernet/IP are lacking. They also did not validate their model through studies and implementations of different attacks.

Faramondi et al. [26] created an ICS testbed with water distribution as its hardware process. They implemented the physical process with real hardware and used miniCPS as a simulation tool for the control system and networking infrastructure. One of the highlights of this study is the use of multiple controllers, which are essential for implementing attacks that target communication between controllers. They also collected network and system data during normal and under attack operations. This dataset gives AI/ML researchers the possibility for future IDS research.

Although these systems resolve some of the mentioned problems for physical testbeds, such as required time and cost, the reproduction of these systems still

depends on the hardware reproduction. Also, the researchers still have to face technical problems in working with the hardware.

2.3. Virtual Testbeds

Virtual testbeds have no hardware implementation and implement all ICS components using software simulations. Carlos Queiroz et al. [27] proposed SCADASim, a simulation tool to create SCADA simulations. The strength of this tool is its ability to integrate external devices and applications. SCADASim is built on top of OMNET++, a discrete event simulation engine. They extend abstract SScheduler, SGate, and SProxy in OMNET++ to create SCADA components such as Remote Terminal Unit (RTU), PLC, and Master Terminal Unit (MTU). They also implemented two types of cyberattacks: D-DoS and MitM with spoofing attacks. However, an interface to use real physical processes is missing.

In a similar work, Antonioli and Tippenhauer proposed MiniCPS, a toolkit to simulate cyber-physical systems [28]. This toolkit has the base classes for simulating control system components, network protocols, and physical layer interactions. It is built in Python on top of Mininet, a lightweight real-time network emulator for a collection of end-hosts, links, switches, and routers; however, it also inherits Mininet constraints such as using a single Linux kernel for all simulated nodes. Antonioli et al. mainly use MiniCPS to model the communications and control aspects of a water treatment testbed at Singapore University [13], but their original purpose was to create a framework to connect software and hardware simulations of ICS components. Therefore, they use IP-based industrial protocols to emulate the network protocols. MiniCPS extend Mininet with tools to simulate PLCs, HMIs, industrial protocols such as Modbus/TCP and Ethernet/IP, and an API to connect to physical layer simulations. In the MiniCPS paper [28], the authors also implemented an on-the-fly-change attack scenario and MitM attack with ARP spoofing. Many other testbeds use MiniCPS for realizing their ICS testbeds [13, 26, 29]. However, to the best of our knowledge, SCADASim and MiniCPS do not provide any solution for dis-

tributed control processes, and they lack a component to log network traffic and process states. Moreover, MiniCPS is built on top of other network simulators, implying various simulation constraints.

A cyber-physical experimentation environment was presented by Béla Genge et al. [3] article. They used Emulab to simulate a virtual topology as a network layer and Simulink to create the HIL process while using the internal PLC memories to perform read and write actions. Their testbed shortcomings include limited industrial network protocol implementation, non-reusable implementation for other experiments, lack of attack study, and event/state logging.

Another virtual testbed to model and study cyberattacks is a virtual gas pipeline and its controlling system, proposed by Morris et al. [30]. They simulate network, PLC, HMI, and HIL. They also validate their simulation through various attack implementations. They tried to randomize system states by periodic HMI change commands to minimize the possibility of unintended patterns. Although they used Modbus over serial lines to implement Modbus-TCP communications, there is a lack of implementation of other industrial protocols.

Formby and Rad [31] designed Graphical Realism Framework for Industrial Control Systems (GRFICS), which virtualizes a sample ICS, from the operator interface down to realistic simulations of the physical process, visualized in a 3D game engine. They used a simulated version of a chemical process for the HIL process and an Open-PLC code generator for PLC simulation. They connected ICS components using standard ICS network protocols. To validate their model, they also studied several cyberattacks such as Modbus Buffer Overflow, PLC Program Modifications, and Modbus Command Injection. Although GRFICS has a visual presentation, which makes it suitable for education, it does not have any network segmentation required for idle cybersecurity studies. The graphical presentation also works with just their sample chemical process, which interferes with the use of other control processes.

This section studied several ICS testbeds and showed that using physical and semi-physical testbeds are not always possible due to hardware cost, high implementation time, and technical complexities. For this reason, the ICSSIM

framework presented in this paper is mainly designed to build virtual ICS security testbeds. However, it could also be used in semi-physical testbeds since it could be connected to hardware instruments through file communications. This section also examines the shortcomings of existing virtual ICS testbeds, making them not ideal testbeds for ICS security research. Section III investigates the needed testbed features to address shortcomings of the existing virtual ICS testbeds, which will be used as guidelines for building ICSSIM.

3. Requirements & Design Objectives

An ideal industrial security testbed must have features to support complex controlling scenarios and offer capabilities that facilitate the experimentation process. We combined the missing features of testbeds described in the previous section with some of the required features mentioned in the literature, such as [3, 32, 28, 21], to create a comprehensive list of testbed requirements. This section enumerates industrial security testbed requirements and design objectives and also explains how the ICSSIM has responded to these requirements.

Versatility: a testbed capable of simulating diverse controlling scenarios requires testbed versatility in implementing a physical process and control system. However, existing testbeds mainly involve a concrete implementation of a specific control process in which it is not possible to replace the control process or change the control logic. ICSSIM is a generic framework capable of simulating many concrete control system instances. We can use build-in base classes to create a new process control or integrate them with external applications and hardwired devices.

Comprehensiveness: control systems consist of different components such as physical processes, network communications, and control system components. Each component is imperative for the specific class of cybersecurity experiments. For example, intrusion detection could work based on network analysis and finding anomalies in network packets or could work based on tracing physical process status. However, most existing testbeds have implemented only part of

the control system based on their specific experiment requirements. Restricted testbed implementations and datasets provided by such testbeds may not be appropriate for experiencing a wide range of cybersecurity experiments. ICSSIM provides a solution to simulate all fundamental parts of an industrial control system, including ICS components, network, and physical process. Therefore, we can study the control system security both from the network and control state aspects.

