

**UNIVERSITY OF VERONA**

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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



# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Contribution . . . . .	1
1.2	Outline . . . . .	1
<b>2</b>	<b>Background</b>	<b>3</b>
2.1	Industrial Control Systems in a nutshell . . . . .	3
2.2	ICS components . . . . .	4
2.2.1	SCADA systems . . . . .	4
2.2.1.1	SCADA architecture . . . . .	5
2.2.2	Field devices . . . . .	7
2.2.3	Programmable Logic Controllers . . . . .	7
2.2.3.1	PLC Architecture . . . . .	8
2.2.3.2	PLC Programming . . . . .	9
2.2.3.3	PLC Security . . . . .	10
2.2.4	Remote Terminal Units . . . . .	11
2.2.5	Human-Machine Interface . . . . .	12
2.2.6	Cybersecurity components . . . . .	12
2.3	Communication Networks . . . . .	13
2.3.1	ICS Communication Protocols . . . . .	13
2.3.1.1	Modbus . . . . .	13
2.3.1.2	EtherNet/IP . . . . .	17
2.3.1.3	Common Industrial Protocol (CIP) . . . . .	19
2.3.1.4	Other Protocols . . . . .	20

<b>3</b>	<b>State of the Art</b>	<b>21</b>
3.1	Literature on Process Comprehension . . . . .	22
3.2	Ceccato et al.'s methodology for analyzing water-tank systems . . . . .	24
3.2.1	Testbed . . . . .	25
3.2.2	Scanning of the System and Data Pre-processing . . .	28
3.2.3	Graphs and Statistical Analysis . . . . .	30
3.2.4	Invariants Inference and Analysis . . . . .	31
3.2.5	Business Process Mining and Analysis . . . . .	33
3.2.6	Application . . . . .	34
3.2.7	Limitations . . . . .	38
<b>4</b>	<b>A framework to improve Ceccato et al.'s work.</b>	<b>39</b>
4.1	Phase 1: Pre-processing . . . . .	39
4.2	Phase 2: Graph Analysis . . . . .	39
4.3	Phase 3: Invariants Analysis . . . . .	39
4.3.1	Invariants Generation . . . . .	39
4.4	Phase 4: Business Process Analysis . . . . .	39
4.5	Extra Information on the Physics . . . . .	39
<b>5</b>	<b>Case study: the iTrust SWaT System</b>	<b>41</b>
<b>6</b>	<b>Our framework at work: reverse engineering of the SWaT system</b>	<b>43</b>
6.1	Pre-processing . . . . .	43
6.2	Graph Analysis . . . . .	43
6.2.1	Conjectures About the System . . . . .	43
6.3	Invariants Analysis . . . . .	43
6.3.1	Actuators Detection . . . . .	43
6.3.2	Daikon Analysis and Results Comparing . . . . .	43
6.4	Extra information on the Physics . . . . .	43
6.5	Business Process Analysis . . . . .	43
<b>7</b>	<b>Conclusions</b>	<b>45</b>
7.1	Discussions . . . . .	45



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7.2 Guidelines . . . . .	45
7.3 Future work . . . . .	45
<b>List of Figures</b>	<b>47</b>
<b>List of Tables</b>	<b>49</b>
<b>References</b>	<b>51</b>



