

UNIVERSITY OF VERONA

Department of COMPUTER SCIENCE

Master's Degree in
COMPUTER SCIENCE AND ENGINEERING

Master Thesis

**Towards Process Comprehension of Industrial
Control Systems: a Framework for Analyzing
Industrial Systems**

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*“If you spend more on coffee than on IT security, you
will be hacked. What’s more, you deserve to be hacked”*
(Richard Clarke)

Abstract

Bla bla bla

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Introduction

LOREM ipsum dolor bla bla bla. Ma dove metto l'abstract? Prova di interlinea che direi posso anche andare bene, ma bisogna poi vedere il tutto come si incastra alla fine, in modo da ottenere un bel risultato alla vista.

1.1 Contribution

Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum.

1.2 Outline

The thesis is structured as follows:

Chapter 2: provides background on the topics covered in this thesis: Industrial Control Systems (ICSs), Supervisory Control And Data Acquisition (SCADA), Programmable Logic Controllers (PLCs) and other devices, industrial communication protocols.

Chapter 3:

Chapter 4:

Chapter 5:

Chapter 6:

Chapter 7:

Chapter 2

Background

2.1 Industrial Control Systems in a nutshell

1 INDUSTRIAL CONTROL SYSTEMS (ICSs) are information systems used to
2 control industrial processes such as manufacturing, product handling,
3 production, and distribution [1].

4 ICSs are often found in critical infrastructure facilities such as power
5 plants, oil and gas refineries, and chemical plants.

6 ICSs are different from traditional IT systems in several key ways. Firstly,
7 ICSs are designed to control physical processes, whereas IT systems are
8 designed to process and store data. This means that ICSs have different
9 requirements for availability, reliability, and performance. Secondly, ICSs
10 are typically deployed in environments that are harsh and have limited
11 resources, such as extreme temperatures and limited power. Thirdly, the
12 protocols and hardware used in ICSs are often proprietary and not widely
13 used outside of the industrial sector.

14 ICSs are becoming increasingly connected to the internet and other net-
15 works, which has led to increased concerns about their security. Industrial
16 systems were not originally designed with security in mind, and many of
17 them have known vulnerabilities that could be exploited by attackers. Ad-
18 ditionally, the use of legacy systems and equipment can make it difficult to

19 implement security measures. As a result, ICSs are increasingly seen as a
20 potential target for cyber attacks, which could have serious consequences
21 for the safe and reliable operation of critical infrastructure.

22 The increasing connectivity of ICSs and the associated security risks
23 have led to a growing interest in the field of ICS security. Researchers
24 and practitioners are working to develop new security technologies, stan-
25 dards, and best practices to protect ICSs from cyber attacks. This includes
26 efforts to improve the security of ICS networks and devices, as well as the
27 development of new monitoring and detection techniques to identify and
28 respond to cyber attacks.

29 **2.2 ICS components**

30 *Industrial control systems* (ICSs) are composed of several different com-
31 ponents that work together to monitor and control industrial processes.

32 **2.2.1 SCADA systems**

33 *Supervisory Control And Data Acquisition (SCADA)* is a system of soft-
34 ware and hardware elements that allows industrial organizations to [2]:

- 35 • Control industrial processes locally or at remote locations
- 36 • Monitor, gather, and process real-time data
- 37 • Directly interact with devices such as sensors, valves, pumps, mo-
38 tors, and more through human-machine interface (HMI) software
- 39 • Record events into a log file

40 The SCADA software processes, distributes, and displays the data,
41 helping operators and other employees analyze the data and make im-
42 portant decisions.

43 SCADA systems are known for their ability to monitor and control
44 large-scale industrial processes, and for their ability to operate over long

distances. This makes them well-suited for use in remote locations or for controlling processes that are spread out over a wide area. However, the same features that make SCADA systems so useful also make them vulnerable to cyber attacks.

SCADA systems were not originally designed with security in mind, and many of them have known vulnerabilities that could be exploited by attackers. Additionally, the use of legacy systems and equipment can make it difficult to implement security measures. As a result, SCADA systems are increasingly seen as a potential target for cyber attacks, which could have serious consequences for the safe and reliable operation of critical infrastructure.

To secure SCADA systems, it is important to implement security measures such as network segmentation, secure communication protocols, and access control. Additionally, it is important to monitor SCADA systems for unusual activity and to implement incident response procedures to quickly detect and respond to any security breaches.

2.2.1.1 SCADA architecture

According to the *Purdue Enterprise Reference Architecture* (PERA), or simply **Purdue Model**, SCADA architecture consists in **six levels** each representing a functionality [3], as shown in Figure 2.1:

- Level 0 (**Processes**): contains **field devices** (2.2.2), or *sensors*.
- Level 1 (**Intelligent Devices**): includes **local or remote controllers** that sense, monitor and control the physical process, such as **PLCs** (2.2.3) and **RTUs** (2.2.4). Controllers interface directly to the field devices reading data from sensors and sending commands to actuators.
- Level 2 (**Control Systems**): contains computer systems used to supervising and monitoring the physical process: they provide a **Human-Machine Interface** (HMI, 2.2.5) and *Engineering Workstations* (EW) for operator control.

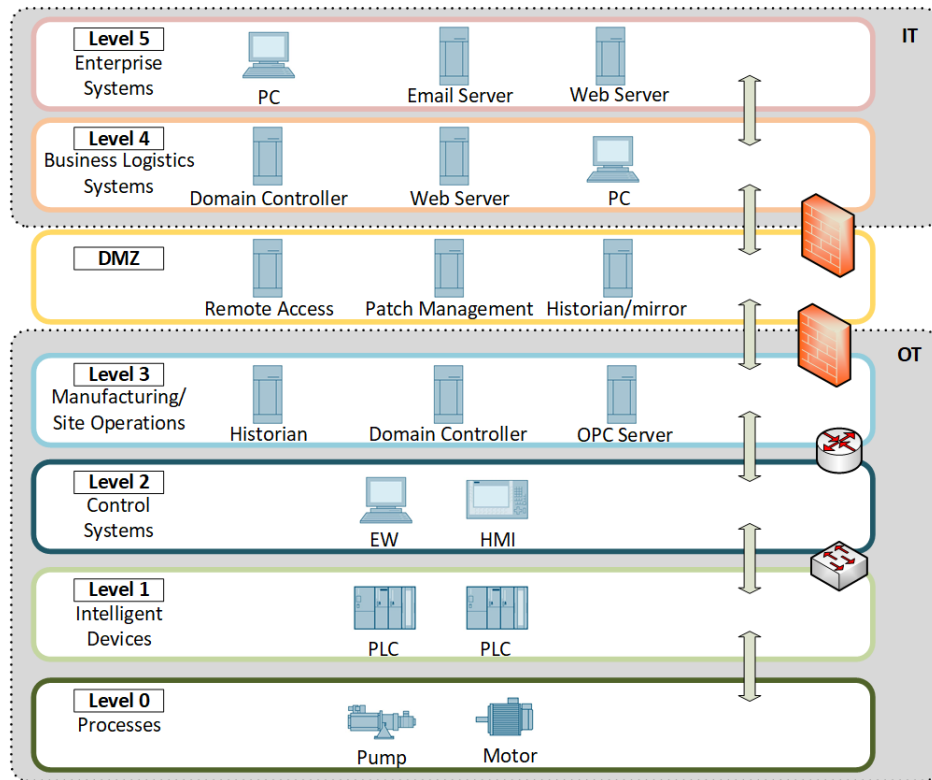


Figure 2.1: SCADA architecture schema

- Level 3 (**Manufacturing/Site Operations**): comprises systems used to manage the production workflow for plant-wide control: they collate informations from the previous levels and store them in Data Historian servers.
- Industrial Demilitarized Zone (DMZ)**: intermediate level that connects the *Operational Technology* (OT) part (levels 0-3) with the *Information Technology* (IT) part of the system (levels 4 and 5). Communication takes place indirectly through services such as *proxy servers* and *remote access servers*, which act as intermediaries between the two environments.
- Level 4 (**Business Logistics Systems**): collect and aggregates data from the Manufacturing/Site Operations level overseeing the IT-related activities to generate **reporting** to the Enterprise System layer. At

this layer we can find application and e-mail servers, and *Enterprise Resource Planning* (ERP) systems.

- Level 5 (**Enterprise Systems**): represents the enterprise network, used for the business-to-business activities and for business-to-client purpose services. At Enterprise Systems level are typical IT services such as mail servers, web servers and all the systems used to manage the ongoing process.

2.2.2 Field devices

Field devices are the **sensors** and **actuators** that are used to collect data from the process and control it. Examples of field devices include temperature sensors, pressure sensors, valves and pumps.

2.2.3 Programmable Logic Controllers

A *Programmable Logic Controller* (PLC) is a **small and specialized industrial computer** having the capability of controlling complex industrial and manufacturing processes [4].

Compared to relay systems and personal computers, PLCs are optimized for control tasks and industrial environments: they are rugged and designed to withdraw harsh conditions such as dust, vibrations, humidity and temperature: they have more reliability than personal computers, which are more prone to crash, and they are more compact and require less maintenance than a relay system. Furthermore, I/O interfaces are already on the controller, so PLCs are easier to expand with additional I/O modules (if in a rack format) to manage more inputs and outputs, without reconfiguring hardware as in relay systems when a reconfiguration occurs.

PLCs are more *user-friendly*: they are not intended (only) for computer programmers, but designed for engineers with a limited knowledge in programming languages: control program can be entered with a simple

and intuitive language based on logic and switching operations instead of a general-purpose programming language (*i.e.* C, C++, ...).

2.2.3.1 PLC Architecture

The basic hardware architecture of a PLC consists of these elements [5]:

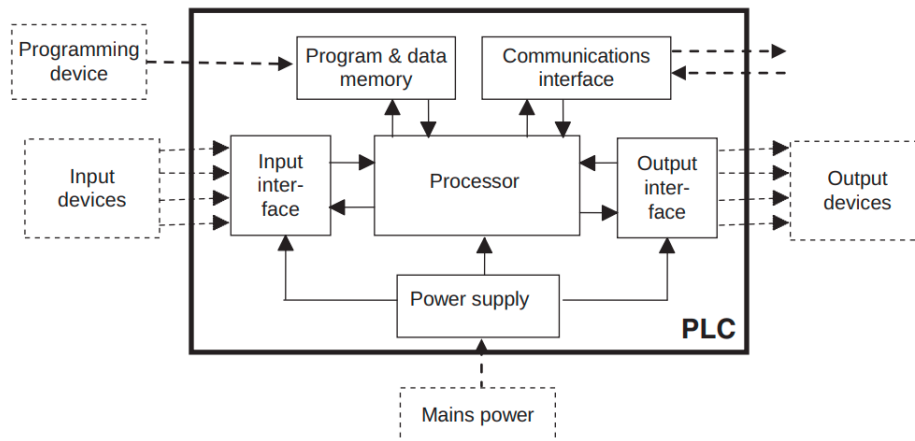


Figure 2.2: PLC architecture

- **Processor unit (CPU):** contains the microprocessor. This unit interpretes the input signals from I/O modules, executes the control program stored in the Memory Unit and sends the output signals to the I/O Modules. The processor unit also sends data to the Communication interface, for the communication with additional devices.
- **Power supply unit:** converts AC voltage to low DC voltage.
- **Programming device:** is used to store the required program into the memory unit.
- **Memory Unit:** consists in RAM memory and ROM memory. RAM memory is used for storing data from inputs, ROM memory for storing operating system, firmware and user program to be executed by the CPU.

- **I/O modules:** provide interface between sensors and final control elements (actuators).
- **Communications interface:** used to send and receive data on a network from/to other PLCs.



Figure 2.3: PLC communication schema

2.2.3.2 PLC Programming

Two different programs are executed in a PLC: the **operating system** and the **user program**.