- **Network Architecture:** the range of network topology in industrial control systems is different from ring to star or even customized topology. ICSSIM does not force any particular constraints on the network architecture and can emulate any network topology.
- **Network Implementation:** real network implementation is the best approach to avoid unwanted simulation errors; however, it reduces the scalability of the testbed. In contrast, network simulation could be achieved with lower cost and time, but it is prone to many errors in detailed implementation, such as network speed, drop rate, and network delay. As a solution, ICSSIM emulates the network using a virtual machine shared network and passes all network packets through real card drivers. This solution reduces the simulation errors while providing testbed scalability.
- **Control System Components:** although the control system components' details vary in operational ICSs, they typically have some components for control and monitoring. ICSSIM contains basic implementation for the main DCS components such as PLC, HMIs, and industrial network protocols. Moreover, it lets users create new components or customize and extend existing components.
- **Physical Process:** physical process simulations can be performed in various ways, including custom python scripts, simulation software implementations like Matlab and Simulink, or hardware implementations. ICSSIM can communicate with external software simulation and hardware imple-

mentation through a file; meanwhile, it could simulate the whole physical process as an internal node. ICSSIM has generic base classes to simulate the physical process. It also has required interfaces to communicate with external software or hardware.

Reproducibility: Replicability and reproducibility are vital factors in scientific experiments. Therefore, having a reproducible testbed provide a ground for researchers to work on an identical testbed and experience similar experiments. Using Docker technology as a foundation for ICSSIM makes it easy to generate reproducible testbeds, reducing error risks and increasing results reliability.

High Fidelity: It is crucial to implement the simulation with full detail related to vulnerable points in providing a testbed for investigating ICS cyber vulnerabilities. For example, a testbed that only provides a single PLC is not suitable to be used for the investigation of cyberattacks that target the communication between PLCs. Implementing realistic details such as realistic architecture and implementing industrial protocols can help in increasing fidelity. ICSSIM tries to implement the ICS details as much as possible to achieve high fidelity. To list a few details, we could mention the realistic implementation of control loops, industrial protocols, and considering the distributed control system with multiple PLCs and sensor errors.

Extendibility: No matter how comprehensively a testbed is developed, it still needs detailed modification and extension when used in new research experiments. The testbed design should allow future growth with reasonable efforts and without impairing existing system functionalities. ICSSIM simulates each ICS component with an isolated Docker container with a private OS kernel. This component isolation makes it easy to extend the framework without side effects on the intact modules. Moreover, the inheritance used in developing the base component codes offers a straightforward approach for extending the framework.

4. ICSSIM-The proposed simulation framework

In this section, we present our proposed framework ICSSIM. This framework includes reference classes for defining an ICS simulation, implementing an industrial network protocol, and cyberattack scripts. It is an open-source¹ framework to reduce the needed time for simulating ICS security testbeds. We describe ICSSIM components in the rest of this section.

4.1. Design & Architecture

The architecture of a typical ICS could vary widely based on the application domain. We designed ICSSIM to support any architecture following “Purdue Enterprise Reference Architecture” [33], shown in Figure 1. The Purdue architecture includes five tiers: (1) sensors and actuators; (2) basic control; (3) supervisory control; (4) Demilitarized Zone (DMZ); and (5) enterprise zone. Tier 1-3 constitute the control zone in the Purdue model. Tier 1 includes HILs with connected sensors and actuators. Tier 2 is basic control and includes controllers or PLCs. Tier 3 includes supervisor control units, such as HMI, engineering workstation system, and historian. The control zone is typically isolated from the above zones with Firewalls, but cyber penetration is still possible through viruses or external HMIs connected to the internet. Tier 4 realizes the demilitarized zone, which acts as an intermediate between the enterprise zone and the control zone for data sharing. Tier 5 is the enterprise zone, a host for non-ICS devices and servers, which supervise data produced by the control zone. In the initial implementation of the ICSSIM testbed, we decided to confide our implementation to Tier 3; however, we could add DMZ and enterprise layers based on future requirements.

We add an attack generator, an observer, and a management network component to the Purdue reference model. The attack generator provides scripts and tools to simulate different cyberattacks. The observer and management network record and analyze network traffic, and log data.