## Introduction

**L**OREM 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.

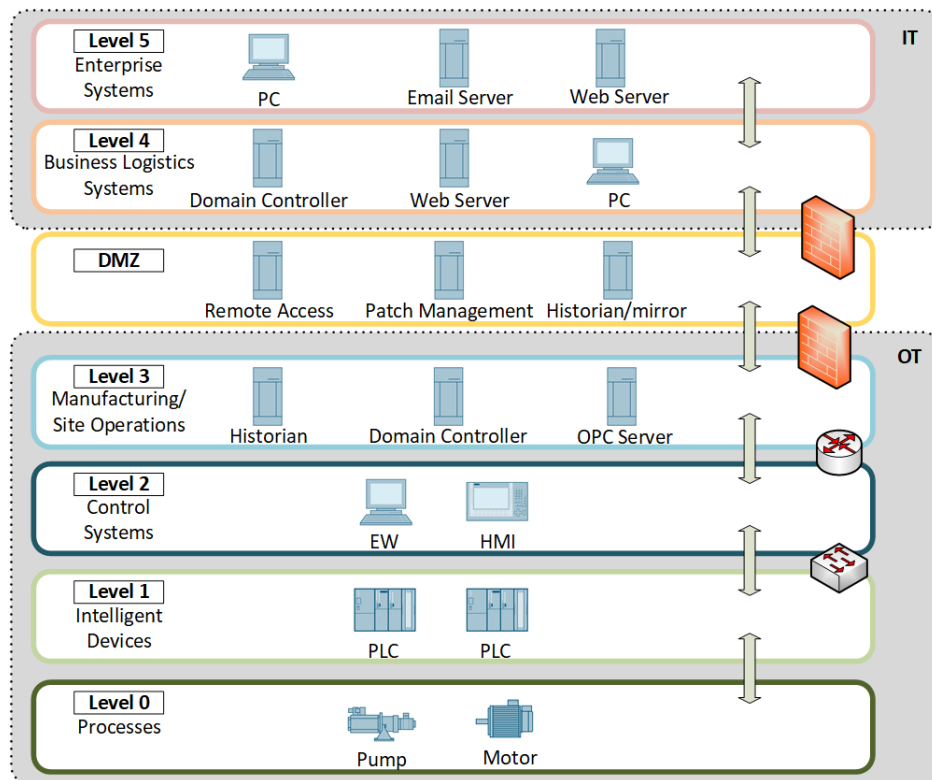


Figure 2.1: SCADA architecture schema

- 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]:

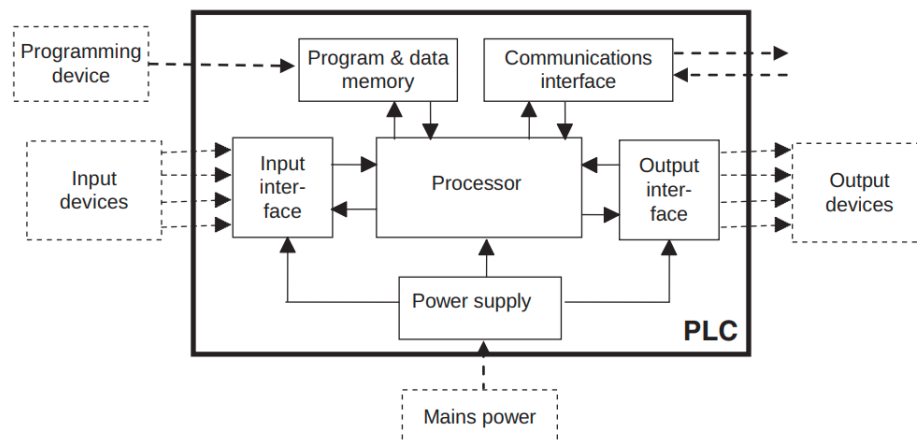


Figure 2.2: PLC architecture

- **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.