The operating system tasks include executing the user program, managing memory areas and the *process image table* (memory registers where inputs from sensors and outputs for actuators are stored).

The user program needs to be uploaded on the PLC via the programming device and runs on the process image table in *scan cycles*: each scan is made up of three phases [6]:

1. reading inputs from the process images table
2. execution of the control code and computing the physical process evolution

146 3. writing output to the process image table to have an effect on the
 147 physical process. At the end of the cycle, the process image table is
 148 refreshed by the CPU

149 Standard PLCs **programming languages** are basically of two types:
 150 **textuals** and **graphicals**. Textual languages include languages such as
 151 *Instruction List (IL)* and *Structured Text (ST)*, while *Ladder Diagrams (LD)*,
 152 *Function Block Diagram (FBD)* and *Sequential Function Chart (SFC)* belong
 153 to the graphical languages.

154 Graphical languages are more simple and immediate comparing to the
 155 textual ones and are preferred by programmers because of their features
 156 and simplicity, in particular the **Ladder Logic programming** (see Figure
 157 2.4 for a comparison).

```

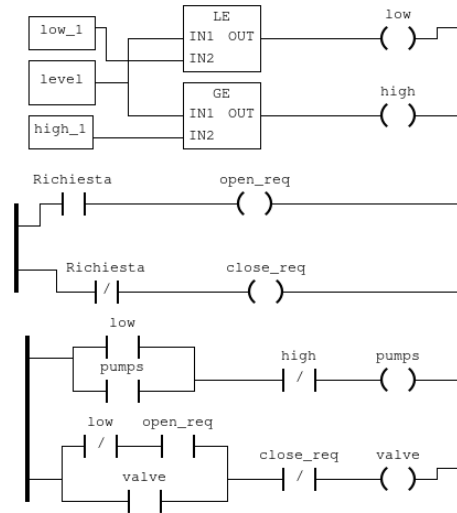
PROGRAM PLC1
VAR
  level AT %IW0 : INT;
  Richiesta AT %QX0.2 : BOOL;
  request AT %IW1 : INT;
  pumps AT %QX0.0 : BOOL;
  valve AT %QX0.1 : BOOL;
  low AT %MX0.0 : BOOL;
  high AT %MX0.1 : BOOL;
  open_req AT %MX0.3 : BOOL;
  close_req AT %MX0.4 : BOOL;
  low_1 AT %MW0 : INT := 40;
  high_1 AT %MW1 : INT := 80;
END_VAR
VAR
  LE3_OUT : BOOL;
  GE7_OUT : BOOL;
END_VAR

LE3_OUT := LE(level, low_1);
low := LE3_OUT;
GE7_OUT := GE(level, high_1);
high := GE7_OUT;
open_req := Richiesta;
close_req := NOT(Richiasta);
pumps := NOT(high) AND (low OR pumps);
valve := NOT(close_req) AND (open_req AND NOT(low) OR valve);
END_PROGRAM

CONFIGURATION Config0
RESOURCE Res0 ON PLC
TASK task0(INTERVAL := T#20ms,PRIORITY := 0);
PROGRAM instance0 WITH task0 : PLC1;
END_RESOURCE
END_CONFIGURATION

```

(a) Example of ST programming



(b) Example of Ladder Logic

Figure 2.4: Comparison between ST language and Ladder Logic

158 2.2.3.3 PLC Security

159 PLCs were originally designed to operate as closed systems, not con-
 160 nected and exposed to the outside world via communication networks:

the question of the safety of these systems, therefore, was not a primary aspect. The advent of Internet has brought undoubted advantages, but has introduced problems relating to the safety and protection of PLCs from external attacks and vulnerabilities.

Indeed, a variety of different communication protocols used in ICSs are designed to be efficient in communications, but do not provide any security measure i.e. confidentiality, authentication and data integrity, which makes these protocols vulnerable against many of the IT classic attacks such as *Replay Attack* or *Man in the Middle Attack*.

Countermeasures to enhance security in PLC systems may include [7]:

- protocol modifications implementing **data integrity**, **authentication** and **protection** against *Replay Attacks*
- use of *Intrusion Detection and Prevention Systems* (IDP)
- creation of *Demilitarized Zones* (DMZ) on the network

In addition to this, keeping the process network and Internet separated, limiting the use of USB devices among users to reduce the risks of infections, and using strong account management and maintenance policies are best practices to prevent attacks and threats and to avoid potential damages.

2.2.4 Remote Terminal Units

Remote Terminal Units (RTUs) are computers with radio interfacing similar to PLCs: they transmit telemetry data to the control center or to the PLCs and use messages from the master supervisory system to control connected objects [8].

The purpose of RTUs is to operate efficiently in remote and isolated locations by utilizing wireless connections. In contrast, PLCs are designed for local use and rely on high-speed wired connections. This key difference

allows RTUs to conserve energy by operating in low-power mode for extended periods using batteries or solar panels. As a result, RTUs consume less energy than PLCs, making them a more sustainable and cost-effective option for remote operations.

Industries that require RTUs often operate in areas without reliable access to the power grid or require monitoring and control substations in remote locations. These include telecommunications, railways, and utilities that manage critical infrastructure such as power grids, pipelines, and water treatment facilities. The advanced technology of RTUs allows these industries to maintain essential services, even in challenging environments or under adverse weather conditions.

2.2.5 Human-Machine Interface

The *Human-Machine Interface* (HMI) is the hardware and software interface that operators use to monitor the processes and interact with the ICS.

An HMI shows the operator and authorized users information about system status and history; it also allows them to configure parameters on the ICS such as set points and, send commands and make control decisions [9].

The HMI can be in the form of a physical panel, with buttons and indicator lights, or PC software.

2.2.6 Cybersecurity components

Cybersecurity components, as seen in section 2.2.3.3 about PLCs security, are used to protect ICSs from cyber threats and vulnerabilities. They can include firewalls, *Intrusion Detection and Prevention systems* (IDP), and *Security Information and Event Management* (SIEM) systems.

2.3 Communication Networks

Communication Networks are the networks that are used to connect the different components of the ICS and allow them to communicate with each other. Communication networks can include wired and wireless networks, such as Ethernet/IP, Modbus, DNP3 and others.

2.3.1 ICS Communication Protocols

As mentioned in Section 2.1, industrial systems differ from classical IT systems in the purpose for which they are designed: controlling physical processes the former, processing and storing data the latter. For this reason, ICSs require different communication protocols than traditional IT systems for real time communications and data transfer.

A wide variety of industrial protocols exists: this is because originally each vendor developed and used its own proprietary protocol. However, these protocols were often incompatible with each other, resulting in devices from different vendors being unable to communicate with each other.

To solve this problem, standards were defined with a view to allowing these otherwise incompatible device to intercommunicates.

Among all the various protocols, some have risen to prominence as widely accepted standards. These *de facto* protocols are commonly utilized in industrial systems due to their proven reliability and effectiveness. In the following sections, we will provide a brief overview of some of the most prevalent and widely used protocols in the industry.

2.3.1.1 Modbus

Modbus is a serial communication protocol developed by Modicon (now Schneider Electric) in 1979 for use with its PLCs [10] and designed expressly for industrial use: it facilitates interoperability of different devices

connected to the same network (sensors, PLCs, HMIs, ...) and it is also often used to connect RTUs to SCADA acquisition systems.

Modbus is the most widely used communication protocol among industrial systems because it has several advantages:

- simplicity of implementation and debugging
- it moves raw bits and words, letting the individual vendor to represent the data as it prefers
- it is, nowadays, an **open** and *royalty-free* protocol: there is no need to sustain licensing costs for implementation and use by industrial device vendors

Modbus is a **request/response** (or *master/slave*) protocol: this makes it independent of the transport layer used.

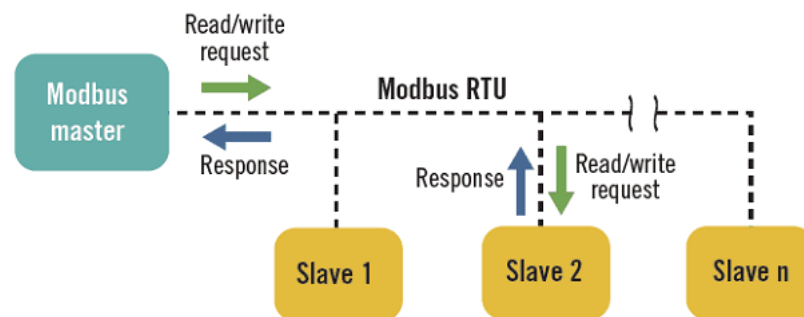


Figure 2.5: Modbus Request/Response schema

In this kind of architecture, a single device (master) can send requests to other devices (slaves), either individually or in broadcast: these slave devices (usually peripherals such as actuators) will respond to the master by providing data or performing the action requested by the master using the Modbus protocol. Slave devices cannot generate requests to the master [11].

259 There are several variants of Modbus, of which the most popular and
260 widely used are Modbus RTU (used in serial port connections) and Mod-
261 bus TCP (which instead uses TCP/IP as the transport layer). Modbus TCP
262 embeds a standard Modbus frame in a TCP frame (see Figure 2.6): both
263 masters and slaves listen and receive data via TCP port 502.

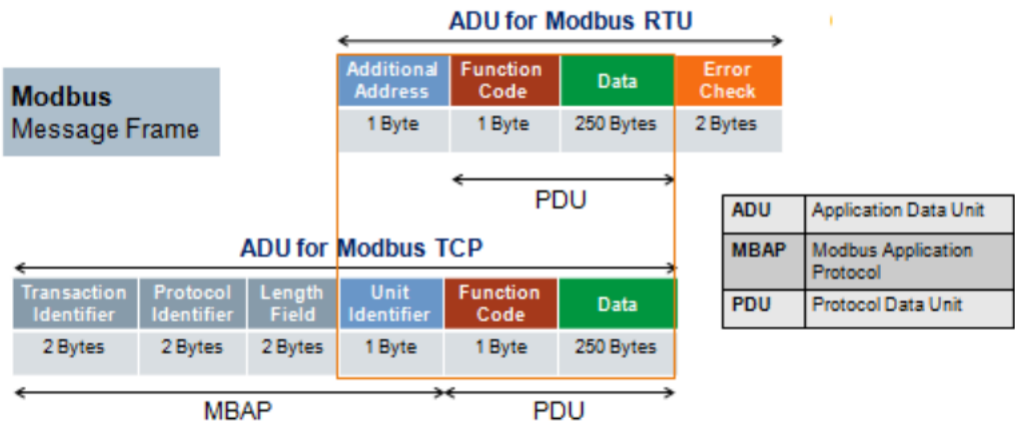


Figure 2.6: Modbus RTU frame and Modbus TCP frame

264 **Modbus registers** Modbus provides four object types, which map the
265 data accessed by master and slave to the PLC memory:

- 266 • *Coil*: binary type, read/write accessible by both masters and slaves
- 267 • *Discrete Input*: binary type, accessible in read-only mode by masters
268 and in read/write mode by slaves
- 269 • *Analog Input*: 16 bits in size (word), are accessible in read-only mode
270 by masters and in read/write mode by slaves
- 271 • *Holding Register*: 16 bits in size (word), accessible in read/write mode
272 by both masters and slaves. Holding Registers are the most com-
273 monly used registers for output and as general memory registers.

274 **Modbus Function Codes** *Modbus Function Codes* are specific codes used
275 by the Modbus master within a request frame (see Figure 2.6) to tell the

276 Modbus slave device which register type to access and which action to
277 perform on it.

278 Two types of Function Codes exists: for data access and for diagnostic
279 Function Codes list for data access are listed in Table 2.1:

Function Code	Description
FC01	Read Coils
FC02	Read Discrete Input
FC03	Read Holding Registers
FC04	Read Analog Input Registers
FC05	Write/Force Single Coil
FC06	Write/Force Single Holding Register
FC15	Write/Force Multiple Coils
FC16	Write/Force Multiple Holding Registers

Table 2.1: Modbus Function Codes list

280 **Modbus Security Issues** Despite its simplicity and widespread use, the
281 Modbus protocol does not have any security feature, which exposes it to
282 vulnerabilities and attacks.