¹<https://github.com/AlirezaDehlaghi/ICSSIM/>

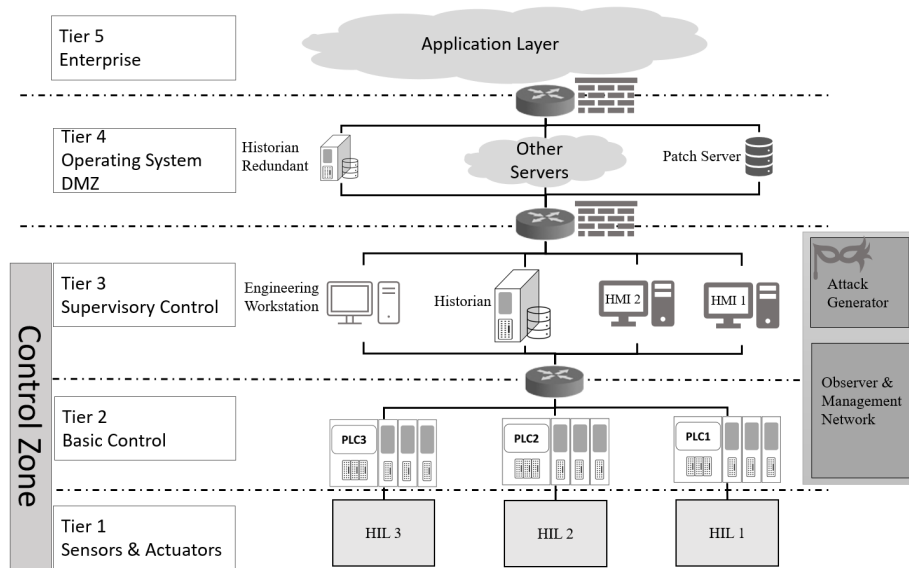


Figure 1: ICSSIM reference architecture

4.2. Simulation Environment

ICSSIM runs the simulation components in separated virtual environments, each with a private operating system kernel. For example, ICSSIM implements each HMI, PLC, Attacker, or HIL on a standalone virtual operating system. Therefore, simulation components have private IPs, configurable network drivers, and independent communication with other components. Using virtualization provides a more realistic simulation of what exists in the real world, and it paves the road to investigate a variety of cyber threats.

ICSSIM offers two environments to run virtual operating systems. The first is the Docker container technology². Docker wraps the simulation and its dependencies as a container running on any operating system. Containers deliver OS-level virtualization that provides an isolated environment. Containers act like virtual machines, but they are more lightweight because they run isolated systems on a single server or host OS and use fewer resources. As a result,

²<https://www.docker.com/>

Table 1: Technical Details of Tested Environments

Technology	Description
Docker Host OS	Ubuntu 20.04
Docker	Version: 20.10.12
Docker-Compose	Version: 1.29.2
GNS3	Version: 2.2.26
Memcached	Version: 1.5.22
Python	Version: 3.8
VMWare	Version: 16.2.2

when ICSSIM simulation contains many components, they can all be simulated as stand-alone containers without performance loss.

The second possible environment to run ICSSIM is the Graphical Network Simulator-3 (GNS3)³. Containerized simulations are runnable on GNS3; therefore, GNS3 allows the combination of docker container simulations and real devices used to simulate a complex network. Moreover, GNS3 enables us to emulate network switches and routers through the ‘*Appliance files*’, which improves the ability to simulate cyberattacks that target network devices.

We do not have to decide on the final execution environment when simulating an ICS using this framework since ICSSIM can run on both presented environments based on the container concept. We have tested our framework with both environments. Table 1 presents implementation details of testbed environments.

4.3. Network

The control zone in ICS basically has two separate network layers. The first network layer is between industrial plants (physical process) and controllers (communication between Tier 1 and 2 in Figure 1). Wired industrial equipment

³<https://www.gns3.com/>

to the digital and analog Input/Output cards communicate with controllers through a shared BUS. The second network layer is between ICS components (communication between Tier 2 and 3 in Figure 1), primarily IP-aware communication. The ICSSIM implements both networks to be compatible with GNS3 and Linux Docker environments.

Hardwired layer: is not an IP-aware communication. When using the Docker container environment, defining a shared space between containers enables us to create a hardwired network between Tier 1 and 2 of the testbed. In this approach, we create a file-based database, namely SQLite⁴, and share it between containers. The physical process simulator has *'write'* access to sensor values and *'read'* access to actuator values for recording the physical process. In contrast, PLCs have *'read'* access for sensor values and *'write'* access for actuator values to simulate sending commands to the physical process. However, when using GNS3 for simulation, it is impossible to create a shared file. ICSSIM provides a *'Memcached'* service⁵ on HIL containers to give other containers access to physical variables on the GNS3 environment.

IP-aware layer: is achievable by defining a shared network between containers in the Linux Docker environment or using predefined network switches in the GNS3 environment. Independent of the simulation environment, ICSSIM uses Modbus-TCP as a communication protocol, a widely used communication protocol for operational ICSs. Modbus is an industrial network protocol designed to transfer 16-bit-packets, and ICSSIM extends the base protocol to transfer more data bits.

4.4. ICS component

Figure 2 shows the summarized class diagram for a part of ICSSIM codes. ICSSIM contains base classes for DCS components. *'HMI'* and *'PLC'* classes provide a base for inheritance and developing a customized version. Based

⁴<https://www.sqlite.org/>

⁵<https://memcached.org/>

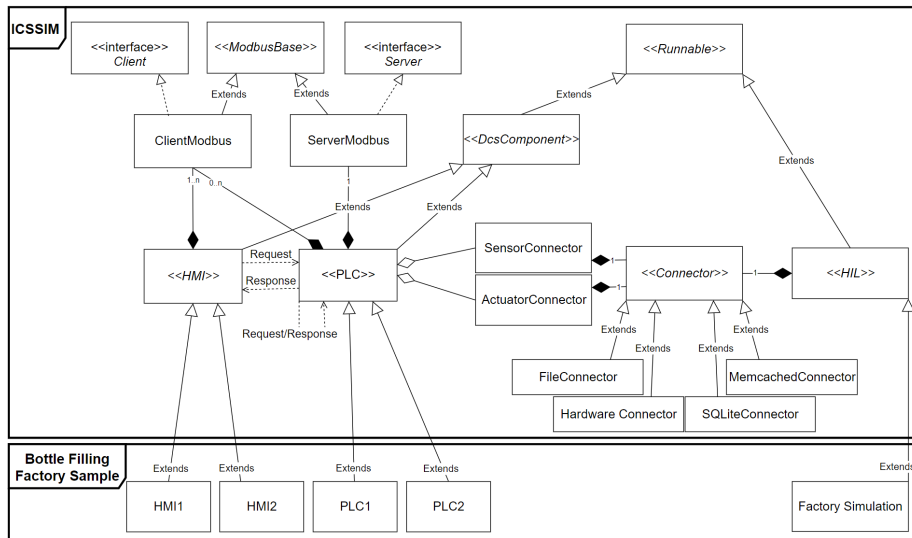


Figure 2: Summarized class diagram for ICSSIM main classes

on the control system configuration, PLCs are connected to several sensors and actuators through ‘*SensorConnector*’ and ‘*ActuatorConnector*’ instances. Each PLC runs a Modbus server to respond to the requests from other DCS components about its connected sensors and actuators. Moreover, PLCs and HMIs have Modbus clients to communicate with other PLCs.

