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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

Chapter 1

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

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

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

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

ICSs are becoming increasingly connected to the internet and other networks, which has led to increased concerns about their security. Industrial 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, ICSs are increasingly seen as a potential target for cyber attacks, which could have serious consequences for the safe and reliable operation of critical infrastructure.

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

2.2 ICS components

Industrial control systems (ICSs) are composed of several different components that work together to monitor and control industrial processes.

2.2.1 SCADA systems

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

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

The SCADA software processes, distributes, and displays the data, helping operators and other employees analyze the data and make important decisions.

SCADA systems are known for their ability to monitor and control 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 (**Intlligent 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.

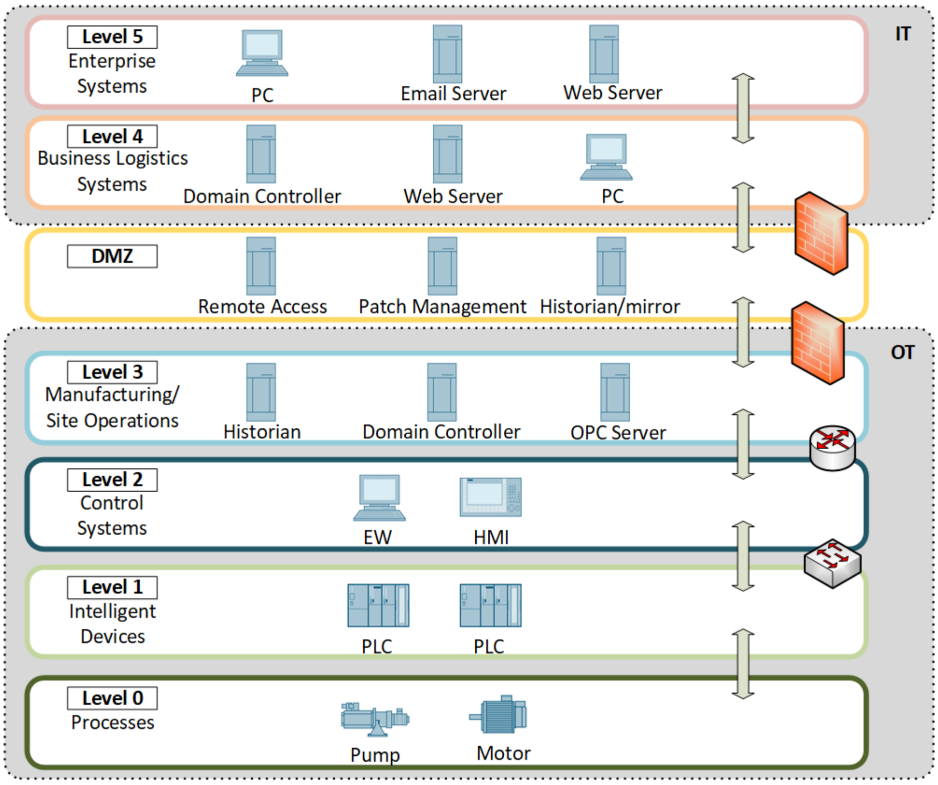


Figure 2.1: *SCADA architecture schema*

- Level 3 (**Manufactoring/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 Manufactoring/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 Enteprise 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 manifacturing 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 a 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 ouputs, without reconfiguring hardware as in relay systems when a reconfiguration occours.

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]:

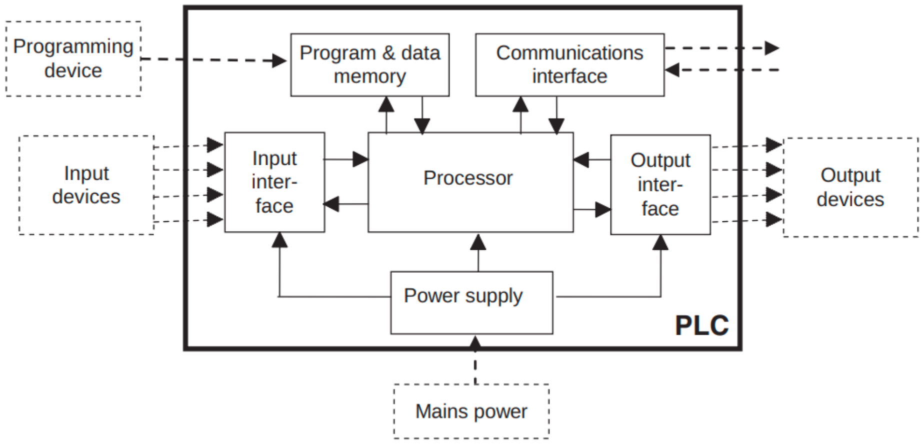


Figure 2.2: *PLC architecture*

- **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.