283 Data in Modbus are transmitted unencrypted (*lack of confidentiality*),
284 with no data integrity controls (*lack of integrity*) and authentication checks
285 (*lack of authentication*), in addition to the *lack of session*. Hence, the protocol
286 is vulnerable to a variety of attacks, such as Denial of Services (DoS), buffer
287 overflows and reconnaissance activities.

288 The easiest attack to bring to the Modbus protocol, however, is **packet**
289 **sniffing**: since, as mentioned earlier, network traffic is unencrypted and
290 the data transmitted is in cleartext, it is sufficient to use a packet sniffer to
291 capture the network traffic, read the packets and thus gather informations
292 about the system such as ip addresses, function codes of requests and to
293 modify the operation of the devices.



Figure 2.7: Example of packet sniffing on the Modbus protocol

To make the Modbus protocol more secure, an encapsulated version was developed within the *Transport Security Layer* (TLS) cryptographic protocol, also using mutual authentication. This version of the Modbus protocol is called **Secure Modbus** or **Modbus TLS**. In addition to this, Secure Modbus also includes X.509-type certificates to define permissions and authorisations [12].

2.3.1.2 EtherNet/IP

EtherNet/IP (where IP stands for *Industrial Protocol*) is an open industrial protocol that allows the *Common Industrial Protocol* (CIP) to run on a typical Ethernet network [13]. It is supported by ODVA [14].

EtherNet/IP uses the major Ethernet standards, such as IEEE 802.3 and the TCP/IP suite, and implements the CIP protocol stack at the upper layers of the OSI stack (see Figure 2.8). It is furthermore compatible with the main Internet standard protocols, such as SNMP, HTTP, FTP and DHCP, and other industrial protocols for data access and exchange such as *Open Platform Communication* (OPC).



Figure 2.8: OSI model for EtherNet/IP stack

310 **Physical and Data Link layer** The use of the IEEE 802.3 standard allows
 311 EtherNet/IP to flexibly adopt different network topologies (star, linear,
 312 ring, etc.) over different connections (copper, fibre optic, wireless, etc.), as
 313 well as the possibility to choose the speed of network devices.
 314 IEEE 802.3 in addition defines at Data Link layer the *Carrier Sense Multiple*
 315 *Access - Collision Detection* (CSMA/CD) protocol, which controls access to
 316 the communication channel and prevents collisions.

317 **Transport layer** At the transport level, EtherNet/IP encapsulates mes-
 318 sages from the CIP stack into an Ethernet message, so that messages can
 319 be transmitted from one node to another on the network using the TCP/IP
 320 protocol. EtherNet/IP uses two forms of messaging, as defined by CIP
 321 standard [13][15]:

- 322 • **unconnected messaging:** used during the connection establishment
 323 phase and for infrequent, low priority, explicit messages. Uncon-
 324 nected messaging uses TCP/IP to transmit messages across the net-
 325 work asking for connection resource each time from the *Unconnected*

Message Manager (UCMM).

- **connected messaging:** used for frequent message transactions or for real-time I/O data transfers. Connection resources are reserved and configured using communications services available via the UCMM.

EtherNet/IP has two types of message connection [13]:

- **explicit messaging:** *point-to-point* connections to facilitate *request-response* transactions between two nodes. These connections use TCP/IP service on port 44818 to transmit messages over Ethernet.
- **implicit messaging:** this kind of connection moves application-specific **real-time I/O data** at regular intervals. It uses multicast *producer-consumer* model in contrast to the traditional *source-destination* model and UDP/IP service (which has lower protocol overhead and smaller packet size than TCP/IP) on port 2222 to transfer data over Ethernet.

Session, Presentation and Application layer At the upper layers, Ethernet/IP implements the CIP protocol stack. We will discuss this protocol more in detail in Section 2.3.1.3.

2.3.1.3 Common Industrial Protocol (CIP)

The *Common Industrial Protocol* (CIP) is an open industrial automation protocol supported by ODVA. It is a **media independent** (or *transport independent*) protocol using a *producer-consumer* communication model and providing a **unified architecture** throughout the manufacturing enterprise [16][17].

CIP has been adapted in different types of network:

- **EtherNet/IP**, adaptation to *Transmission Control Protocol* (TCP) technologies

- 353 • **ControlNet**, adaptation to *Concurrent Time Domain Multiple Access*
354 (CTDMA) technologies
- 355 • **DeviceNet**, adaptation to *Controller Area Network* (CAN) technolo-
356 gies
- 357 • **CompoNet**, adaptation to *Time Division Multiple Access* (TDMA) tech-
358 nologies

359 **CIP objects** CIP is a *strictly object oriented* protocol at the upper layers:
360 each object of CIP has **attributes** (data), **services** (commands), **connec-**
361 **tions**, and **behaviors** (relationship between values and services of attributes)
362 which are defined in the **CIP object library**. The object library supports
363 many common automation devices and functions, such as analog and dig-
364 ital I/O, valves, motion systems, sensors, and actuators. So if the same
365 object is implemented in two or more devices, it will behave the same way
366 in each device [18].

367 **Security** [19] In EtherNet/IP implementation, security issues are the same
368 as in traditional Ethernet, such as network traffic sniffing and spoofing.
369 The use of the UDP protocol also exposes CIP to transmission route ma-
370 nipulation attacks using the *Internet Group Management Protocol* (IGMP)
371 and malicious traffic injection.

372 Regardless of the implementation used, it is recommended that certain
373 basic measures be implemented on the CIP network to ensure a high level
374 of security, such as *integrity*, *authentication* and *authorization*.

375 2.3.1.4 Other Protocols

Chapter 3

State of the Art

IN TRADITIONAL IT, an attacker aims to understand the behavior of a program through various techniques so as to bring attacks aimed at changing its execution flow, functionalities or bypassing limits imposed by the licensing of such software. These attack techniques include a **preliminary study** of the program: a *static analysis* (i.e., a preliminary analysis of the software without it running) and a *dynamic analysis* (i.e., an analysis performed with the program running).

The result of these two preliminary investigation techniques is a **reverse engineering** of the software, which is useful for identifying any weaknesses or bugs and therefore planning an attack.

In the OT context, however, the concept of *reverse engineering* is also associated with that of *process comprehension*, a term coined by Green et al.'s [20] to describe the understanding of the characteristics of the system and the physical elements of within it, that are responsible for its proper functioning.

Not much knowledge exists in the literature regarding the collection and analysis of information concerning the understanding and operation of an ICS: in Section 3.1 we will look at a quick overview of some of the existing literature on the subject and in the following sections we will focus in particular on one of the papers exposed.

3.1 Literature on Process Comprehension

Keliris and Maniatikos The first approach presented in this section is by Keliris and Maniatikos [21]: they present a methodology for automating the reverse engineering of ICS binaries based on a *modular framework* (called ICSREF) that can reverse binaries compiled with CODESYS, one of the most popular and widely used PLC compilers, irrespective of the language used.

Yuan et al. Yuan et al. [22] propose a *data-driven* approach to discovering cyber-physical systems from data directly: to achieve this goal, they have implemented a framework whose purpose is to identify physical systems and transition logic inference, and to seek to understand the mechanisms underlying these cyber-physical systems, making furthermore predictions concerning their state trajectories based on the discovered models.

Feng et al. Feng et al. [23] developed a framework that can generate system *invariant rules* based on machine learning and data mining techniques from ICS operational data log. These invariants are then selected by systems engineers to derive IDS systems from them.

The experiment results on two different testbeds, the *Water Distribution system* (WaDi) and the *Secure Water Treatment system* (SWaT), both located at the iTrust - Center for Research in Cyber Security at the University of Singapore [24], show that under the same false positive rate invariant-based IDSs have a higher efficiency in detecting anomalies than IDS systems based on a residual error-based model.

Pal et al. Pal et al. [25] work is somewhat related to Feng et al.'s: this paper describes a data-driven approach to identifying invariants automatically using *association rules mining* [26] with the aim of generate invariants sometimes hidden from the design layout. The study has the same objective of Feng et al.'s and uses too the iTrust SwaT System as testbed.

Currently this technique is limited to only pair wise sensors and actuators: for more accurate invariants generation, the technique adopted must be capable of deriving valid constraints across multiple sensors and actuators.

Winnicki et al. Winnicki et al. [27] instead propose a different approach to process comprehension based on the **attacker's perspective** and not limited to mere *Denial of Service* (DoS): their approach is to discover the dynamic behavior of the system, in a semi-automated and process-aware way, through *probing*, that is, slightly perturbing the cyber physical system and observing how it reacts to changes and how it returns to its original state. The difficulty and challenge for the attacker is to perturb the system in such a way as to achieve an observable change, but at the same time avoid this change being seen as a system anomaly by the IDSs.

Green et al. Green et al. [20] also adopt an approach based on the attacker's perspective: this approach consists of two practical examples in a *Man in the Middle* (MitM) scenario to obtain, correlate, and understand all the types of information an attacker might need to plan an attack to alter the process while avoiding detection.

The paper shows *step-by-step* how to perform a ICS **reconnaissance**, which is fundamental to process comprehension and thus to the execution of MitM attacks.

Ceccato et al. Ceccato et al. [6] propose a methodology based on a *black box dynamic analysis* of an ICS using a reverse engineering tool to derive from the scans performed on the memory registers of the exposed PLCs and network scans an approximate model of the physical process. This model is obtained by inferring statistical properties, business process and system invariants from data logs.

The proposed methodology was tested on a non-trivial case study, using a testbed inspired by an industrial water treatment plant.

456 In the next section I will examine this latest work in more detail,
457 which will be the basis for my work and thus the subsequent chap-
458 ters of this thesis.

459 3.2 Ceccato et al.'s methodology for analyzing water- 460 tank systems

461 As mentioned earlier, the paper proposes a methodology based on a
462 black box dynamic analysis of an ICS by identifying potential PLCs on the
463 network and scanning the memory registers of the identified controllers
464 to obtain an approximate model of the controlled physical process.

465 The first objective of this black box analysis is to associate the various
466 memory registers of the target PLCs with a correspondence to the basic
467 concepts of an ICS such as sensors (otherwise known as measurements),
468 actuators, setpoints (range of values of a physical variable), network com-
469 munications, and so on.

470 This is performed by analyzing the different types of memory registers as-
471 sociated with the Modbus protocol and trying to figure out what type of
472 data they may contain.

473 The second objective is to put in relation the runtime evolution of these
474 basic concepts.

475 To achieve this, Ceccato et al. developed a prototype tool [28] that per-
476 forms reverse engineering of the physical system through four phases:

- 477 1. **scanning of the system and data pre-processing:** data gathering is
478 performed to generate the data logs of PLCs registers
- 479 2. **graphs and statistical analysis:** provides information about the mem-
480 ory registers using graphs and statistical data derived from the gath-
481 ered data
- 482 3. **invariants inference and analysis:** generates system invariants and
483 allows user to view invariants related to a given sensor or actuator

4. **business process mining and analysis:** reconstructs, from event logs, the business process that shows how process is carried out

In Figure 3.1 we have a schematic representation of the workflow related to this work. We will cover all these phases in detail in the next sections of this chapter.