Moreover, defining new types of DCS components is possible through inheritance of the ‘*DCSComponent*’ class or ‘*Runnable*’ class, which are parent classes for the ‘*PLC*’ and ‘*HMI*’ classes. These base classes provide required functionalities such as networking and periodic execution. For example, to create a new PLC in the simulation, all that needs to be done after inheriting the base class is to provide an input/output signal list, define a loop period, and override the control loop function based on the control model.

4.5. Physical process

As an integral part of ICS, the physical process is commonly simulated using HIL simulation. HIL simulation responds to virtual stimuli and control commands to mimic the physical plant behavior. There are two approaches to

simulate HIL, including hardware and software simulation. As stated in Sections 2.1 and 2.2, hardware simulation is time/cost consuming and reduces scalability, but it generally leads to realistic system modeling. On the other side, software simulations are adaptable, scalable, and easy to implement. ICSSIM supports both approaches to leave researchers free to design their desired testbed.

As shown in Figure 2, ICSSIM defines various *'Connectors'* classes such as *'HardwareConnector'*, *'FileConnector'*, *'SQLiteConnector'*, and *'MemcachedConnector'*. These connectors act as adaptors between HIL and ICS. Realization of *'HardwareConnector'* class helps ICSSIM to communicate with the hardware Modbus-TCP communication. To communicate hardware with other protocols, testbed developers should override the *'HardwareConnector'* class and implement a hardware-specific communication protocol.

HIL software simulation can be achieved with ICSSIM internal Python scripting or third-party software such as Matlab or Simulink. In order to develop a simulation script using ICSSIM, we have to inherit a class from the "HIL" base class and develop a logic to simulate the control process. The simulation process state variables will persist in SQLite or Memcached database using the *'SQLiteConnector'* and *'MemcachedConnector'*. ICSSIM could also communicate with external software simulations such as Matlab or Simulink using files. *'FileConnector'* helps ICSSIM write the command control into the files and read state variables from the file. In this approach, the third-party software is responsible to update state variables based on the process model and command controls.

4.6. Attacker component

ICSSIM adds an *'Attack Generator'* node to the ICS architecture to simulate attackers' behaviors. We suppose that attacker has access to the control zone network. This assumption is based on a scenario in which an HMI is infected using malware and, given its access to the ICS internal network, performs malicious operations on the system. The *'Attack Generator'* component in Figure 1 shows the attacker node, which acts as a malicious HMI.

ICSSIM implements the *'Attack Generator'* as a standalone container that

runs several attacks against other containers. The base operating system image on the attacker is '*Kali Linux*'⁶ which is an open-source, Debian-based Linux distribution. It embeds several software programs, scripts, and settings to facilitate various information security tasks, such as penetration testing, security research, and cyberattacks. Using these cybersecurity tools, ICSSIM prepares several bash scripts which take the target as input and apply the specified cyberattack on the specified target to disrupt the functioning of the industrial system. ICSSIM provides three types of attack scripts: reconnaissance, D-DoS, and false data injection attacks using MitM attack.

The reconnaissance attack aims to gather information, such as media access control address (MAC address) and IP addresses for alive nodes in the target network. This type of attack does not directly impact process control, but it can be used to pave the way for such attacks. We implement this attack in several ways. We run Ettercap software⁷ to get information about the alive nodes in the systems. Ettercap is a free and open-source network security tool capable of sniffing network packets. It also can read Address Resolution Protocol (ARP) tables of the alive nodes to find information about other hibernated nodes. The second approach to implement reconnaissance attacks is using NMap⁸ software. NMap is a free and open-source utility for network discovery and security analysis. Using Nmap, we could find alive nodes and open ports on them. The script to apply attack and run Ettercap and NMap is provided in ICSSIM.

The D-DoS attack tries to disrupt the system's regular operations. This attack occurs when a myriad of fake nodes request service simultaneously. These requests saturate the bandwidth or targeted system resources, which leads to the target system failure. The ICSSIM implements the D-DoS attack by creating multiple fake HMIs that constantly read from the PLCs. Assuming a successful reconnaissance attack, scanning PLCs' IPs and active ports for the Modbus

⁶<https://www.kali.org/>

⁷<https://www.ettercap-project.org/>

⁸<https://nmap.org/>

protocol becomes possible. The attacker could then send forged read messages to keep PLCs busy. ICSSIM provides a generic script that takes the target address and applies a D-DoS attack on the specified target.

The ICSSIM also implements the “False Data Injection Attack” using the “Man in the Middle” (MitM) method. In the MitM attack, the attacker position itself in communication between a sender and a receiver to eavesdrop, alter, or forge network packets. The attacker links its MAC address with a legitimate ICS node IP address by constantly sending fake ARP responses. As a result, data sent by the sender to the legitimate ICS node is instead transmitted to the attacker node. The attacker uses Ettercap Filters to change the packet data or forge an entirely new packet and forward the fake message toward the receiver. Using this technique, the attacker could inject false data into the system, appearing like regular network traffic. ICSSIM provides general scripts for applying MitM attack; however, we need to define the attack scenario based on the ICS routines.

5. Example Application

This section shows the ICSSIM functionality to build a proper ICS testbed by generating a sample ICS testbed. We create a bottle filling factory simulation using ICSSIM, a defined open-loop controlling problem introduced by Dietz et al. [29]. We add some details to the original problem that increase computational complexity, but it is still straightforward for the framework to explain. Although this section explains ICSSIM through this sample testbed, building a testbed using ICSSIM is not limited to this example, and we can replace bottle filling factory simulation with any other open-loop controlling process simulations. We also made the source code for the framework and the sample ICS testbed publicly available to be used in other researches⁹.