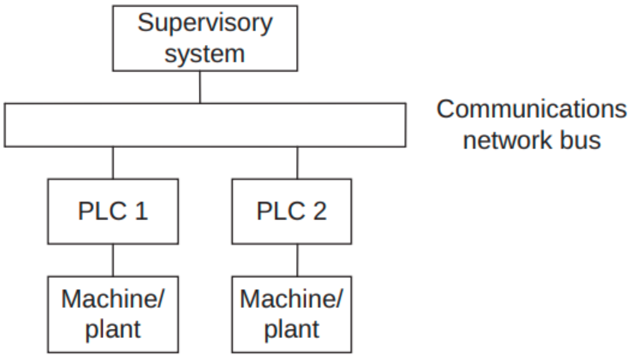


Figure 2.3: *PLC communication schema*

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

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

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

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

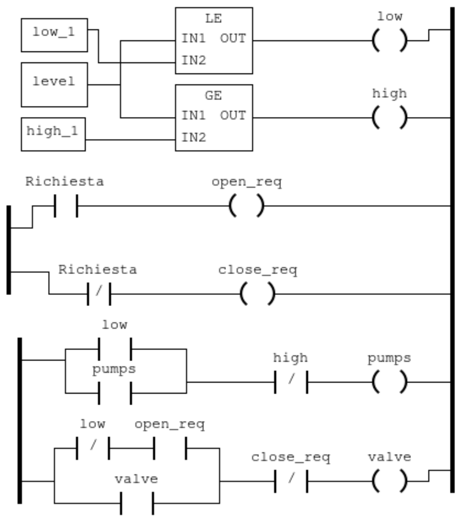
```
PROGRAM PLC1
  VAR
    level AT %IW0 : INT;
    Richiesta AT %QX0.2 : BOOL;
    request AT %IW1 : INT;
    pumps AT %QX0.0 : BOOL;
    valve AT %QX0.1 : BOOL;
    low AT %MX0.0 : BOOL;
    high AT %MX0.1 : BOOL;
    open_req AT %MX0.3 : BOOL;
    close_req AT %MX0.4 : BOOL;
    low_1 AT %MW0 : INT := 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(Richiesta);
  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*

2.2.3.3 PLC Security

PLCs were originally designed to operate as closed systems, not connected 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.

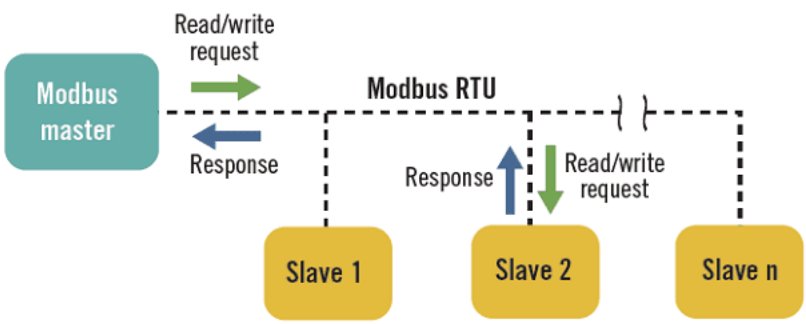


Figure 2.5: *Modbus Request/Response schema*

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].

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

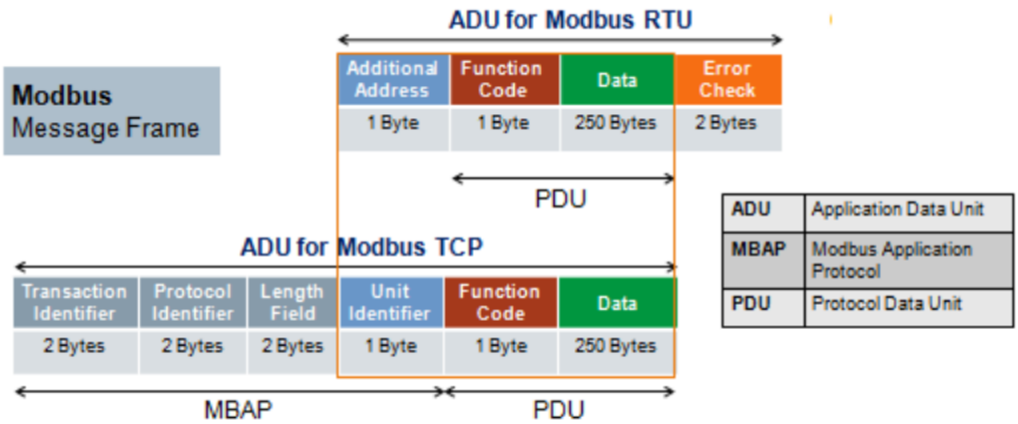


Figure 2.6: *Modbus RTU frame and Modbus TCP frame*

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

- *Coil*: binary type, read/write accessible by both masters and slaves
- *Discrete Input*: binary type, accessible in read-only mode by masters and in read/write mode by slaves
- *Analog Input*: 16 bits in size (word), are accessible in read-only mode by masters and in read/write mode by slaves
- *Holding Register*: 16 bits in size (word), accessible in read/write mode by both masters and slaves. Holding Registers are the most commonly used registers for output and as general memory registers.

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

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

Two types of Function Codes exists: for data access and for diagnostic 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*

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

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

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

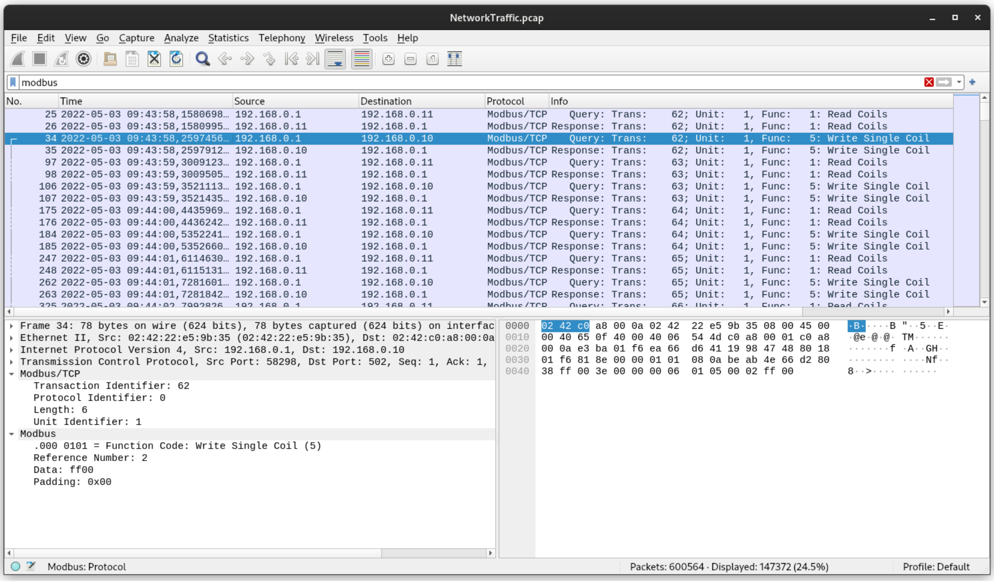


Figure 2.7: Example of packet sniffing on the Modbus protocol

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).

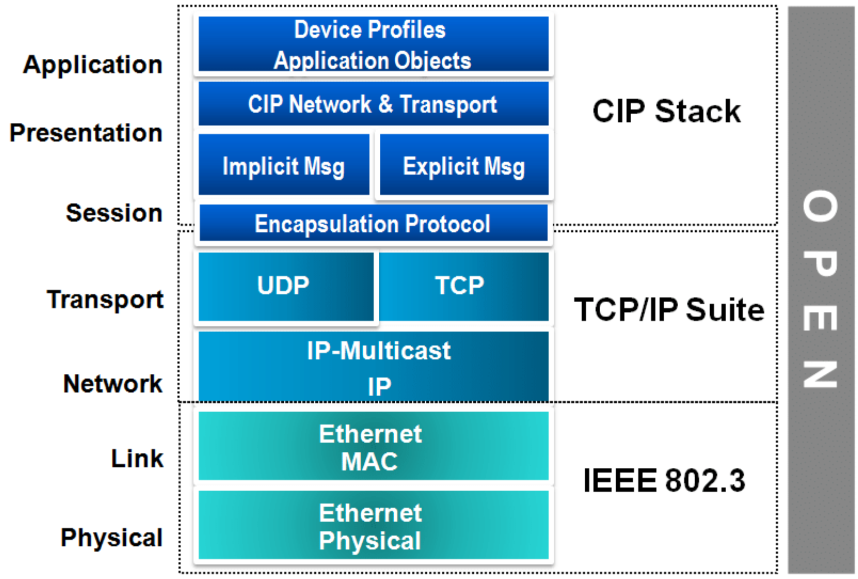


Figure 2.8: OSI model for EtherNet/IP stack

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

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

- **unconnected messaging:** used during the connection establishment phase and for infrequent, low priority, explicit messages. Unconnected messaging uses TCP/IP to transmit messages across the network 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

- **ControlNet**, adaptation to *Concurrent Time Domain Multiple Access* (CTDMA) technologies
- **DeviceNet**, adaptation to *Controller Area Network* (CAN) technologies
- **CompoNet**, adaptation to *Time Division Multiple Access* (TDMA) technologies

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

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

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