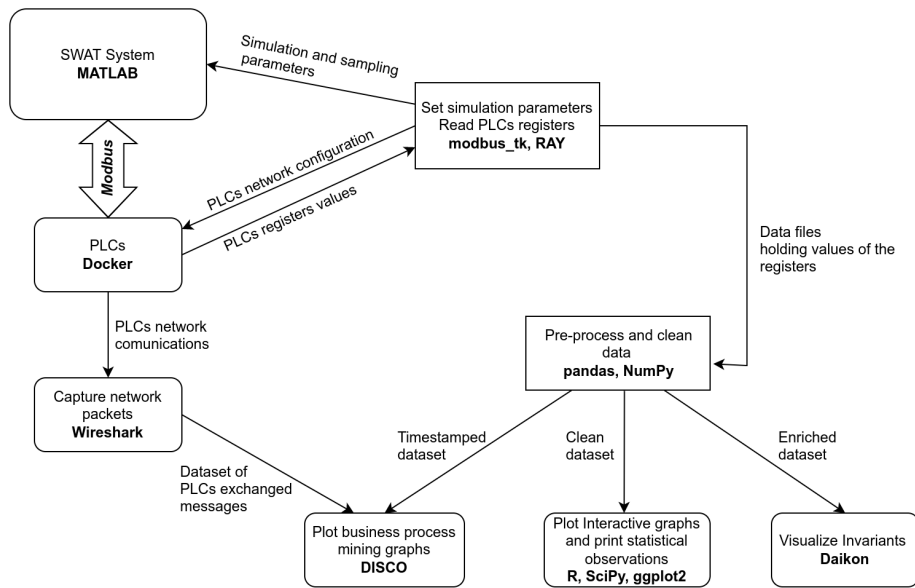


Figure 3.1: Overview

3.2.1 Testbed

Before describing the various phases of the methodology, let's take a look at the testbed on which this methodology will be tested. The testbed used to test this methodology is a (very) simplified version of the iTrust SWaT system [29] implemented by Lanotte et al. [30]: in Figure 3.2 we can see a graphical representation of the testbed. This simplified version consists of three stages, each controlled by a dedicated PLC:

Stage 1 At the first stage, a **tank** with a capacity of 80 gallons (identified by the code T-201) is filled with raw water by the P-101 pump: the

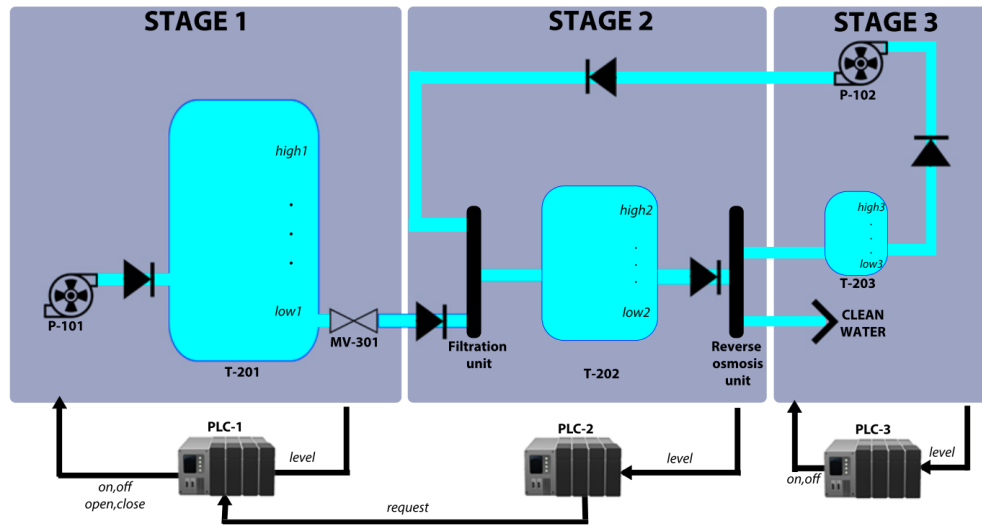


Figure 3.2: The simplified SWaT system used for running Ceccato et al. methodology

498 MV-301 valve (where MV stands for *motorized valve*), also connected
 499 to the T-201 tank, flushes out the water collected in the tank to send
 500 it to the second stage, first to the *filtration unit* (here not identified by
 501 any sensor) and from there to a **second tank**, identified by the code
 502 T-202 and with a capacity of 20 gallons.

503 **Stage 2** At the second stage, water contained in T-202 flows into the *reverse*
 504 *osmosis unit* (RO, which in this case also acts as a valve, extracting wa-
 505 ter continuously: however, it is not identified as a pump) to reduce
 506 organic impurities in the same water. The water then flows from the
 507 RO unit to the third and last stage.

508 **Stage 3** At the third stage, the water from the RO unit is divided according
 509 to whether standards are met: if the water is clean it will be fed into
 510 the distribution system, otherwise it will go to a *backwash tank*, iden-
 511 tified by code T-203 and a capacity of one gallon. The water in this
 512 tank will then be pumped back to the stage 2 *filtration unit* through
 513 pump P-102.

514 As mentioned, each stage corresponds to a PLC that controls it, PLC1,

515 PLC2 and PLC3, respectively. Let us briefly see the behavior of each of
516 them:

517 **PLC1** PLC1 checks the level of tank T-201 distinguishing three cases:

- 518 • if T-201 reaches the *low setpoint low1* (hardcoded in memory reg-
519 isters), pump **P-101 is opened** and valve **MV-301 is closed**, so
520 that the tank can be filled
- 521 • if T-201 reaches *high setpoint high1* (also hardcoded in the mem-
522 ory registers), pump **P-101 is closed**
- 523 • in intermediate cases, **PLC1 waits for request from PLC2** to
524 open/close valve MV-301: if a request to open the valve MV-
525 301 arrives, water will flow from T-201 to T-202, otherwise the
526 valve is closed. In both situations, pump P-101 remains closed

527 **PLC2** PLC2 monitors the level of tank T-202, behaving accordingly de-
528 pending on the level of water in it. Here again there are three cases
529 to consider:

- 530 • if the water level reaches the *low setpoint low2* (also hardcoded
531 in the memory registers), PLC2 sends a request to PLC1 via a
532 Modbus channel to **open valve MV-301** in order to flow water
533 from tank T-201 to tank T-202. The transmission channel is im-
534 plemented by copying a boolean value from a memory register
535 of PLC2 to a corresponding register of PLC1
- 536 • if the water level reaches the *high setpoint high2* instead (hard-
537 coded in the memory registers as the previous setpoints), PLC2
538 sends PLC1 a **close request** for valve MV-301
- 539 • In intermediate cases, the valve remains open (closed) while the
540 tank is filling (emptying)

541 **PLC3** PLC3 monitors the level of the T-203 backwash tank, behaving ac-
542 cordingly. Here there are only two cases to consider: if the tank

reaches the *low setpoint low3*, pump **P103 is set to off**, so that the backwash tank can be filled: otherwise, if the *high setpoint high3* is reached, pump **P103 is opened** and the entire content of the backwash tank pumped back to the filter unit of T-202.

3.2.2 Scanning of the System and Data Pre-processing

Scanning tool The Ceccato et al. scanning tool is closely derived from a project I did [31] for the "*Network Security*" and "*Cyber Security for IoT*" courses taught by Professors Massimo Merro and Mariano Ceccato, respectively, in the 2020/21 academic year. The original project involved, in its first part, the recognition within a network of potential PLCs listening on the standard Modbus TCP port 502 using the Nmap module for Python, obtaining the corresponding IP addresses: then a (sequential) scan of a given range of the memory registers of the found PLCs was performed to collect the register data. The data thus collected were saved to a file in *JavaScript Object Notation* (JSON) format for later use in the second part of my project.

The scanning tool by Ceccato et. al works in a similar way, but extends what I originally did by trying to discover other ports on which the Modbus protocol might be listening (since in many realities Modbus runs on different ports than the standard one, according to the concept of *security by obscurity*) and, most importantly, by **parallelizing and distributing the scan** of PLC memory registers through the Ray module [32], specifying moreover the desired granularity of the capture. An example of raw data capture can be seen at Listing 3.1:

```
"127.0.0.1/8502/2022-05-03 12_10_00.591": {  
  "DiscreteInputRegisters": {"%IX0.0": "0"},  
  "InputRegisters": {"%IW0": "53"},  
  "HoldingOutputRegisters": {"%QW0": "0"},  
  "MemoryRegisters": {"%MW0": "40", "%MW1": "80"},
```

```
572     "Coils": {"%QX0.0": "0"}}}
```

Listing 3.1: Example of registers capture

573 The captured data includes PLC's IP address, Modbus port and times-
574 tamp (first line), type and name of registers with their values read from
575 the scan (subsequent lines).

576 The tool furthermore offers the possibility, in parallel to the memory
577 registers scan, of **sniffing network traffic** related to the Modbus protocol
578 using the *Man in the Middle* (MitM) technique on the supervisory control
579 network using a Python wrapper for tshark/Wireshark [33] [34]. An ex-
580 ample of raw data obtained with this sniffing can be seen in Listing 3.2:

```
581 Time,Source,Destination,Protocol,Length,Function
582   ↳ Code,Destination Port,Source Port,Data,Frame
583   ↳ length on the wire,Bit Value,Request Frame,
584   ↳ Reference Number,Info
585 2022-05-03 11:43:58.158,IP_PLC1,IP_PLC2,Modbus/TCP
586   ↳ ,76,Read Coils,46106,502,,76,TRUE,25,, "Response
587   ↳ : Trans: 62; Unit: 1, Func: 1: Read Coils"
```

Listing 3.2: Example of raw network capture

588 **Data Pre-processing** The data collected by scanning the memory regis-
589 ters of the PLCs are then reprocessed by a Python script and converted
590 in order to create a distinct raw dataset in *Comma Separated Value* for-
591 mat (CSV) for each PLC, containing the memory register values associ-
592 ated with the corresponding controller registers. These datasets are repro-
593 cessed again through the Python modules for **pandas** [35] and **NumPy** [36]
594 by another script to first perform a **data cleanup**, removing all those mem-
595 ory registers that do not take values and are therefore useless within the
596 system, **merged** into a single dataset, and finally **enriched** with additional
597 data¹.

¹Not all additional data are calculated and entered automatically by the tool: some are manually inserted.

598 This process leads to the creation of two copies of the full dataset: one
 599 enriched with the additional data, but not timestamped, which will be
 600 used for the invariant analysis; the other unenriched, but timestamped,
 601 which will be used for business process mining.

602 3.2.3 Graphs and Statistical Analysis

603 The paper mentions the presence of a *mild graph analysis*, performed
 604 with **R** [37] at the time of data gathering to find any uncovered patterns,
 605 trends and identify measurements and/or actuator commands through
 606 the analysis of registers holding mutable values.

607 There is actually no trace of this within the tool: *graph analysis* and *sta-*
 608 *tistical analysis* of the data contained in the PLC memory registers are in-
 609 stead performed using the **matplotlib** libraries and statistical algorithms
 610 made available by the **SciPy** libraries [38], through two separate Python
 611 scripts (see Figure 3.3).

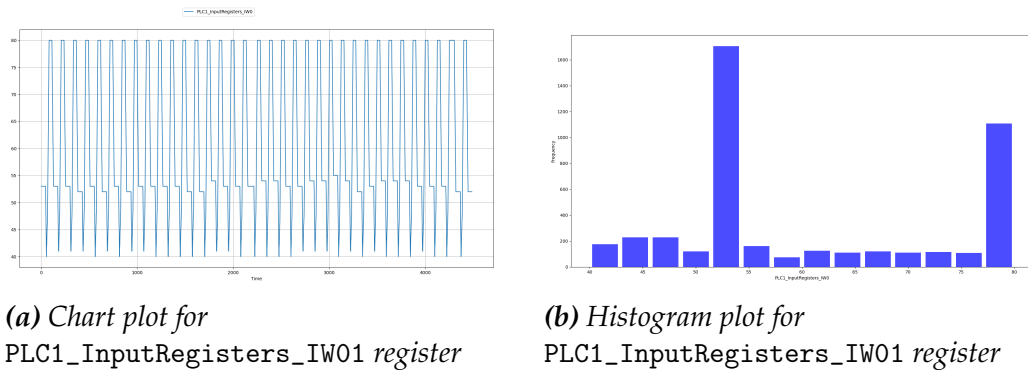


Figure 3.3: Output graphs from graph analysis

612 The first script plots the charts, one at the time, of certain registers en-
 613 tered by the user from the command line, plots in which one can see the
 614 trend of the data and get a first basic idea of what that particular regis-
 615 ter contains (a measurement, an actuation, a hardcoded setpoint, ...) and
 616 possibly the trend; the second script, instead, shows a **histogram and sta-**
 617 **tistical informations** about the register entered as command-line input.