⁹<https://github.com/AlirezaDehlaghi/ICSSIM/>

5.1. Sample Physical Process

The bottle-filling factory control process is responsible for filling bottles using a water tank repository. Figure 3 shows the overall scenario including process and hardware. The proposed control process consists of two main hardware zones, each controlled by a standalone PLC, called PLC-1 and PLC-2. PLC-1 manages the water tank and its input and output valves. PLC-2 manages the conveyor belts to replace the filled bottle with an empty one.

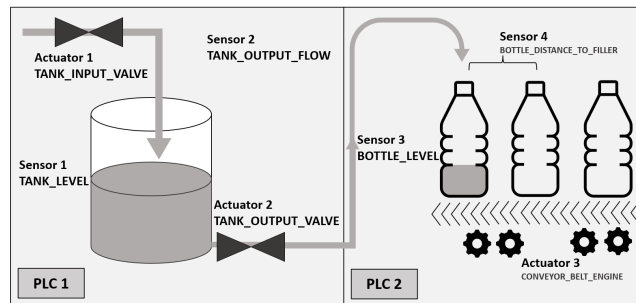


Figure 3: The Sample bottle filling plant

Table 2 presents the assumption related to the physical equipment, but these assumptions are not mandatory and are configurable through the configuration file. We developed ‘*FactorySimulation.py*’ python script, which inherits the ‘*HIL*’ base class in ICSSIM. This code runs in a standalone Docker container and is responsible for simulating physical laws; meanwhile, it updates the physical state, such as water level, in a 50ms period.

5.2. Sample Control System

A sample DCS system is proposed for the bottle filling factory consisting of two PLCs, two HMIs, a node to simulate the attacker, a network, and a node to play as an IDS component responsible for information gathering and providing logs.

Network Architecture: Figure 4 presents the network architecture for the bottle filling factory. The proposed network architecture realizes the first three

Table 2: Physical Properties for for the sample bottle filling plant

Property	Value
Tank Levels	10
Tank Level Capacity	3 Lit
Tank Inlet Flow	0.2 Lit/s
Tank Outlet Flow	0.1 Lit/s
Bottle Level	2
Bottle Level Capacity	0.75 Lit
Distance Between Bottles	0.2 m
Conveyor Belt Speed	0.05 m/s
Tank Level Sensor Error	1% (Uniform)
Bottle Level Sensor Error	1% (Uniform)
Bottle Position Sensor Error	5% (Uniform)

layers of Purdue reference architecture. The connection between Tier 1 and 2 is hardwired, which is implemented using the shared memory in Docker container technology. To simulate the control system network, we import the Westermo¹⁰ switch hub code as an appliance file to the GNS3 environment¹¹. Therefore, using real switch code on a simulation environment, a Local Area Network (LAN) is created to realize a network between Tier 2 and 3¹². We also assume that the attacker, as a malicious HMI, has access to this network; therefore, we consider an additional node to act as an attacker in this architecture.

Signals: Preparing a signal list, including input/output/control signals, is an important step in developing control systems. Table 3 presents the signal list for the sample bottle filling factory (defined in the ‘*Configs.py*’ script file).

¹⁰<https://www.westermo.com/>

¹¹Westermo Switch with WeOSS.11.X-3 as operating system.

¹²This framewrok is built for the ICS security experiment within the EU project InSecTT.

We specifically used industrial switch frameware provided by Westermo (InSecTT partner) to launch real switch codes in our testbed as an appliance file in the GNS3 environment.

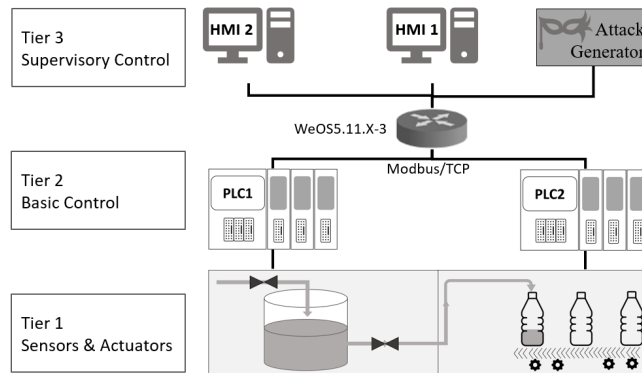


Figure 4: Network architecture for the sample bottle filling plant

Input signals deliver sensor data to PLCs, while output signals send control commands to actuators. We also define five control signals to realize users' command control through HMIs. For example, using these control signals, the user can change the *'minimum'* or *'maximum'* threshold of the tank or set the conveyor belt engine *'on'* or *'off'* manually. The user can also assign control to the PLCs by sending *'auto'* control commands to the processors.

PLCs: The control system is responsible for real-time monitoring and process control. PLCs continuously receive the users' control commands and sensor values to operate the actuator in the physical system. PLC-1 constantly reads the water level sensor and manages the tank input valve status to maintain the tank water level between the maximum and minimum thresholds. It is also responsible for reading the pipe flow sensor and changing the tank output valve status based on other controllers' requests. PLC-2 turns the conveyor belt engine *'on'* and *'off'* based on pipe flow sensor and water level sensor values to replace a filled bottle with an empty one. Although these two PLCs are responsible for automatic control of the actuators, users can overwrite the control commands through the HMI interfaces.