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 Maniatakos [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 constrains 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 comprenension 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.

In the next section I will examine this latest work in more detail, which will be the basis for my work and thus the subsequent chapters of this thesis.

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

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

The first objective of this black box analysis is to associate the various memory registers of the target PLCs with a correspondence to the basic concepts of an ICS such as sensors (otherwise known as measurements), actuators, setpoints (range of values of a physical variable), network communications, and so on.
This is performed by analyzing the different types of memory registers associated with the Modbus protocol and trying to figure out what type of data they may contain.
The second objective is to put in relation the runtime evolution of these basic concepts.

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

1. **scanning of the system and data pre-processing**: data gathering is performed to generate the data logs of PLCs registers

2. **graphs and statistical analysis**: provides information about the memory registers using graphs and statistical data derived from the gathered data

3. **invariants inference and analysis**: generates system invariants and 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.

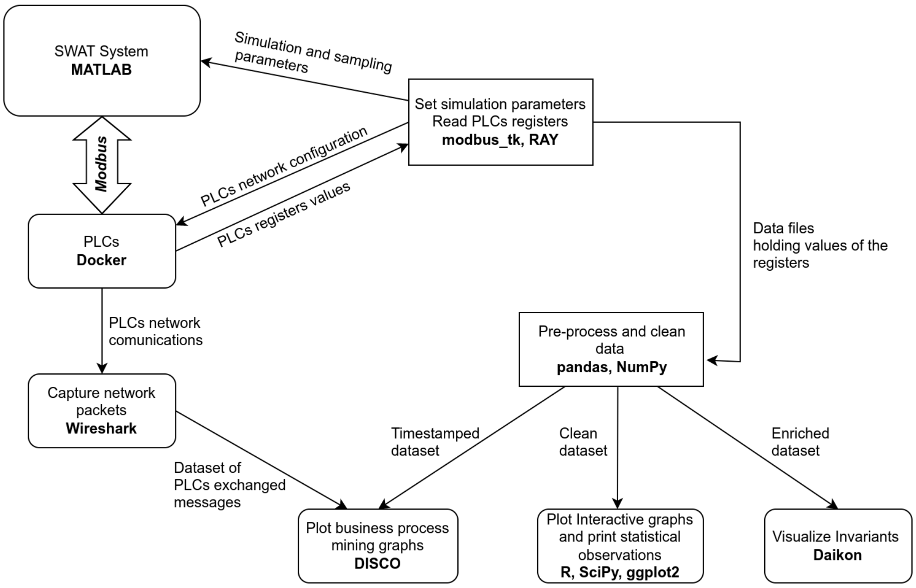


Figure 3.1: *Overview*

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

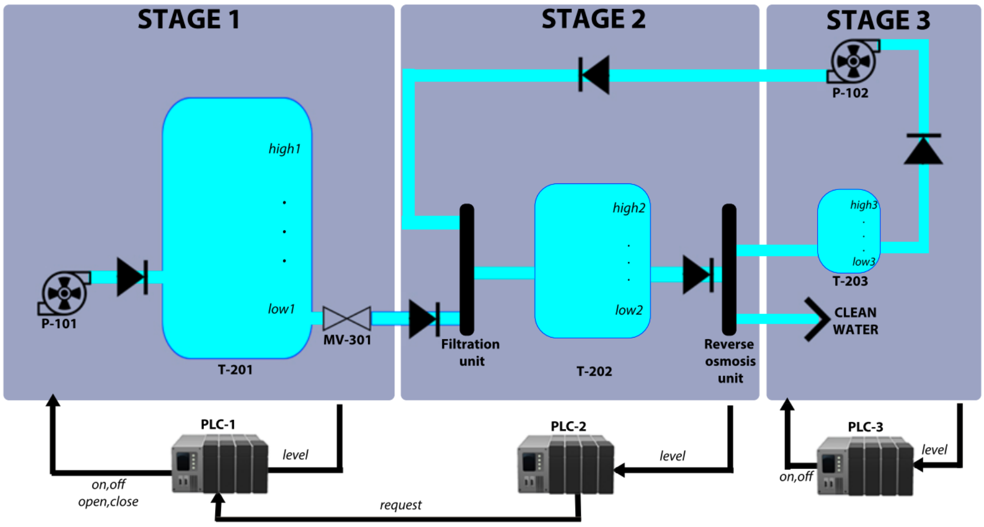


Figure 3.2: *The simplified SWaT system used for running Ceccato et al. methodology*

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

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

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

As mentioned, each stage corresponds to a PLC that controls it, PLC1, PLC2 and PLC3, respectively. Let us briefly see the behavior of each of them:

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

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

PLC2 PLC2 monitors the level of tank T-202, behaving accordingly depending on the level of water in it. Here again there are three cases to consider:

- if the water level reaches the *low setpoint low2* (also hardcoded in the memory registers), PLC2 sends a request to PLC1 via a Modbus channel to **open valve MV-301** in order to flow water from tank T-201 to tank T-202. The transmission channel is implemented by copying a boolean value from a memory register of PLC2 to a corresponding register of PLC1
- if the water level reaches the *high setpoint high2* instead (hardcoded in the memory registers as the previous setpoints), PLC2 sends PLC1 a **close request** for valve MV-301
- In intermediate cases, the valve remains open (closed) while the tank is filling (emptying)

PLC3 PLC3 monitors the level of the T-203 backwash tank, behaving accordingly. 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"},
  "Coils": {"%QX0.0": "0"}}
```