These informations include:

- the mean, median, standard deviation, maximum value and minimum value
- two tests for the statistical distribution: *Chi-squared* test for uniformity and *Shapiro-Wilk* test for normality, as shown in Listing 3.3:

```

Chi-squared test for uniformity
Distance      pvalue      Uniform?
12488.340     0.00000000      NO

Shapiro-Wilk test for normality
Test statistic      pvalue      Normal?
0.844      0.00000000      NO

Stats of PLC1_InputRegisters_IW0
Sample mean = 60.8881; Stddev = 13.0164; max = 80;
↪ min = 40 for 4488 values

```

Listing 3.3: Statistical data for PLC1_InputRegisters_IW0 register

3.2.4 Invariants Inference and Analysis

For invariant analysis Ceccato et al. rely on **Daikon** [39], a framework to **dynamically detect likely invariants** within a program. An *invariant* is a property that holds at one or more points in a program, properties that are not normally made explicit in the code, but within assert statements, documentation and formal specifications: invariants are useful in understanding the behavior of a program (in our case, of the cyber physical system).

Daikon uses *machine learning* techniques applied to arbitrary data with the possibility of setting custom conditions for analysis by using a specific file [40] with a *.spinfo* extension (see Listing 3.4). The framework is

645 designed to find the invariants of a program, with various supported pro-
646 gramming languages, starting from the direct execution of the program
647 itself or passing as input the execution run (typically a file in CSV format):
648 the authors of the paper tried to apply it by analogy also to the execution
649 runs of a cyber physical system, to extract the invariants of this system.

```
650 PPT_NAME aprogram.point:::POINT  
651 VAR1 > VAR2  
652 VAR1 == VAR3 && VAR1 != VAR4
```

Listing 3.4: Generic example of a .spinfo file for customizing rules in Daikon

653 Therefore, Daikon is fed with the no-timestamp enriched dataset ob-
654 tained in the pre-processing phase (in the paper, the timestamped dataset
655 is erroneously mentioned as input): a simple bash script launches Daikon
656 (optionally specifying the desired condition for analysis in the .spinfo file),
657 which output is simply redirected to a text file containing the general in-
658 variants of the system (i.e., valid regardless of any custom condition speci-
659 fied), those generated based on the custom condition in the .spinfo file, and
660 those generated based on the negation of the condition. When the analy-
661 sis is finished, the user is asked to enter the name of a registry to view its
662 related invariants.

663
664 Some examples of invariants derived from the enriched dataset may be:

- 665 • measurements bounded by some setpoint
- 666 • Actuators state changes occurred in the proximity of setpoints or,
667 vice versa, proximity of setpoints upon the occurrence of a regular
668 actuator state change
- 669 • state invariants of some actuator correspond to a specific trend in
670 the evolution of the measurement (ascending, descending, or stable)
671 or, vice versa, the measurement trend corresponds to a specific state
672 invariant of some actuator

3.2.5 Business Process Mining and Analysis

Process mining is the analysis of operational processes based on the event log [41]: the aim of this analysis is to **extract useful informations** from the event data to **reconstruct and understand the behavior** of the business process and how it was actually performed.

Process mining for the system under consideration starts from the event logs obtained from scanning the memory registers of the PLCs and sniffing the network communications related to the Modbus protocol, described in Subsection 3.2.2 and representing the *execution trace* of the system: through a Java program, information is extracted and combined from these event logs, and the result saved in a CSV format file.

This file is fed to **Disco** [42], a commercial process mining tool, which generates an *activity diagram* similar to UML Activity Diagram and whose nodes represent the activities while the edges represent the relations between these activities: in Figure 3.4 we can see an example of this diagram referred to PLC2 of the testbed.

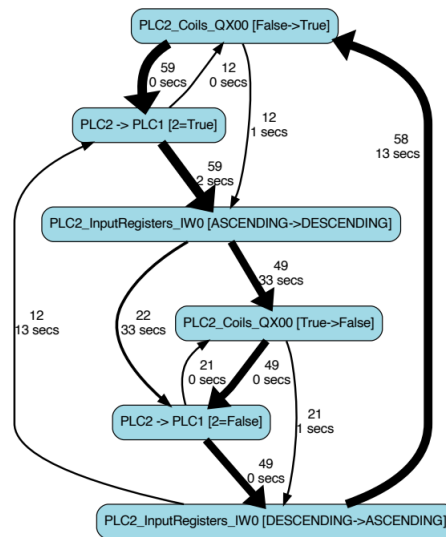


Figure 3.4: An example of Disco generated activity diagram for PLC2

The *business process* obtained in this way provides an **overview of the system** and makes it possible to **make conjectures** about its behavior, par-

691 ticularly between changes in actuator state and measurement trends (i.e.,
 692 a given change in state of some actuators corresponds to a specific mea-
 693 surement trend and vice versa), and with the possibility of **establishing**
 694 **causality** between Modbus communications and state changes within the
 695 physical system.

696 3.2.6 Application

697 In this section we will see how the black box analysis presented above
 698 in its various phases is applied in practice, using the testbed described in
 699 Subsection 3.2.1. The methodology supports a *top-down approach*: that
 700 is, we start with an overview of the industrial process and then gradually
 701 refine our understanding of the process by descending to a higher and
 702 higher level of detail based on the results of the previous analyses and
 703 focusing on the most interesting parts of the system for further in-depth
 704 analysis.

705 **Data Collection and Pre-processing** According to what is described in
 706 the paper, the data gathering process lasted six hours, with a granular-
 707 ity of one data point per second (a full system cycle takes approximately
 708 30 minutes). Each datapoint consists of 168 attributes (55 registers plus
 709 a special register concerning the tank slope of each PLC) after the en-
 710 richment. In addition, IP addresses are automatically replaced by an ab-
 711 stract name identified by the prefix PLC followed by a progressive integer
 712 (PLC1, PLC2, PLC3), in order to make reading easier.

713 **Graphs and Statistical Analysis** It is unclear from the paper where ex-
 714 actly the information that follows was derived (graph analysis? Statistical
 715 analysis? Human reading of the dataset?), however, three properties about
 716 the contents of the registers were discovered:

717 *Property 1:* PLC1_MemoryRegisters_MW0, PLC1_MemoryRegisters_MW1,
 718 PLC2_MemoryRegisters_MW0, PLC2_MemoryRegisters_MW1,
 719 PLC3_MemoryRegisters_MW0 and PLC3_MemoryRegisters_MW1

registers contain constant integer values (40, 80, 10, 20, 0, 10 respectively)². We may speculate that they may be (relative) hardcoded **setpoints**.

Property 2: PLC1_Coils_QX01, PLC1_Coils_QX02, PLC2_Coils_QX01, PLC2_Coils_QX02, PLC3_Coils_QX01 and PLC3_Coils_QX03 contain mutable binary (Boolean) values. We can assume that these registers can be associated with the **actuators** of the system.

Property 3: PLC1_InputRegisters_IW0, PLC2_InputRegisters_IW0 and PLC3_InputRegisters_IW0 registers contain mutable values.

Property 3 suggests that those registers might contain **values related to measurements**: it is therefore necessary to investigate further to see if the conjecture (referred to as *Conjecture 1* in the paper) is correct.

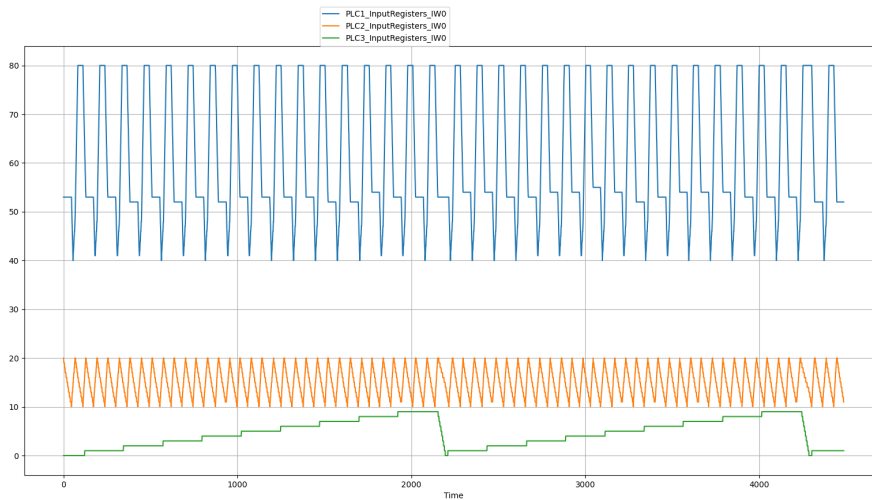


Figure 3.5: Execution traces of InputRegisters_IW0 on the three PLCs

The graph analysis of the InputRegisters_IW0 registers of the three PLCs (summarized in Figure 3.5 with a single plot) not only seems to confirm the conjecture, but also allows the measurements to be correlated with

²From my tests on the original tool and dataset, the PLC3_MemoryRegisters_MW0 register is deleted during the *pre-processing* phase, as it is recognized as an unused register because of the constant value "0" it takes on. This leads me to assume that the properties are derived from a human read of the dataset prior to the *pre-processing* phase.

the contents of the MemoryRegisters_MW0 and MemoryRegisters_MW1 registers to the measurements, which represent the **relative setpoints of the measurements**.

Hence, we have *Conjecture 2* described in the paper referring to the relative setpoints:

740

741 *Conjecture 2:*

742 - 40 and 80 are the relative setpoints for PLC1_InputRegisters_IW0

743 - 10 and 20 are the relative setpoints for PLC2_InputRegisters_IW0

744 - 0 and 9 are the relative setpoints for PLC3_InputRegisters_IW0

745 Further confirmation of this conjecture may come from statistical analysis. Indeed, in the example in Listing 3.1, some statistical data are given for the register PLC1_InputRegisters_IW0, including the maximum value and the minimum value: these values are, in fact, 80 and 40 respectively.

749 **Business Process Mining and Analysis** With Business Process Mining, the authors aim to **visualize and highlight relevant system behaviors** by relating PLC states and Modbus commands.

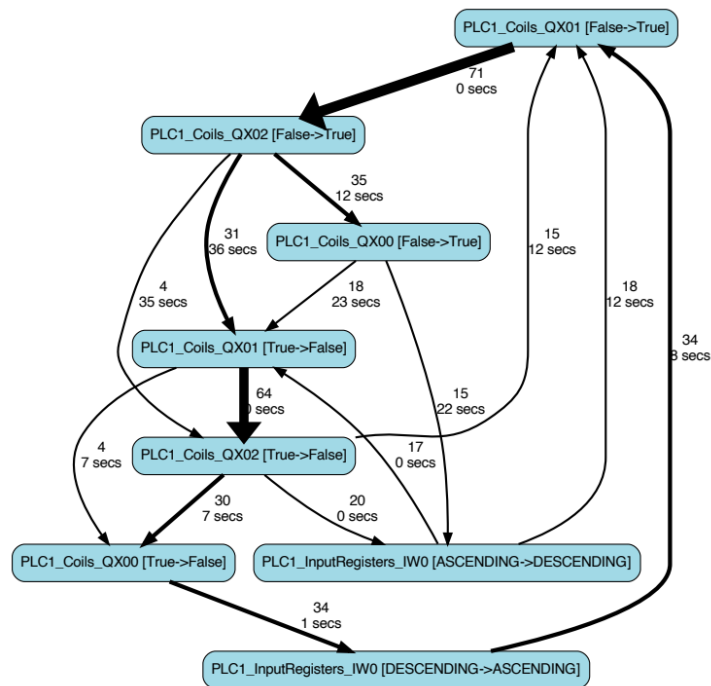
752 Through analysis of the activity diagrams shown in Figure 3.6, drawn through Disco, we derive the following properties and conjectures:

754 *Property 4:* PLC2 sends messages to PLC1 (see Figure 3.6b) which are recorded to PLC1_Coils_QX02.