HMIs: Are responsible for displaying the system's current state and sending control commands to the controllers. Figure 5 shows the HMI-1 snapshot, which presents all signal values through a console interface. It has three columns

Table 3: signal list for sample bottle filling plant

Name	Type	Range	PLC
tank_input_valve_state	Output	On/Off	1
tank_input_valve_mode	Control	On/Off/Auto	1
tank_level_value	Input	\mathbb{R}	1
tank_level_max	Control	\mathbb{R}	1
tank_level_min	Control	\mathbb{R}	1
tank_output_valve_state	Output	On/Off	1
tank_output_valve_mode	Control	On/Off/Auto	1
tank_output_flow_value	Input	\mathbb{R}	1
conveyor_belt_engine_state	Output	On/Off	2
conveyor_belt_engine_mode	Control	On/Off/Auto	2
bottle_level_value	Input	\mathbb{R}	2
bottle_level_max	Control	\mathbb{R}	2
bottle_distance_to_filler_value	Input	\mathbb{R}	2

showing the variable's name, control signal, and value. We also develop HMI-2 to enable users to send control commands interactively. For example, the HMI user can change the bottle filling levels or manually turn the conveyor belt 'on' or 'off'.

[HMI1 - 17:51:13] (Latency 12.71ms)		
tank_input_valve	Auto	>>>
tank_level	Min:3.0 Max:7.0	3.6492
tank_output_valve	Auto	>>>
tank_output_flow		>>>
conveyor_belt_engine	Auto	X
bottle_level	Max:1.8	0.8458
bottle_distance_to_filler		0.7699

Figure 5: HMI-1 representing the bottle filling plant status

5.3. Attack Scenarios

We validate the ICS simulation by implementing three types of cyberattacks: D-DoS attack, reconnaissance attack, and false data injection using MitM. We present the result of applying these attacks in Section 6.

Reconnaissance Attacks: In this attack, the attacker collects information about the studied ICS. The attacker looks for active IPs and open ports in the network and stores the received information for future attacks. This is done by executing the Ettercap and NMap scripts, which ICSSIM already provides. The only assumption considered here is that the attacker somehow has access to the network switch; however, the attacker has no pre-knowledge about the network structure.

D-DoS Attack: ICSSIM simulates D-DoS attacks using multiple fake threads that forge thousands of fake read requests per second and send them to PLCs to make them unavailable. HMI1 reads all the signals presented in Table 3

periodically; therefore, finding the Modbus address of all signals is possible for an attacker through the scan attack, and as a result, each of these signals can be used as a D-DoS target. We implemented a D-DoS attack using a script to create 800 fake threads to read from PLCs for 60 seconds continuously.

MitM Attack: In this type of attack, the attacker secretly alters the communications between two ICS components. We can divide the MitM attacks scenarios into the following categories based on the communication parties:

- **PLC to PLC:** The attacker targets the communication between PLCs and changes control logic commands and messages. Since the proper distributed control is achievable only through the precise synchronous cooperation of PLCs, any communication disruption between the PLCs can lead to a disaster. For example, in a proposed bottle filling factory, PLC-1 must always know the bottle water level and bottle position to issue a proper control command for the tank outlet valve. In this example, any alternation in communication between controllers can lead to system malfunction.
- **HMI to PLC:** The attacker targets the communication between HMIs and PLCs; therefore, he could forge user commands to change the system status. In our use case, we consider scenarios in which attackers randomly change the actuators' status by forging the user control command for 15 seconds. We create three scenarios by changing the target actuator to each tank input valve, tank output valve, or conveyor belt.
- **PLC to IDS:** The attacker could target PLC communications with other ICS components such as Historian or IDS. As a representative for this category, we suppose that the attacker spoof the communication between a PLC and an IDS. Therefore, based on incorrect information reaching other ICS components, that component may behave incorrectly. For example, IDS could generate some false alarms upon receiving contaminated data. As IDS is responsible for monitoring system variables, all 12 system variables defined in the Table 3 could be the target for this type of attack.

Table 4: Attack scenarios for the sample bottle filling plant

Attack Type	Num	Attack Description	Targets Signal
Scan	1	Applying reconnaissance attack using Ettercap	-
	1	Applying reconnaissance attack using NMAP	-
D-DoS	12	Applying D-DoS attack by activating 800 reading threads for 60 S	All Signals
MitM	2	Alter the communication between PLCs, change the value of system state variables.	Bottle Water Level + Bottle Position
	3	Targets the communication between HMIs and PLCs, and randomly change the actuators' status by forging the user control command for 15 seconds	Tank Input Valve + Tank Output Valve + Conveyor Belt Status
	12	Target communication of PLCs with other ICS	All Signal

Table 4 summarize the attack scenarios that were considered for the sample bottle filling factory.

6. Results and Discussion

To experiment with IDS and IPS using ICS testbeds, we need attack threat implementations that compromise system security. This section shows that testbeds created using ICSSIM are suitable for cybersecurity research since they could simulate different types of cyberattacks. To this end, we will apply attacks provided by ICSSIM on the bottle filling example application and show that

these attacks effectively compromise the testbed security.

Assuming that the attacker has access to the network, an attacker needs to obtain information about ICS architecture to carry out malicious attacks. The *Reconnaissance* attack is one of the most common methods attackers use to obtain critical system information such as IP addresses, MAC addresses, open ports, and communication protocols. To compromise our testbed security against unauthorized information gathering, we run ICSSIM scripts in the attacker component to perform the Reconnaissance attack using '*Nmap*' and '*Ettercap*' tools against the ICS testbed. Figure 6 shows discovered information about ICS testbed components using the Reconnaissance attack applied on the sample bottle filling factory testbed. This figure shows that the attacker is able to find the IP addresses, hostnames, and status of all PLCs, HMIs, and even the network switch. This attack can also discover more detailed information about each ICS component, including the MAC address and open ports on each component. Figure 7 shows the collected information about the PLC1 component. This figure shows that the attacker found the IP addresses, hostnames, MAC addresses, and also the open ports on PLC1 (as it shows that PLCs have a port open (port 502), typically used for Modbus-TCP communications). Although this attack did not negatively affect the control system, this image shows that the attack was applied correctly and led to critical information disclosure.