Listing 3.1: *Example of registers capture*

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

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

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

Listing 3.2: *Example of raw network capture*

Data Pre-processing The data collected by scanning the memory registers of the PLCs are then reprocessed by a Python script and converted in order to create a distinct raw dataset in *Comma Separated Value* format (CSV) for each PLC, containing the memory register values associated with the corresponding controller registers. These datasets are reprocessed again through the Python modules for **pandas** [35] and **NumPy** [36] by another script to first perform a **data cleanup**, removing all those memory registers that do not take values and are therefore useless within the system, **merged** into a single dataset, and finally **enriched** with additional data[1].

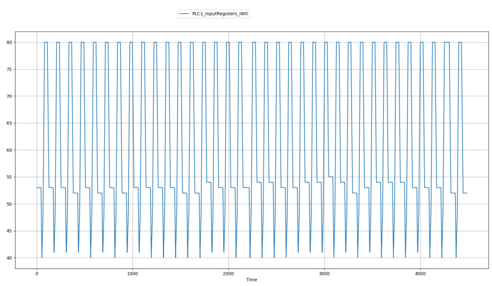
This process leads to the creation of two copies of the full dataset: one enriched with the additional data, but not timestamped, which will be used for the invariant analysis; the other unenriched, but timestamped, which will be used for business process mining.

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

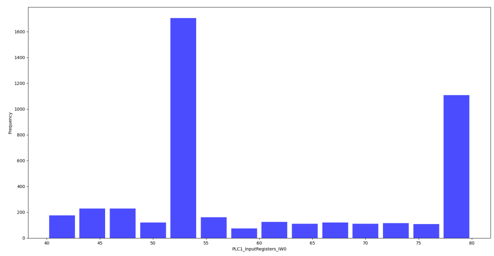
3.2.3 Graphs and Statistical Analysis

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

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



***(a)** Chart plot for* `PLC1_InputRegisters_IW01` *register*



***(b)** Histogram plot for* `PLC1_InputRegisters_IW01` *register*

***Figure 3.3:** Output graphs from graph analysis*

The first script plots the charts, one at the time, of certain registers entered by the user from the command line, plots in which one can see the trend of the data and get a first basic idea of what that particular register contains (a measurement, an actuation, a hardcoded setpoint, ...) and possibly the trend; the second script, instead, shows **a histogram and statistical 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 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.