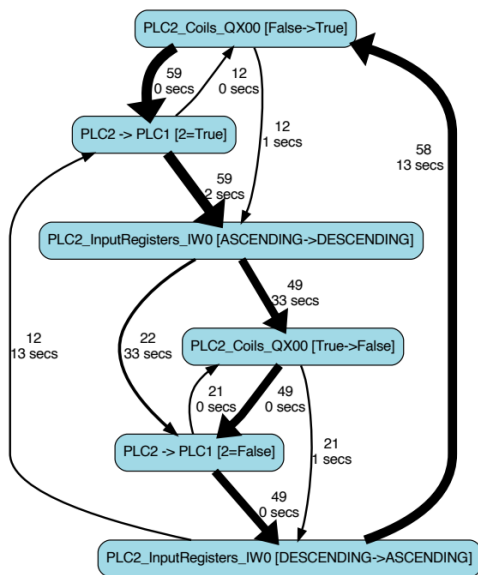
756 *Conjecture 3:* PLC2_Coils_QX00 determines the trend in tank T-202 (Figure 3.6b).

758 When this register is set to *True*, the input register PLC2_InputRegisters_IW0 related to the tank controlled by PLC2 starts an **ascending trend**; vice versa, when the coil register is set to *False*, the input register starts a **descending trend**.

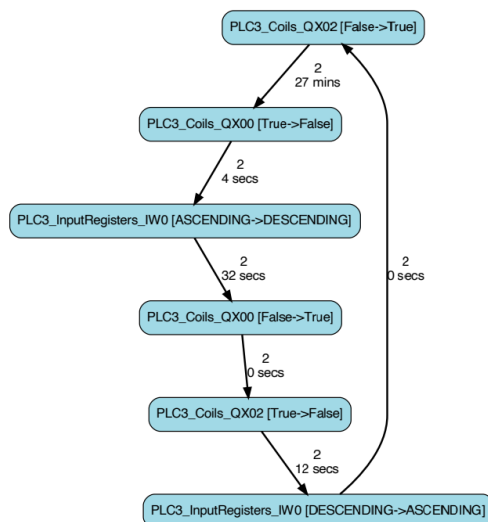
762 *Conjecture 4:* If PLC1_Coils_QX00 change his value to *True*, trend in tank T-201, related to PLC1_InputRegisters_IW0 and controlled by PLC1, become **ascending** (see Figure 3.6a)



(a) States in PLC1



(b) States and Modbus command in PLC2



(c) *States in PLC3*

Figure 3.6: Business process with states and Modbus commands for the three PLCs

765 **Conjecture 5:** PLC3_Coils_QX00 starts a **decreasing trend** in tank T-203,
 766 related to PLC3_InputRegisters_IW0 and controlled by PLC3, whereas
 767 PLC3_Coils_QX02 starts an **increasing trend** on the tank (see Figure
 768 3.6c)

769 **Invariants Inference and Analysis** The last phase of the analysis of the
 770 example industrial system is invariant analysis, performed through Daikon
 771 framework. At this stage, an attempt will be made to confirm what has
 772 been seen previously and to derive new properties of the system based on
 773 the results of the Daikon analysis.

774 To get gradually more and more accurate results, the authors presum-
 775 ably performed more than one analysis with Daikon, including certain
 776 rules within the *splitter information file* (see Section 3.2.4 and Listing 3.4)
 777 based on specific conditions placed on the measurements, for example, the
 778 level of water contained in a tank. Given moreover the massive amount
 779 of invariants generated by Daikon's output, it is not easy to identify and
 780 correlate those that are actually useful for analysis: this must be done man-
 781 ually.

782 However, it was possible to have confirmation of the conjectures made
 783 in the previous stages of the analysis: starting with the setpoints, analyz-
 784 ing the output of the invariants returned by Daikon³ reveals that

```
785
786 PLC1_InputRegisters_IW0 >= PLC1_MemoryRegisters_MW0 == 40.0
787 PLC1_InputRegisters_IW0 <= PLC1_MemoryRegisters_MW1 == 80.0
788 PLC2_InputRegisters_IW0 >= PLC2_MemoryRegisters_MW0 == 10.0
789 PLC2_InputRegisters_IW0 <= PLC2_MemoryRegisters_MW1 == 20.0
790 PLC3_InputRegisters_IW0 >= PLC3_MemoryRegisters_MW0 == 0.0
791 PLC3_InputRegisters_IW0 <= PLC3_MemoryRegisters_MW1 == 9.0
```

792
 793 i.e., that the MemoryRegisters_MW0 and MemoryRegisters_MW1 registers of

³The invariants shown here are a manual summary and derivation of those actually returned in output by Daikon. I will discuss this more in Section 3.2.7

each PLC contain the **absolute minimum and maximum setpoints**, respectively (*Property 5*).

There is also a confirmation regarding *Property 4*: from the computed invariants it can be seen that

```
PLC1_Coils_QX01 == PLC1_Coils_QX02 == PLC2_Coils_QX00
```

and from this derive that there is a **communication channel between PLC2 and PLC1**, where the value of PLC2_Coils_QX00 is copied to PLC1_Coils_QX01 and PLC1_Coils_QX02 (*Property 6*).

Regarding the **relationships between actuator state changes and measurement trends**, invariant analysis yields the results summarized in the following rules:

Property 7: Tank T-202 level *increases* iif PLC1_Coils_QX01 == True. Otherwise, if PLC1_Coils_QX01 == False will be *non-increasing*.

This is because if the coil is *True* the condition

```
PLC2_InputRegisters_IW0 == PLC2_MemoryRegisters_MW0 == 20.0 && PLC2_slope > 0
```

is verified. On the opposite hand, if the coil is *False*, the condition

```
PLC2_InputRegisters_IW0 == PLC2_MemoryRegisters_MW0 == 20.0 && PLC2_slope <= 0
```

is verified. The *slope* is an auxiliary attribute indicating the trend of the measurement: increasing if > 0, decreasing if < 0, stable otherwise.

Property 8: Tank T-201 level *increases* iif PLC1_Coils_QX00 == True. On the other hand, if PLC1_Coils_QX00 == False and if PLC1_Coils_QX01 == True the level will be *non-decreasing*.

Property 9: Tank T-203 level *decreases* iif PLC3_Coils_QX00 == True. It will be *non-decreasing* if PLC1_Coils_QX00 == False.

The last two properties concern the **relationship between actuator state changes and the setpoints**: it is intended to check what happens to the actuators when the water level reaches one of these setpoints. From the analysis of the relevant invariants, the following properties are derived:

824 **Property 10:** Tank T-201 reaches the upper absolute setpoint when
825 PLC1_Coils_QX00 changes its state from *True* to *False*. If the coil changes
826 from *False* to *True*, the tank reaches its absolute lower setpoint.

827 **Property 11:** Tank T-203 reaches the upper absolute setpoint when
828 PLC3_Coils_QX00 changes its state from *True* to *False*. If the coil changes
829 from *False* to *True*, the tank reaches its absolute lower setpoint.

830 3.2.7 Limitations

831 The methodology proposed by Ceccato et al. is certainly valid and
832 offers a good starting point for approaching the reverse engineering of
833 an industrial control system from the attacker's perspective, while also
834 providing a tool to perform this task.

835 The limitations of this approach, however, all lie in the tool mentioned
836 above and also in the testbed described in Section 3.2.1. In this section
837 I will explain which are the criticisms of each phase, while in Chapter 4
838 I will formulate proposals to improve and make this methodology more
839 efficient.

840 **General Criticism** The general critical aspects of the application of this
841 approach are many: the primary one concerns the fact that the proposed
842 tool seems to be built specifically for the testbed used and that it is not
843 applicable to other contexts, even to the same type of industrial control
844 system (water treatment systems, in this case).

845 What severely limits the analysis performed with the tool implemented
846 by Ceccato et al. is the use of *ad hoc* solutions and *a posteriori* interventions
847 done manually on the datasets after the data gathering process: I will dis-
848 cuss this last aspect in more detail later.

849 Moreover, there is the presence of many *hardcoded* variables and condi-
850 tions within the scripts: this makes the system unconfigurable and unable
851 to properly perform the various stages of the analysis as errors can occur
852 due to incorrect data and mismatches with the system under analysis.

Having considered, furthermore, only the Modbus protocol for network communications between the PLCs is another major limiting factor and does not help the methodology to be adaptable to different systems communicating with different protocols (sometimes even multiple ones on the same system).

Let us now look at the limitations and critical aspects of each phase.

Testbed The testbed environment used by Ceccato et. al is entirely simulated, from the physical system to the control system. The PLCs were built with **OpenPLC** [43] in a Docker environment [44], while the physics part was built through **Simulink** [45].

OpenPLC is an open source cross-platform software that simulates the hardware and software functionality of a physical PLC and also offers a complete editor for PLC program development with support for all standard languages: *Ladder Logic* (LD), *Function Block Diagram* (FBD), *Instruction List* (IL), *Structured Text* (ST), and *Sequential Function Chart* (SFC). It is for sure an excellent choice for creating a zero-cost industrial or home automation and *Internet of Things* (IoT) system that is easy to manage via a dedicated, comprehensive and functional web interface. In spite of these undoubted merits, however, there are (at the moment) **very few supported protocols**: the main one and also referred to in the official documentation is **Modbus**, while the other protocol is DNP3.

The biggest problem with the testbed, however, is not with the controller part, but with the **physical part**: first of all, it must be said that although this is something purely demonstrative even though it is fully functional, the implemented Simulink model is really **oversimplified** compared to the iTrust SWaT system, which itself is a scaled-down version of a real water treatment plant. In fact, in the entire system there are only three actuators, two of which are connected to the same tank and controlled by the same PLC, and sensors related only to the water level in the system's tanks: in a real system there are many more *field devices*, which can mon-

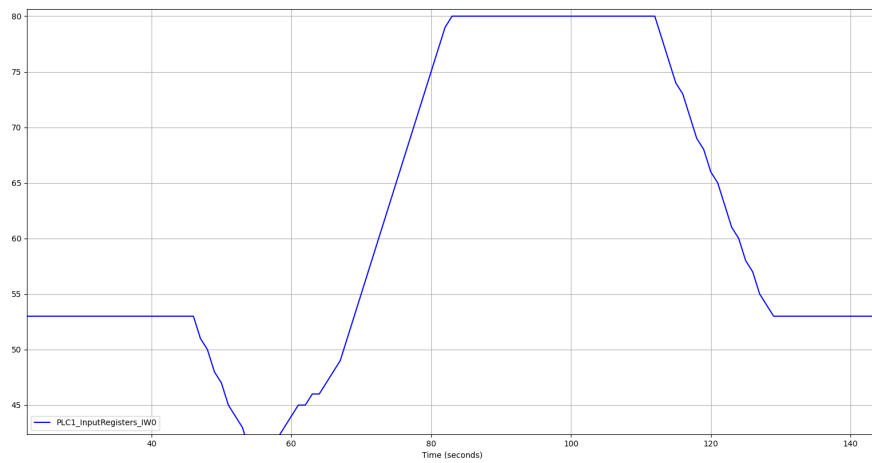
itor and control other aspects of the system beyond the mere contents of the tanks. Consider, for example, measuring and controlling the chemicals in the water, the pressure of the liquid in the filter unit, or more simply the amount of water flow at a given point or time.