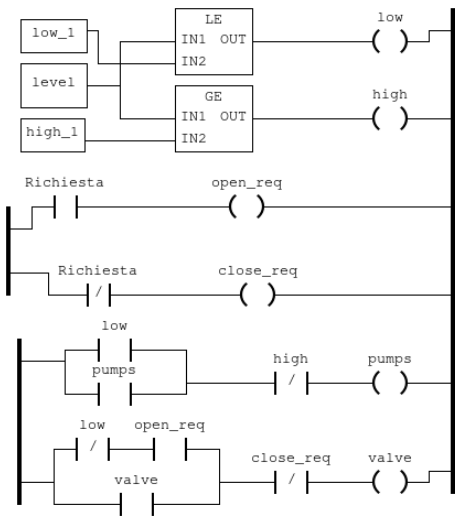
154 Graphical languages are more simple and immediate comparing to the  
155 textual ones and are preferred by programmers because of their features  
156 and simplicity, in particular the **Ladder Logic programming** (see Figure  
157 2.4 for a comparison).

```
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.

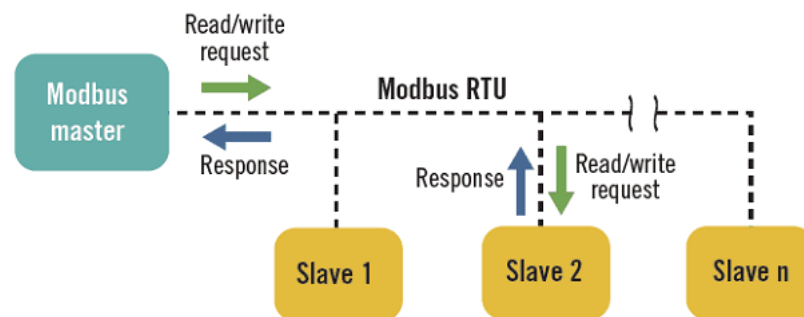


Figure 2.5: Modbus Request/Response schema

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.

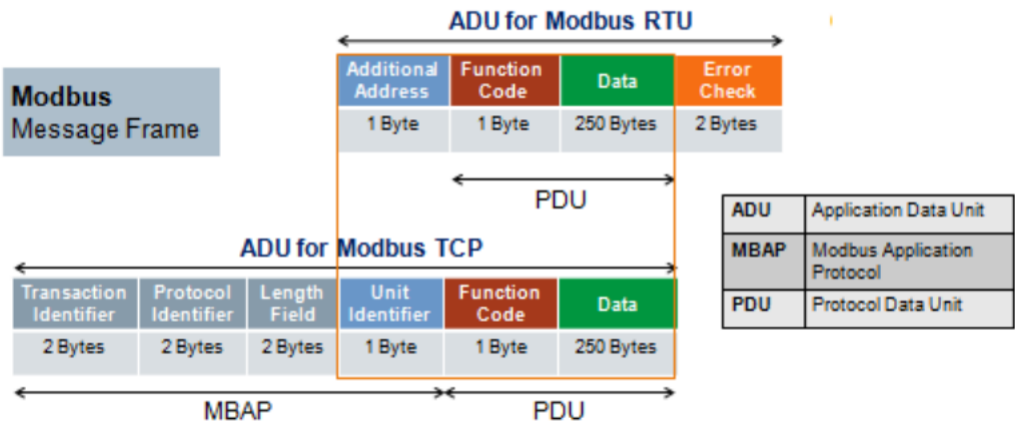


Figure 2.6: Modbus RTU frame and Modbus TCP frame

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. **invariant 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.

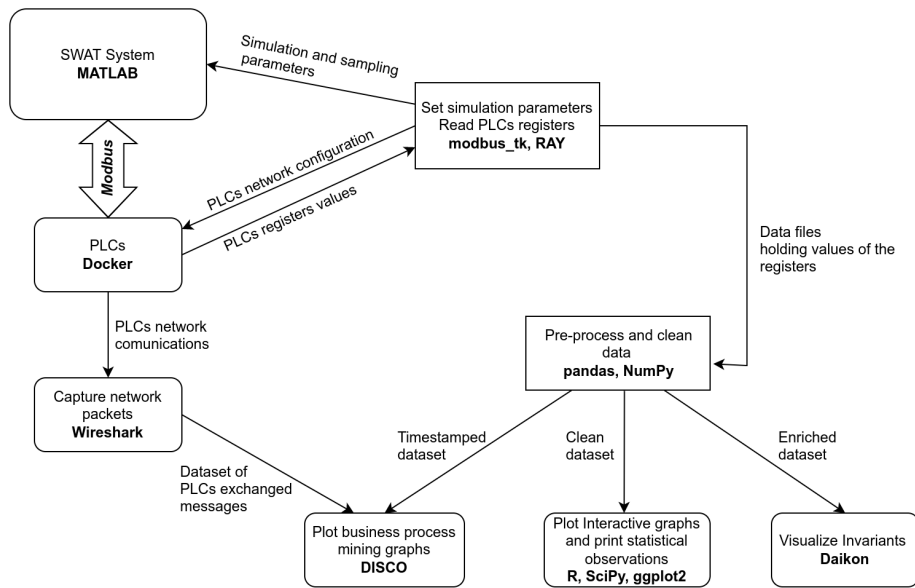


Figure 3.1: Overview

### 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

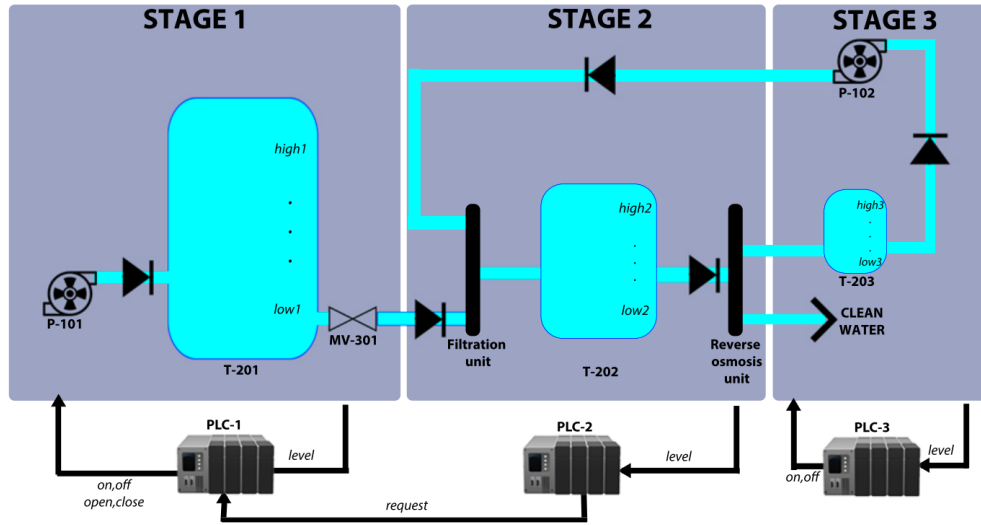


Figure 3.2: The simplified SWaT system used for running Ceccato et al. methodology

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 data

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).

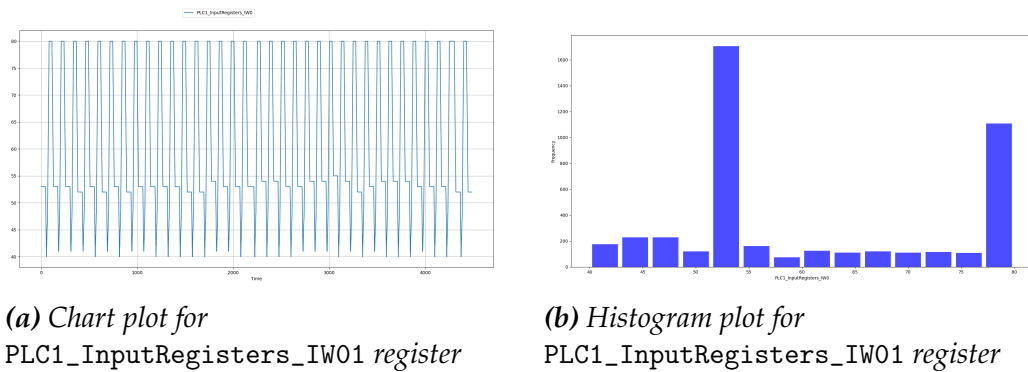


Figure 3.3: Output graphs from graph analysis

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.  
 618 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 designed to find the invariants of a program, with various supported programming languages, starting from the direct execution of the program itself or passing as input the execution run (typically a file in CSV format):