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

- measurements bounded by some setpoint
- Actuators state changes occourred 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 Businness 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.

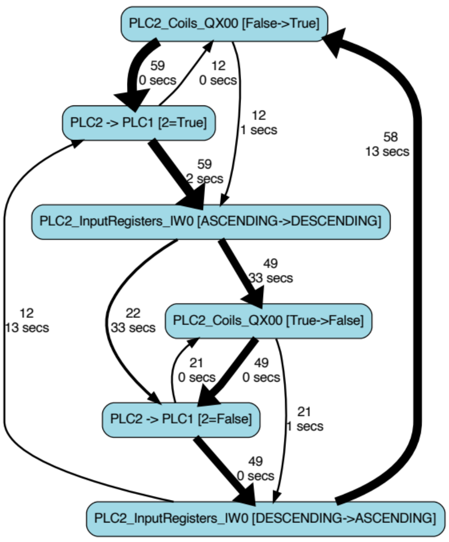


Figure 3.4: *An example of Disco generated activity diagram for PLC2*

The *business process* obtained in this way provides an **overview of the system** and makes it possible to **make conjectures** about its behavior, particularly between changes in actuator state and measurement trends (i.e., a given change in state of some actuators corresponds to a specific measurement trend and vice versa), and with the possibility of **establishing causality** between Modbus communications and state changes within the physical system.

3.2.6 Application

In this section we will see how the black box analysis presented above in its various phases is applied in practice, using the testbed described in

Subsection 3.2.1. The methodology supports a ***top-down*** **approach**: that is, we start with an overview of the industrial process and then gradually refine our understanding of the process by descending to a higher and higher level of detail based on the results of the previous analyses and focusing on the most interesting parts of the system for further in-depth analysis.

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

Graphs and Statistical Analysis It is unclear from the paper where exactly the information that follows was derived (graph analysis? Statistical analysis? Human reading of the dataset?), however, three properties about the contents of the registers were discovered:

Property 1: `PLC1_MemoryRegisters_MW0`, `PLC1_MemoryRegisters_MW1`, `PLC2_MemoryRegisters_MW0`, `PLC2_MemoryRegisters_MW1`, `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 mu-

[2]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.

table 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.

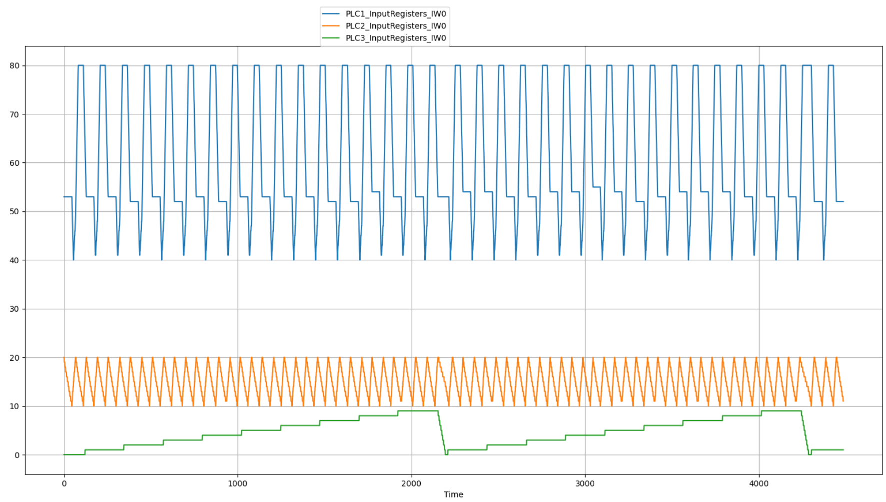


Figure 3.5: *Execution traces of InputRegisters_IW0 on the three PLCs*

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 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:

Conjecture 2:

- 40 and 80 are the relative setpoints for `PLC1_InputRegisters_IW0`
- 10 and 20 are the relative setpoints for `PLC2_InputRegisters_IW0`

- 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.