All these must be considered and represent a number of additional variables that makes analysis and consequently reverse engineering of the system more difficult.

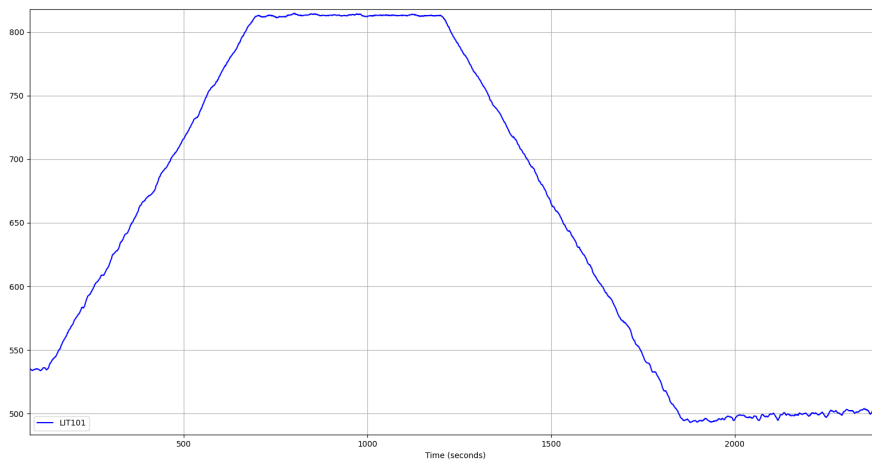
The second critical aspect concerns the **simulation of the physics of the liquid** inside the tanks: Simulink does not consider the fact that inside a tank that is filling (emptying) the liquid in it undergoes **fluctuations** which cause the level sensor not to see the water level constantly increasing (decreasing) or at most being stable at each point of detection. Figure 3.7 exemplifies more clearly with an example the concept just expressed: these oscillations cause a **perturbation** in the data.

This issue leads to the difficulty, on a real physical system, of **correctly calculating the trend of a measurement** by using the slope attribute: if this was obtained with a too low granularity, the trend will be oscillating between increasing and decreasing even when in reality this would be in general increasing (decreasing) or stable; on the other hand, if the slope was obtained with a too high granularity there is a loss of information and the trend may be "flattened" with respect to reality.

In the present case, the slope in the Simulink model was calculated statically *point-to-point*, thus with a granularity of one second: an averagely careful reader will have already guessed that this granularity is inapplicable to the real system in Figure 3.7b. As we will later see, we need to **operate on the data perturbations** to be able to obtain a suitable granularity and a correct calculation of the slope and consequently of the measurement trend.



(a)



(b)

Figure 3.7: Water physics compared: simulated physics in the Simulink model (a) and physics in a real system (iTrust SWaT) (b). Fluctuations in the tank level in (b), almost completely absent in (a), can be appreciated.

911 **Pre-processing** In the pre-processing phase, the authors make use of a
 912 Python script to merge all the datasets of the individual PLCs into a single
 913 dataset, remove the (supposedly) unused registers, and finally enrich the
 914 obtained dataset with additional attributes. These attributes are:

- 915 • the previous value of all registers

- 916 • some additional relative setpoints named $PLC_x_Max_safety$ and
917 $PLC_x_Min_safety$ (where x is the PLC number), which represent a
918 kind of alert on reaching the maximum and minimum water levels
919 of the tanks
- 920 • the measurement slope, that is, the trend of the water level in the
921 system tanks along the system cycles.

922 Merging the datasets of all individual PLCs into a single dataset rep-
923 resenting the entire system can be a sound practice if the system to be
924 analyzed is (very) small as is the testbed analyzed here, consisting of a few
925 PLCs and especially a few registers. If, however, the complexity of the
926 system increases, this type of merging can become counterproductive and
927 make it difficult to analyze and understand the data obtained in subse-
928 quent steps.

929 In short, there is no possibility to analyze only a subsystem and thus make
930 the analysis faster and more understandable. Moreover, a data gathering
931 can take up to days, and the analyst/attacker may need to make an anal-
932 ysis of the system isolating a precise time range, ignoring everything that
933 happens before and/or after: all of this, with the tool we have seen, cannot
934 be done.

935 Regarding the additional attributes, looking at the code of the script
936 that performs the enrichment, I observed that **some attributes were man-**
937 **ually inserted** after the merging phase: I am referring in particular to
938 the attributes $PLC_x_Max_safety$ and $PLC_x_Min_safety$, whose references
939 were moreover hardcoded into the script, and the *slope* whose calculation
940 method I mentioned in the previous paragraph about the testbed limita-
941 tions.

942 In the end, only the attribute *prev* related to the value at the previous point
943 of the detection is inserted automatically for all registers, moreover with-
944 out the possibility to choose whether this attribute should be extended to
945 all registers or only to a part.

Graphs and Statistical Analysis Describing the behavior of graphical analysis in Section 3.2.3 I had already mentioned that only one register plot at a time was shown and not, for example, a single window containing the charts of all registers entered by the user as input from the command line, such as in Figure 3.5.

While displaying charts for individual registers still provides useful information about the system such as the distinction between actuators and measurements and the general trend of the latter, single display does not allow one to catch, or at least makes it difficult, the relationship that exists between actuators and measurements, where it exists, because a view of the system as a whole is missing.

In this way, the risk is to make conjectures about the behavior of the system that may prove to be at least imprecises, if not inaccurates.

On the other hand, regarding the statistical analysis, two observations need to be made: the first is that for the given system, I personally was unable to appreciate the usefulness of the generated histogram, as it does not provide any particular new information that has not already been obtained from the graphical analysis (except maybe something marginal); the second observation is that precisely the plot of the histogram "hides" the statistical informations obtained: these are in fact shown on the terminal from which the script is launched, but to an uncaredful eye or one unfamiliar with the script's behavior they can easily be interpreted as simple debugging output, since at the same time the window containing the histogram plot is shown. In general, however, little statistical information is provided.

Business Process Mining and Analysis Concerning the data mining, this is a purely *ad hoc solution*, designed to work under special conditions: first, the timestamped dataset of the physical process and the one obtained after the packet sniffing operation of Modbus traffic on the network need to be synchronized and have the same granularity, in this case one event per second.

977 It is relatively easy, therefore, to find correspondences between Modbus
978 commands sent over the network and events occurring on the physical
979 system, such as state changes in actuators, due in part to the fact that the
980 number of communications over the network is really small (see Section
981 3.2.1). In a real system, network communications are much more numer-
982 ous and involve many more devices even in the same second: finding the
983 exact correspondence with what is happening in the cyber physical system
984 becomes much more difficult.

985 Since this is, as mentioned, an *ad hoc* solution, only the Modbus proto-
986 col is being considered: as widely used as this industrial protocol is, other
987 protocols that are widely used such as EtherNet/IP (see Section 2.3.1.2)
988 should be considered in order to extend the analysis to other industrial
989 systems that use a different communication network.

990 The other limiting aspect of the business process mining phase is the
991 **process mining software** used to generate the activity diagram. As men-
992 tioned in Section 3.2.5, the process mining software used by Ceccato et
993 al. is **Disco**: this is commercial software, with an academic license lasting
994 only 30 days (although free of charge), released for Windows and MacOS
995 operating systems only, which makes its use under Linux systems impos-
996 sible except by using emulation environments such as Wine.
997 For what is my vision and training as a computer scientist, it would have
998 been preferable to use a *cross-platform, freely licensed open source* software
999 alternative to Disco: one such software could have been **ProM Tools** [46],
1000 a framework for process mining very similar to Disco in functionality, but
1001 fitting the criteria just described, or use Python libraries such as **PM4PY**
1002 [47], which offer ready-to-use algorithms suitable for various process min-
1003 ing needs.

1004 **Invariants Inference and Analysis** The limitation in this case is princi-
1005 pally Daikon: this software is designed to compute the invariants of a soft-
1006 ware from its live execution or from a file containing its execution flow, not
1007 to find the invariants of a cyber physical system. Since there are currently

no better consolidated alternatives for inferring invariants, however, an attempt was still made to use Daikon as best as possible.

```

daikon version 5.8.14, released October 6, 2022; http://plse.cs.washington.edu/daikon.
Reading splitter info files
(read 1 spinfo file, 1 splitter)
Reading declaration files .aprogram.point::POINT: 1 of 1 splitters successful

(read 1 decls file)
Processing trace data; reading 1 dtrace file:

Warning: No non-obvious non-suppressed exclusive invariants found in
aprogram.point::POINT
Warning: No non-obvious non-suppressed exclusive invariants found in
aprogram.point::POINT
=====
aprogram.point::POINT
PLC2_MemoryRegisters_MW1 == PLC3_MemoryRegisters_MW1
PLC1_MemoryRegisters_MW0 == 40.0
PLC1_MemoryRegisters_MW1 == 80.0
PLC1_Coils_QX00 one of { 0.0, 1.0 }
PLC1_Coils_QX01 one of { 0.0, 1.0 }
PLC1_Coils_QX02 one of { 0.0, 1.0 }
PLC2_MemoryRegisters_MW1 == 10.0
PLC2_MemoryRegisters_MW2 == 20.0
PLC2_Coils_QX00 one of { 0.0, 1.0 }
PLC3_InputRegisters_IW0 >= 0.0
PLC3_Coils_QX00 one of { 0.0, 1.0 }
PLC3_Coils_QX02 one of { 0.0, 1.0 }
prev_PLC1_Coils_QX00 one of { 0.0, 1.0 }
prev_PLC1_Coils_QX01 one of { 0.0, 1.0 }
prev_PLC2_Coils_QX00 one of { 0.0, 1.0 }
prev_PLC3_InputRegisters_IW0 >= 0.0
prev_PLC3_Coils_QX00 one of { 0.0, 1.0 }
prev_PLC3_Coils_QX02 one of { 0.0, 1.0 }
PLC1_Max_safety == 77.0

```

Figure 3.8: Example of Daikon's output

The biggest problem with Daikon applied to the computation of invariants of an industrial system is the difficult reading of the resulting output: the software in fact returns a very long list of invariants, one invariant per line, many of no use and without correlating invariants that may have common features or deriving additional information from them. The process of screening and recognizing the significant invariants, as well as the correlation between them, must be done by a human: certainly not an easy task given the volume of invariants one could theoretically be faced with (hundreds and hundreds of invariants). An example of Daikon's output

1019 can be seen in Figure 3.8.

1020 The bash script used in this phase of the analysis does not help at all
1021 in deriving significant invariants more easily: it merely launches Daikon
1022 and saves its output to a text file by simply redirecting the stdout to file.
1023 No data reprocessing is done during this step. In addition, if a condition
1024 is to be specified to Daikon before performing the analysis, it is necessary
1025 each time to edit the .spinfo file by manually entering the desired rule, an
1026 inconvenient operation when multiple analyses are to be performed with
1027 different conditions each time.

Chapter 4

A framework to improve Ceccato et al.'s work.

1028 **I**N CHAPTER 3, I presented the state of the art of *process comprehension* of
1029 an Industrial Control System (ICS) focusing later on the methodology
1030 proposed by Ceccato et al. [6][Section 3.2], explaining what it consists of,
1031 its practical application on a testbed, and most importantly highlighting
1032 its limitations and critical issues (see Section 3.2.7).