The second attack we have implemented in this article is the *D-DoS* attack. To apply the D-DoS attack, we need to review how a PLC works. A PLC works through cycles, where it send process control command repeatedly. For example, the loop control in our example application is 200 ms, which means that PLCs read the sensor values and send the process command to actuators every 200 ms. The controller must perform its control tasks before the end of each control loop; otherwise, the following loop starts with a delay (logic execution delay), which negatively affects the controlling process. The D-DoS attack could target PLCs using overwhelming them with a torrent of '*read*' requests to impose additional processing on the controller. This additional processing load on processors increases the processors' response time and puts the control

```

1 # Nmap 7.80 scan initiated Thu Mar  3 14:00:10 2022
as: nmap -p- -oG |ip_nmap.txt 192.168.0.1-255
2 Host: 192.168.0.1 (dlinkrouter)      Status: Up
3 Host: 192.168.0.1 (dlinkrouter)      Status: Up
4 Host: 192.168.0.11 (plc1.icsnet)     Status: Up
5 Host: 192.168.0.11 (plc1.icsnet)     Ports: 502/-
open/tcp//mbap///      Ignored State: closed (65534)
6 Host: 192.168.0.12 (plc2.icsnet)     Status: Up
7 Host: 192.168.0.12 (plc2.icsnet)     Ports: 502/-
open/tcp//mbap///      Ignored State: closed (65534)
8 Host: 192.168.0.21 (hmi1.icsnet)     Status: Up
9 Host: 192.168.0.21 (hmi1.icsnet)     Status: Up
10 Host: 192.168.0.22 (hmi2.icsnet)    Status: Up
11 Host: 192.168.0.22 (hmi2.icsnet)    Status: Up
12 Host: 192.168.0.41 (d793561cecd4)   Status: Up
13 Host: 192.168.0.41 (d793561cecd4)   Status: Up
14 # Nmap done at Thu Mar  3 14:00:24 2022 -- 255 IP
addresses (6 hosts up) scanned in 13.37 seconds

```

Figure 6: Reconnaissance attack log on example bottle filing factory using ICSSIM Nmap script

```

7 Nmap scan report for plc1.icsnet (192.168.0.11)
8 Host is up (0.000014s latency).
9 Not shown: 65534 closed ports
10 PORT      STATE SERVICE
11 502/tcp   open  mbap
12 MAC Address: 02:42:C0:A8:00:0B (Unknown)

```

Figure 7: Part of disclosures information about PLC1 in result of Reconnaissance attack

system in an unstable state.

Using the gathered information with the Reconnaissance attack, the attacker knows the IP address and the Modbus port for PLCs to forge fake requests and could compromise control system availability. To simulate a D-DoS attack on our testbed example, we used the *'DDoSAttacker.py'* class in the ICSSIM to create 800 attacker nodes that constantly send fake *'read'* messages to the processors.

We examined two parameters to demonstrate D-DoS attack consequences,

including *'logic execution delay'* and PLC *'response time'*. *'Logic execution delay'* indicates how late a PLC executes its control logic. *'Response time'* shows the PLC's delay in responding to other PLCs. A control system tries to keep these parameters as low as possible to increase system responsiveness. We expect the D-DoS attack to increase these parameters considerably. We recorded these two parameters for PLC1 during 60 seconds of normal operation and 60 seconds under D-DoS attack operation to provide a base for comparison.

Figure 8 shows *'logic execution delay'* for PLC1 during 60 seconds of normal operation and 60 seconds of D-DoS attack. It shows that logic execution delay in the absence of attack is always less than 10 ms, which means PLC1 executes its control logic properly. However, during the next 60 seconds and in the presence of the D-DoS attack, the logic execution delay increases. Moreover, sometimes the *'logic execution delay'* exceeds 200 ms, which means PLC1 completely misses one control loop and cannot perform its controlling tasks.

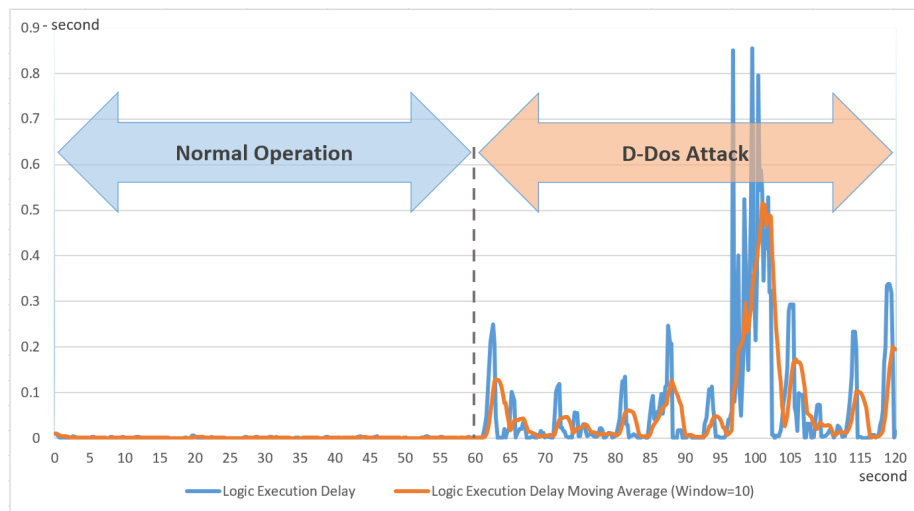


Figure 8: *'Logic execution delay'* of PLC1 during 60 seconds of normal operation and 60 seconds (60 to 120 seconds) of D-DoS attack

We also studied PLC's response time to evaluate the impact of the D-DoS attack. We know that PLCs communicate with each other to perform control

tasks. D-DoS attack increases the message latency between controllers. Figure 9 shows the PLC1 response time to other PLCs for the same interval as Figure 8. This figure shows that the PLC1's response time is always less than 50 ms during normal operation. However, the PLC1's response time becomes unpredictable during the D-DoS attack period. Moreover, PLC1's response time exceeds 200 ms occasionally, which means other PLCs miss PLC1's response due to PLC1's long response time. Figures 8 and 9 show that the implemented D-DoS attack successfully disrupted the normal behavior of the control system and could compromise the safety of the physical process.