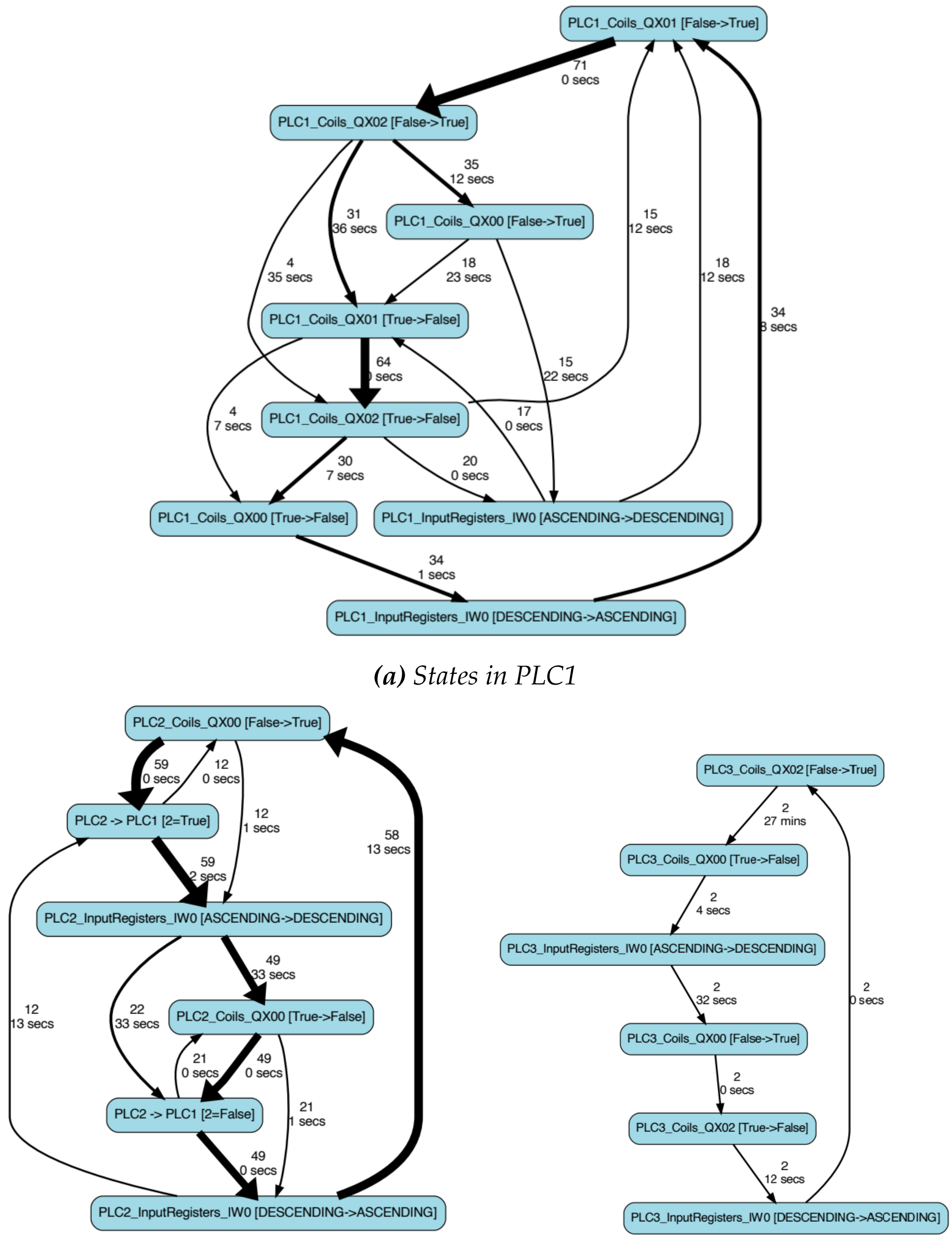
Through analysis of the activity diagrams shown in Figure 3.6, drawn through Disco, we derive the following properties and conjectures:

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)

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



(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*

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

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

However, it was possible to have confirmation of the conjectures made in the previous stages of the analysis: starting with the setpoints, analyzing the output of the invariants returned by Daikon[3] reveals that

```
PLC1_InputRegisters_IW0 >= PLC1_MemoryRegisters_MW0 == 40.0
PLC1_InputRegisters_IW0 <= PLC1_MemoryRegisters_MW1 == 80.0
PLC2_InputRegisters_IW0 >= PLC2_MemoryRegisters_MW0 == 10.0
PLC2_InputRegisters_IW0 <= PLC2_MemoryRegisters_MW1 == 20.0
PLC3_InputRegisters_IW0 >= PLC3_MemoryRegisters_MW0 == 0.0
PLC3_InputRegisters_IW0 <= PLC3_MemoryRegisters_MW1 == 9.0
```

i.e., that the `MemoryRegisters_MW0` and `MemoryRegisters_MW1` registers of 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