1033 In this chapter I will present **my proposals to improve the methodol-**
1034 **ogy** presented in the previous chapter, overcoming (or at least trying to do
1035 so) the criticalities mentioned above by almost completely rewriting the
1036 original framework, enhancing its functionalities and inserting new ones
1037 where possible, while keeping its general structure and approach: the sys-
1038 tem analysis will in fact consist of the same four steps as in the original
1039 methodology (Data Pre-processing, Graph and Statistical Analysis, Busi-
1040 ness Process Mining and Invariants Inference), but each of them will be
1041 deeply revised in order to provide a richer, clearer and more complete
1042 process comprehension of the industrial system to be analyzed and its be-
1043 havior.

1044 As it may have already been noted, my proposals do not involve im-
1045 proving the data gathering phase: this is due simply to the fact that the
1046 novel framework will not be tested on the same case study used by Cec-
1047 cato et, al. (Section 3.2.1), but on a different case study, the ITrust SWaT

1048 system [29], of which (some) datasets containing the execution trace of
1049 the physical system and the network traffic scan are already provided by
1050 iTrust itself. For more details about this case study, see Chapter 5.

1051 4.1 Phase 0: General Improvements

1052 The implementation of the novel framework for ICSs analysis starts
1053 from several assumptions:

- 1054 1. it must be implemented in a **single programming language**
- 1055 2. it must be **independent of the system** to be analyzed
- 1056 3. It must provide greater **flexibility and ease of use** for the user at
1057 every stage

1058 In the following subsections, these three points will be discussed in more
1059 detail.

1060 4.1.1 Single Programming Language

1061 The original tool was implemented using various programming lan-
1062 guages in each of the different phases: from Python up to Java, passing
1063 through Bash scripting.

1064 In my opinion, this heterogeneity makes it more difficult and less intuitive
1065 for the user to operate on the tool: moreover, the use of multiple technolo-
1066 gies makes it more difficult to maintain the code and add new features,
1067 particularly if only a single person is managing the code (he/she might be
1068 proficient in one language, but little of the others).

1069 For these reasons, I decided to use a single programming language, to
1070 ensure homogeneity to the framework and ease of use and maintenance
1071 of the code for anyone who wants to manage it in the future: I chose to
1072 use Python, because of its simplicity and easy readability combined with
1073 its versatility and powerfulness: moreover, Python can count on a massive
1074 number of available libraries and packages that meet all kinds of needs.

4.1.2 System Independence

One of the biggest limitations of Ceccato et al.'s tool that I highlighted in Section 3.2.7 is the fact that it is **highly dependent on the testbed used**: that is, it is *not* possible to configure any of the tool's parameters to analyze different industrial systems.

To overcome this issue and make my framework independent of the system to be analyzed, also eliminating all references to hardcoded variables and values present in the previous tool, I decided to use a **general configuration file**, named *config.ini*, in which the user can, at will, customize all the parameters necessary to perform the analysis of the targeted system.

General Configuration File *config.ini* The configuration file *config.ini* for the framework I am presenting in this thesis is intended, as mentioned, to make it customizable in order to fit a variety of different systems and allow for their analysis. Here the user can configure general parameters and options, such as paths to read from or write files to, or related to individual analysis phases.

The file is divided into sections, each covering a different aspect of the configuration: each section contains user-customizable constants that will then be called within the Python scripts that constitute the framework. An example can be appreciated in Listing 4.1:

```
[PATHS]
root_dir = /home/marcuzzo/UniVr/Tesi
project_dir = %(root_dir)s/PLC-RE
input_dataset_directory = %(root_dir)s/
    ↳ datasets_SWaT/2015
net_csv_path = %(root_dir)s/datasets_SWaT/2015/
    ↳ Network_CSV

[DEFAULTS]
dataset_file = PLC_SWaT_Dataset.csv
granularity = 10
number_of_rows = 20000
```

```
1107     skip_rows = 100000
1108
1109     [DAIKON]
1110     daikon_dir = daikon
1111     daikon_invariants_dir = %(daikon_dir)s/
1112     ↪ Daikon_Invariants
1113     daikon_results_dir = %(daikon_invariants_dir)s/
1114     ↪ results
1115     daikon_results_file_original = daikon_results_full.
1116     ↪ txt
1117     inv_conditions_file = Inv_conditions.spinfo
1118     max_security_pct_margin = 1
1119     min_security_pct_margin = 2
1120
1121     ...
```

Listing 4.1: Example of config.ini file

1122 4.1.3 Flexibility and Ease on Use

1123 The lack of flexibility and ease of use in a tool can be a significant dis-
1124 advantage, limiting its effectiveness and making it challenging for the user
1125 to get the desired outcomes. The original tool suffered from these limita-
1126 tions, with users having to run scripts from the command line, with little
1127 to no options or parameters available to customize the analysis. As a re-
1128 sult, the tool was not user-friendly and lacked the flexibility to adapt to
1129 specific user needs.

1130 To settle these issues, I enhanced the command-line interface in the
1131 novel framework by adding new options and parameters. These new fea-
1132 tures provide the user with greater flexibility, enabling to specify param-
1133 eters and options that allow for more in-depth analysis and focused re-
1134 sults analyzing data more effectively and efficiently. With these enhance-
1135 ments, the framework has become more user-friendly, reducing the learn-
1136 ing curve and making it more accessible to a wider range of users.

This, in turn, makes the framework more valuable and useful, increasing its adoption and effectiveness across a range of industries and applications.

Moreover, with new options and parameters users no longer have to rely solely on the command line interface, which can be challenging and intimidating for those with limited technical expertise. Instead, users can now access a range of customizable options and parameters, making the tool more intuitive and user-friendly.

Overall, the enhancements made to the framework represent a significant step forward in making it more effective, efficient, and user-friendly.

4.2 Phase 1: Data Pre-processing

Data Pre-processing phase is probably the most delicate and significant one: depending on how large the industrial system to be analyzed is, the data collected, and how it is enriched using the additional attributes, the subsequent system analysis will provide more or less accurate outcomes.

The previous tool has many limitations, especially at this stage: it is not possible to isolate a subsystem (either on a temporal basis or on the number of PLCs to be analyzed - the system is considered in its whole), and many of the additional attributes were actually added manually: moreover, for those automatically entered, there is no way to specify which register type to associate the additional attribute with.

All this, combined with the fact that in the tool code many references to attributes and registers are hardcoded, makes the analysis of the system much more difficult and the obtained results less accurate in terms of quantity and quality.

In the novel framework these problems have been overcome by introducing the possibility, starting from the datasets of individual PLCs obtained from data gathering process, to select a subsystem from the command line both on a temporal basis and of the PLCs to be considered;

1166 I have also redesigned the whole process of enrichment of the resulting
1167 dataset, eliminating the manual entry of additional attributes and giving
1168 the user the possibility to be able to decide which type of additional at-
1169 tribute to associate with a given register.

1170 In addition to this, at the end of the pre-processing operation, it is possi-
1171 ble to perform a brief preliminary analysis of the obtained dataset in order
1172 to estimate which registers are connected to actuators, which to measure-
1173 ments, and which represent hardcoded relative setpoints or constants: this
1174 operation also makes it possible to be able to refine the enrichment step by
1175 setting the relevant parameters in the *config.ini* file

1176

1177 In the next sections we will look in more detail at what has been accom-
1178 plished.

1179 4.2.1 Subsystem Selection

1180 In the previous tool, the datasets in CSV format referring to each single
1181 PLC are placed in a fixed directory (hardcoded in the script) from which
1182 the dedicated script later perform merge and enrichment of them all, re-
1183 sulting in a single dataset representing the entire process trace of the in-
1184 dustrial system as an output. As mentioned, the script makes no provision
1185 to choose the individual PLCs to be analyzed, nor to decide on a temporal
1186 range over which to perform the analysis: in fact, it may happen that dur-
1187 ing the period of scanning and data gathering there is a so-called *transient*,
1188 i.e., a general state in which the industrial system is still initializing before
1189 actually reaching full operation; or, more simply, there is the need to ana-
1190 lyze the process of only a specific part of the industrial system in a certain
1191 period of interest: whatever the motivation, the lack of elasticity and op-
1192 tions to provide to the user makes the analysis much more complex than
1193 it might be, affecting even the later phases, as the number of variables to
1194 be analyzed becomes enormously higher.

1195 In addition, it is not possible to specify an output CSV file where to save
1196 the resulting dataset: at each dataset creation and enrichment operation,

therefore, the resultant file will be overwritten. This is very awkward when making comparisons between two different execution traces, for example, unless the files are renamed manually.

Let's see how all these issues were solved in the novel framework I developed: first of all, in the general *config.ini* file there are some general default settings about paths, and among them the one concerning the directory where to place the datasets of the individual PLCs to be processed. In addition to this option, there are other ones that define further aspects related to the operations performed in this phase. Listing 4.2 shows the settings in question:

```
[PATHS]
root_dir = /home/marcuzzo/Univr/Tesi
project_dir = %(root_dir)s/PLC-RE
input_dataset_directory = %(root_dir)s/
    ↳ datasets_SWaT/2015
net_csv_path = %(root_dir)s/datasets_SWaT/2015/
    ↳ Network_CSV

[DEFAULTS]
dataset_file = PLC_SWaT_Dataset.csv # Default
    ↳ output dataset
granularity = 10 # slope granularity
number_of_rows = 20000 # Seconds to consider
skip_rows = 100000 # Skip seconds from beginning
```

Listing 4.2: Paths and parameters for the Pre-processing phase in config.ini file

Concurrently, the same options can be specified by the user via the command line of the new Python script (named *mergeDatasets.py* and contained in the directory pre-processing of the project) and will override the default ones found in *config.ini*. These options are:

- **-s or --skiprows:** seconds to jump from the beginning of the file. This option is useful in case the system has an initial transient or to start the analysis from a certain point in the dataset

- 1228 • **-n** or **--nrows**: reference temporal period in seconds (rows) for the
1229 analysis from the beginning of the dataset or from the point specified
1230 in the **-s** option or in the corresponding setting in *config.ini*.
1231 This option makes a **selection** on the data of the dataset.
- 1232 • **-p** or **--plcs**: PLCs to be merged and enriched. The user can specify
1233 the desired PLCs by indicating the CSV file names of the associated
1234 datasets with no limitations on number.
1235 This option makes a **projection** on the data of the dataset.
- 1236 • **-d** or **--directory**: performs the merge and enrichment of all CSV files
1237 contained in the directory specified by user, overriding the default
1238 setting in *config.ini*. It is in fact the old functionality of the previous
1239 tool, maintained here to give the user more flexibility and convenience in case he wants to perform the analysis on the whole system.
1240 This is also the default behavior in case the **-p** option is not specified.
1241
- 1242 • **-o** or **--output**: specifies the name of the file in which the obtained
1243 dataset will be saved. It must necessarily be a file in CSV format.
- 1244 • **-g** or **--granularity**: specifies a granularity that will be used to calculate the measurement slope during the dataset enrichment phase.
1245 We will discuss this later in Section 4.2.2.
1246

1247 **4.2.2 Dataset Enrichment**

1248 **4.2.3 Brief Analysis of the Subsystem**

1249 **4.3 Phase 2: Graphs and Statistical Analysis**

1250 **4.4 Phase 3: Invariants Analysis**

1251 **4.4.1 Invariants Generation**

1252 **4.5 Phase 4: Business Process Analysis**

Chapter 5

Case study: the iTrust SWaT System

Chapter **6**

Our framework at work: reverse engineering of
the SWaT system

6.1 Pre-processing

6.2 Graph Analysis

6.2.1 Conjectures About the System

6.3 Invariants Analysis

6.3.1 Actuators Detection

6.3.2 Daikon Analysis and Results Comparing

6.4 Extra information on the Physics

6.5 Business Process Analysis

Chapter 7

Conclusions

7.1 Discussions

7.2 Guidelines

7.3 Future work

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