the authors of the paper tried to apply it by analogy also to the execution runs of a cyber physical system, to extract the invariants of this system.

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

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

Therefore, Daikon is fed with the no-timestamp enriched dataset obtained in the pre-processing phase (in the paper, the timestamped dataset is erroneously mentioned as input): a simple bash script launches Daikon (optionally specifying the desired condition for analysis in the *.spinfo* file), which output is simply redirected to a text file containing the general invariants of the system (i.e., valid regardless of any custom condition specified), those generated based on the custom condition in the *.spinfo* file, and those generated based on the negation of the condition. When the analysis is finished, the user is asked to enter the name of a registry to view its related invariants.

663

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

- measurements bounded by some setpoint
- Actuators state changes occurred in the proximity of setpoints or, vice versa, proximity of setpoints upon the occurrence of a regular actuator state change
- state invariants of some actuator correspond to a specific trend in the evolution of the measurement (ascending, descending, or stable) or, vice versa, the measurement trend corresponds to a specific state 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.

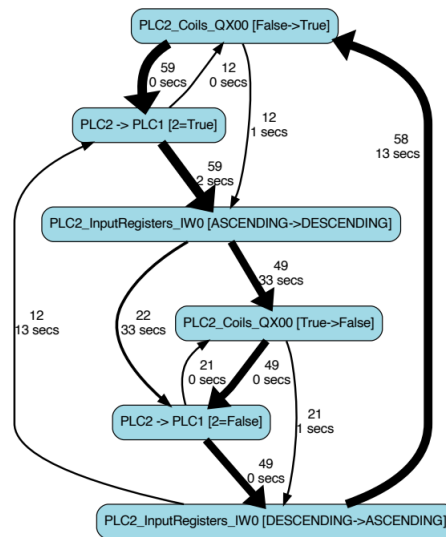


Figure 3.4: An example of Disco generated activity diagram for PLC2

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:

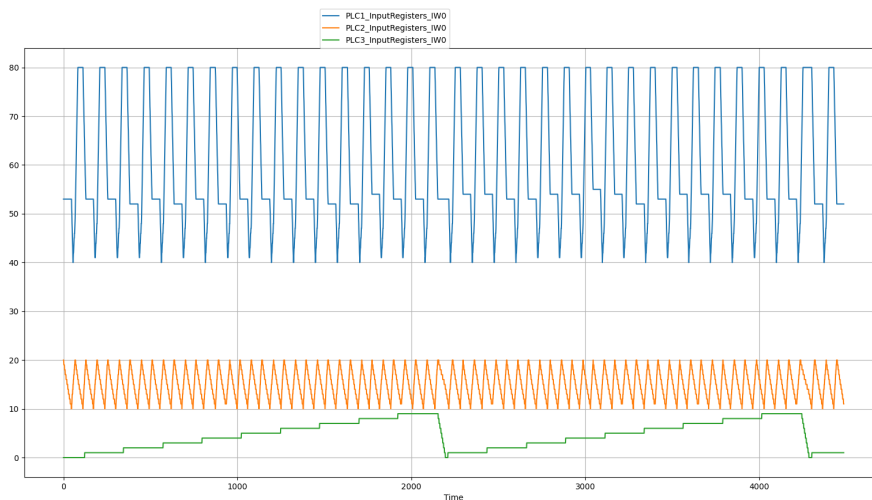
717 *Property 1:* PLC1\_MemoryRegisters\_MW0, PLC1\_MemoryRegisters\_MW1,  
 718 PLC2\_MemoryRegisters\_MW0, PLC2\_MemoryRegisters\_MW1,  
 719 PLC3\_MemoryRegisters\_MW0 and PLC3\_MemoryRegisters\_MW1

registers contain constant integer values (40, 80, 10, 20, 0, 10 respectively)<sup>1</sup>. 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

<sup>1</sup>From 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

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.

**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.

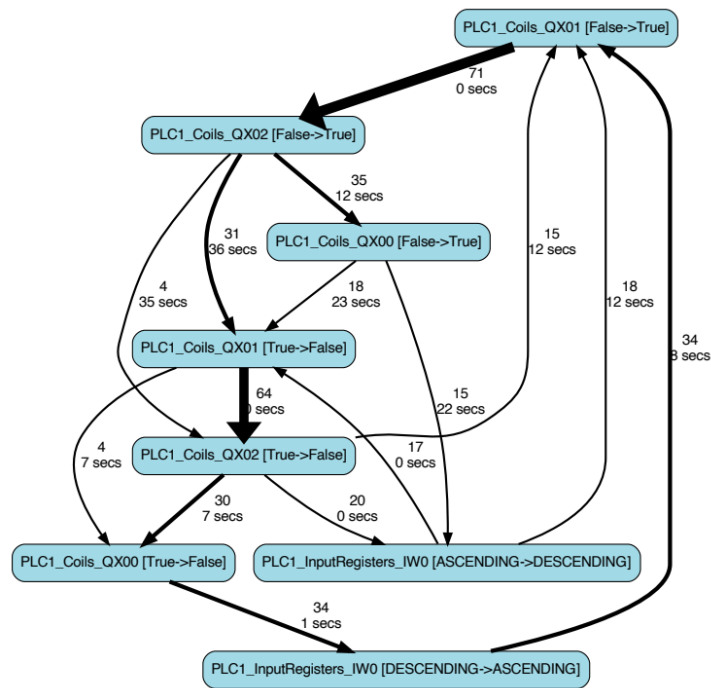
Through analysis of the activity diagrams shown in Figure 3.6, drawn through Disco, we derive the following properties and conjectures:

*Property 4:* PLC2 sends messages to PLC1 (see Figure 3.6b) which are recorded to PLC1\_Coils\_QX02.

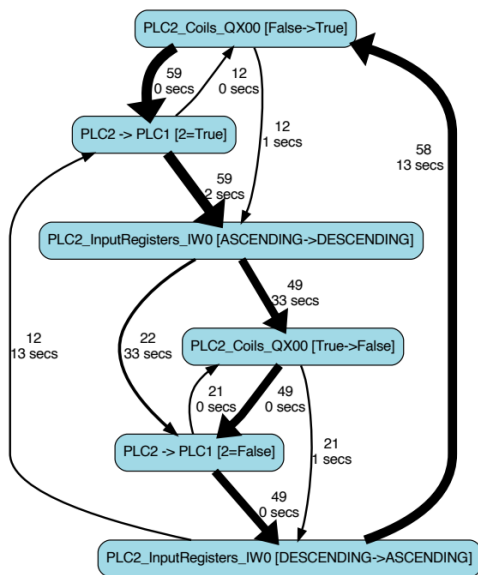
*Conjecture 3:* PLC2\_Coils\_QX00 determines the trend in tank T-202 (Figure 3.6b).

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**.

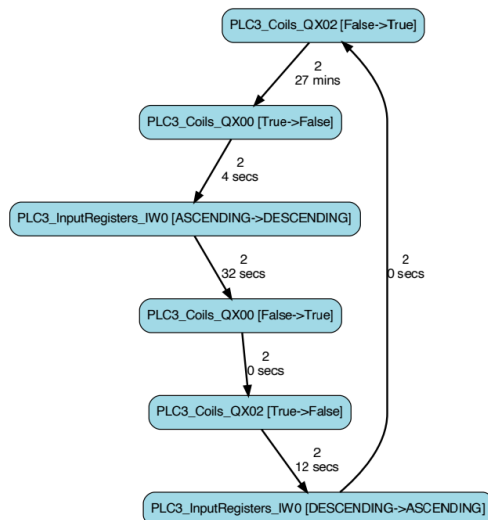
*Conjecture 4:* If PLC1\_Coils\_QX00 change his value to *True*, trend in tank T-201, related to PLC1\_InputRegisters\_IW0 and controlled by PLC1, become **ascending** (see Figure 3.6a)



(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, re-  