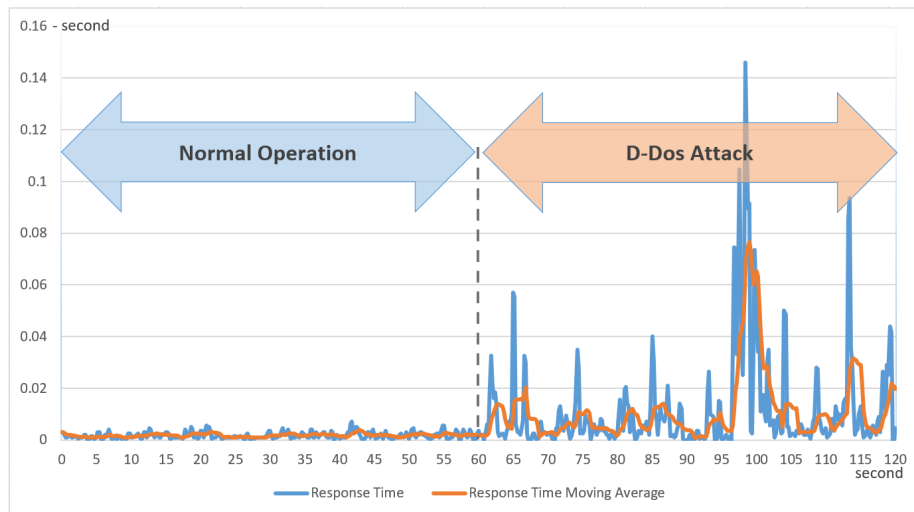


Figure 9: PLC1's response time to the other PLCs during 60 seconds normal operation 60 seconds (60 to 120 seconds) of D-DoS attack

The third attack that we have implemented is the 'false data injection attack' using MitM, as described in Section 5.3. Here, we used the 'Ettercap' tool to apply the MitM attack and the 'Wireshark' tool to sniff network traffics. To show the successful execution of this attack, we selected a sample control command from HMI2 to PLC1 and compared network traffic in the normal state and when the system was under MitM attack. Figure 10a shows the captured packets for sending the command from HMI2 to PLC1 in the normal state.

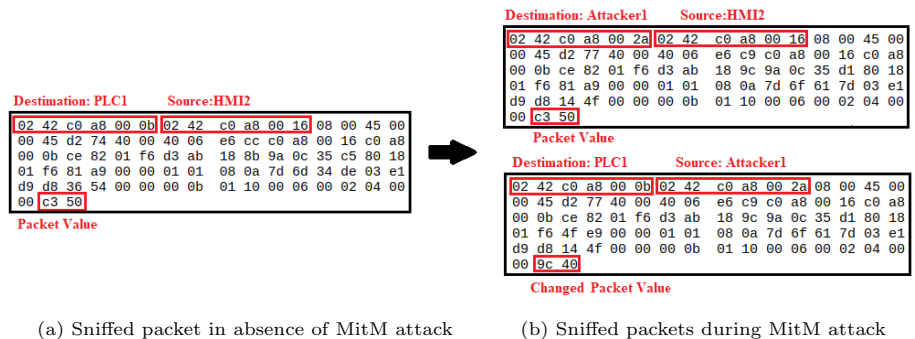


Figure 10: MitM effects on packets

In contrast, Figure 10b shows that MitM poisoning forces HMI2 to send its commands to the attacker node instead. Therefore, the attacker could change the payload and forward the packet with the false data to the actual destination. This sample shows how ICSSIM can simulate 'false data injection attacks' using the MitM attack.

7. Conclusion & Future Works

In this article, we take a brief look at the few recent Industrial Control System (ICS) testbeds and examine their strengths and weaknesses. We also provide a list of ICS testbed requirements based on the experience from the studied ICS testbeds. We then developed the ICSSIM framework to produce ICS simulation testbeds capable of meeting the listed requirements. We also explained how testbeds built with ICSSIM could address the shortcomings of previous testbeds. To demonstrate ICSSIM, we used it to design a testbed for a sample bottle filling plant. We also attacked the plant with reconnaissance, D-DoS, and false data injection attacks to simulate its cyber threats. The results show that the attacks were effective and that we could compromise the security of the system.

Having an ICS testbed equipped with various cyber attacks paves the road for AI-based intrusion detection. This enables researchers to apply different attacks to the ICS in a safe and controlled environment. Meanwhile, they could

assess and improve intrusion detection algorithms and techniques. Moreover, generating a dataset from normal and under cyberattack states of ICS testbeds can help conduct cybersecurity research and AI-based intrusion detection without a physical testbed.

Further work is certainly required to include additional features to facilitate a broader range of experiments and further attempts for effective intrusion detection. Therefore, one of the most important future works is to generate a dataset, including system variables and network logs' details. Another improvement for this testbed is adding physical processes to obtain more accurate simulations. Another challenge would be using time series algorithms and recurrent neural networks to develop a functional IDS for the testbeds. We believe that these methods can detect ICS cyberattacks effectively.

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