[3] The 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

```
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:

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

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

3.2.7 Limitations

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

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

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

What severely limits the analysis performed with the tool implemented by Ceccato et al. is the use of *ad hoc* solutions and *a posteriori* interventions done manually on the datasets after the data gathering process: I will discuss this last aspect in more detail later.
Moreover, there is the presence of many *hardcoded* variables and conditions within the scripts: this makes the system unconfigurable and unable to properly perform the various stages of the analysis as errors can occur 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.

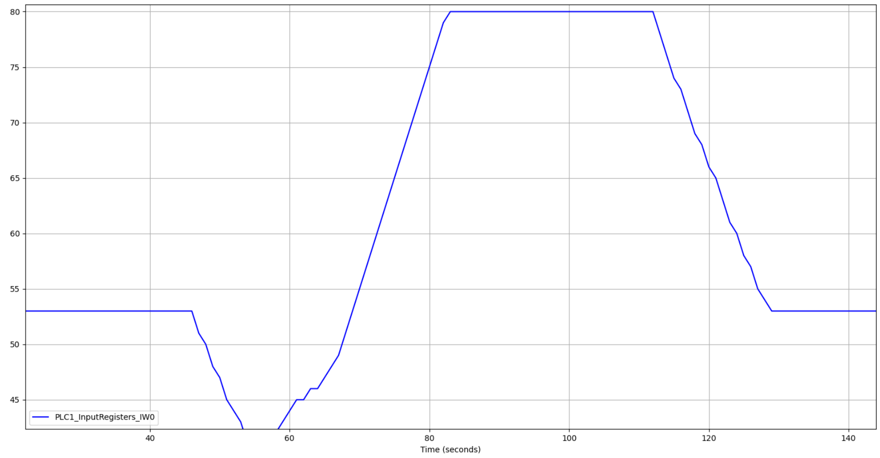
Testbed The testbed environment used by Ceccato et. al is entirely simulated, from the physical system to the control system. The PLCs were built with **OpenPLC** [43] in a Docker environment [44], while the physics part was built through **Simulink** [45].

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.

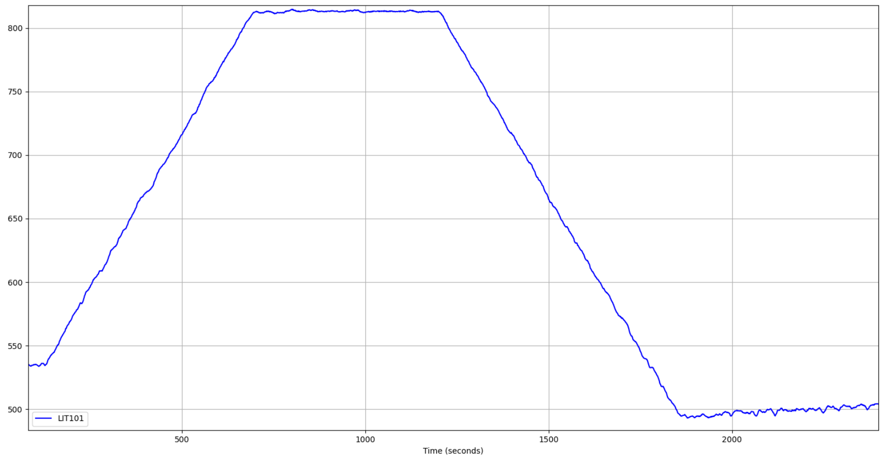
The biggest problem with the testbed, however, is not with the controller part, but with the **physical part**: first of all, it must be said that although this is something purely demonstrative even though it is fully functional, the implemented Simulink model is really **oversimplified** compared to 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 monitor 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.*

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

- the previous value of all registers

- some additional relative setpoints named `PLCx_Max_safety` and `PLCx_Min_safety` (where x is the PLC number), which represent a kind of alert on reaching the maximum and minimum water levels of the tanks

- the measurement slope, that is, the trend of the water level in the system tanks along the system cycles.

Merging the datasets of all individual PLCs into a single dataset representing the entire system can be a sound practice if the system to be anlized is (very) small as is the testbed analyzed here, consisting of a few PLCs and especially a few registers. If, however, the complexity of the system increases, this type of merging can become counterproductive and make it difficult to analyze and understand the data obtained in subsequent steps.
In short, there is no possibility to analyze only a subsystem and thus make the analysis faster and more understandable. Moreover, a data gathering can take up to days, and the analyst/attacker may need to make an analysis of the system isolating a precise time range, ignoring everything that happens before and/or after: all of this, with the tool we have seen, cannot be done.

Regarding the additional attributes, looking at the code of the script that performs the enrichment, I observed that **some attributes were manually inserted** after the merging phase: I am referring in particular to the attributes `PLCx_Max_safety` and `PLCx_Min_safety`, whose references were moreover hardcoded into the script, and the *slope* whose calculation method I mentioned in the previous paragraph about the testbed limitations.
In the end, only the attribute *prev* related to the value at the previous point of the detection is inserted automatically for all registers, moreover without the possibility to choose whether this attribute should be extended to 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 uncareful 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.

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

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

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

Invariants Inference and Analysis The limitation in this case is principally Daikon: this software is designed to compute the invariants of a software from its live execution or from a file containing its execution flow, not 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.

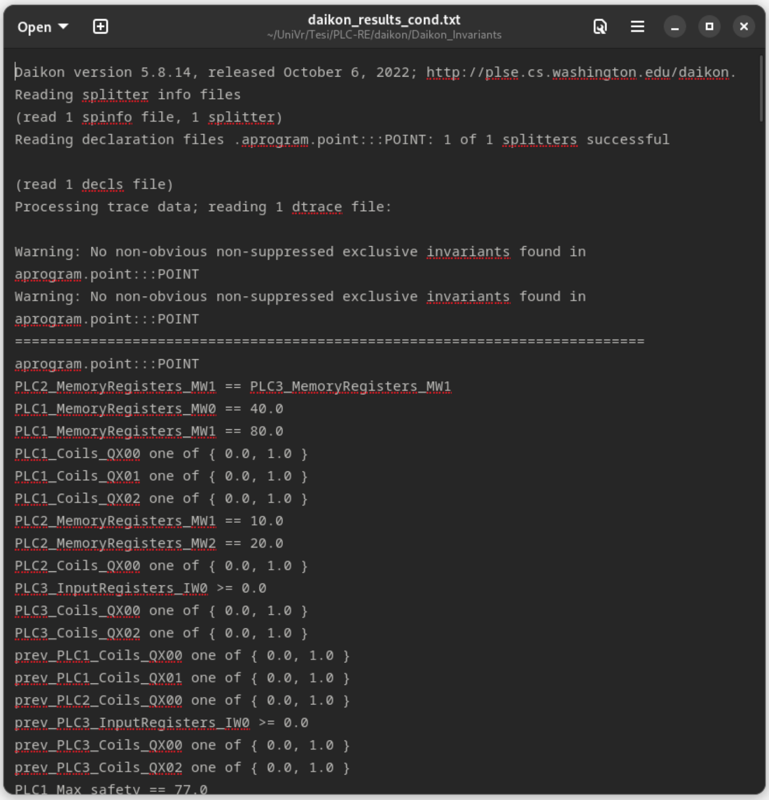


Figure 3.8: *Example of Daikon's output*

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 can be seen in Figure 3.8.

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

Chapter 4

A Framework to Improve Ceccato et al.'s Work.

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

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

As it may have already been noted, my proposals do not involve improving the data gathering phase: this is due simply to the fact that the novel framework will not be tested on the same case study used by Ceccato et, al. (Section 3.2.1), but on a different case study, the ITrust SWaT system [29], of which (some) datasets containing the execution trace of the physical system and the network traffic scan are already provided by iTrust itself. For more details about this case study, see Chapter 5.

4.1 The novel Framework

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

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

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

Single Programming Language The original tool was implemented using various programming languages in each of the different phases: from Python up to Java, passing through Bash scripting.
In my opinion, this heterogeneity makes it more difficult and less intuitive for the user to operate on the tool: moreover, the use of multiple technologies makes it more difficult to maintain the code and add new features, particularly if only a single person is managing the code (he/she might be proficient in one language, but little of the others).

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

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.

Flexibility and Ease on Use The lack of flexibility and ease of use in a tool can be a significant disadvantage, limiting its effectiveness and making it challenging for the user to get the desired outcomes. The original tool suffered from these limitations, with users having to run scripts from the command line, with little to no options or parameters available to customize the analysis. As a result, the tool was not user-friendly and lacked the flexibility to adapt to specific user needs.

To settle these issues, I enhanced the command-line interface in the novel framework by adding new options and parameters. These new features provide the user with greater flexibility, enabling to specify parameters and options that allow for more in-depth analysis and focused results analyzing data more effectively and efficiently. With these enhancements, the framework has become more user-friendly, reducing the learning 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.

4.1.1 Framework Structure

The structure of the novel framework mostly follows the structure of the original tool: it is divided into four main directories each representing the different phases of the analysis (data pre-processing, graphs and statistical analysis, process mining, and invariant analysis), and containing the relevant Python scripts that perform the analysis, as well as subdirectories and any input/output files necessary for the proper behavior of the framework.