766 lated 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

### 784 3.2.7 Limitations



# Chapter **4**

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

## **4.1 Phase 1: Pre-processing**

## **4.2 Phase 2: Graph Analysis**

## **4.3 Phase 3: Invariants Analysis**

### **4.3.1 Invariants Generation**

## **4.4 Phase 4: Business Process Analysis**

## **4.5 Extra Information on the Physics**



# 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**





## List of Figures

2.1	SCADA architecture schema . . . . .	6
2.2	PLC architecture . . . . .	8
2.3	PLC communication schema . . . . .	9
2.4	Comparison between ST language and Ladder Logic . . . . .	10
2.5	Modbus Request/Response schema . . . . .	14
2.6	Modbus RTU frame and Modbus TCP frame . . . . .	15
2.7	Example of packet sniffing on the Modbus protocol . . . . .	17
2.8	OSI model for EtherNet/IP stack . . . . .	18
3.1	Overview . . . . .	25
3.2	The simplified SWaT system used for running Ceccato et al. methodology . . . . .	26
3.3	Output graphs from graph analysis . . . . .	30
3.4	An example of Disco generated activity diagram for PLC2 . . . . .	33
3.5	Execution traces of InputRegisters_IW0 on the three PLCs . . . . .	35
3.6	Business process with states and Modbus commands for the three PLCs . . . . .	37



## List of Tables

2.1	Modbus Function Codes list . . . . .	16
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## References

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