```
.
├── config.ini
├── daikon
│   ├── Daikon_Invariants
│   ├── daikonAnalysis.py
│   └── runDaikon.py
├── network-analysis
│   ├── data
│   ├── export_pcap_data.py
│   └── swat_csv_extractor.py
├── pre-processing
│   ├── mergeDatasets.py
│   └── system_info.py
├── process-mining
│   ├── data
│   └── process_mining.py
└── statistical-graphs
    ├── histPlots_Stats.py
    └── runChartSubPlots.py
```

Listing 4.1: *Novel Framework structure and Python scripts*

Ahead of these directories there is the most important part, that allows the framework to be independent of the industrial control system being analyzed: the *config.ini* file. 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 parameters that will then be called within the Python scripts that constitute the framework. Sections of *config.ini* are:

- **[PATHS]:** defines general paths such as the project root directory and some source directories for datasets
- **[PREPROC]:** contains some parameters needed for the pre-processing phase
- **[DAIKON]:** defines parameters needed for invariant analysis with Daikon
- **[DATASET]:** defines settings and parameters used during the dataset enrichment stage and possibly in further phases
- **[MINING]:** contains parameters used during the process mining phase
- **[NETWORK]:** Contains specific settings for extracting the data obtained from the packet sniffing phase on the ICS network and converting it to CSV format. It also defines the network protocols that are to be analyzed

4.1.2 Python Libraries and External Tools

Since the framework has been entirely developed in Python, I have tried to make use of external tools as little as possible, with the idea of integrating all the various functionalities within the framework and making it independent of further software: the only external tool remaining from the old Ceccato et al. tool is Daikon, precisely because there is currently no better alternative or Python packages that performs the same functionalities.

Instead, large use of Python libraries is made for handling functionality and input data: the fundamental libraries upon which the framework is based are:

- **Pandas**, also used in the previous tool for dataset management, but whose use here has been deepened and extended
- **NumPy**, often used together with Pandas to perform some operations to support it
- **MatPlotLib**, for managing and plotting graphical analysis
- other scientific libraries such as **SciPy**, **StatsModel** [48] and **NetworkX** [49], for mathematical, statistical and analysis operations on the data
- **GraphViz**, for the creation of activity diagrams in the process mining phase

Having now seen the structure of the framework, in the next sections we will go into more detail describing my proposals and what I have done to improve the various stages of the analysis.

4.2 Analysis Phases

4.2.1 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; I have also redesigned the whole process of enrichment of the resulting dataset, eliminating the manual entry of additional attributes and giving the user the possibility to be able to decide which type of additional attribute to associate with a given register. In addition to this, at the end of the pre-processing operation, it is possible to perform a brief preliminary analysis of the obtained dataset in order to estimate which registers are connected to actuators, which to measurements, and which represent hardcoded relative setpoints or constants: this operation also makes it possible to be able to refine the enrichment step by setting the relevant parameters in the *config.ini* file

In the next sections we will look in more detail at what has been accomplished.

4.2.1.1 Subsystem Selection

In the previous tool, the datasets in CSV format referring to each single PLC are placed in a fixed directory (hardcoded in the script) from which the dedicated script later perform merge and enrichment of them all, resulting in a single dataset representing the entire process trace of the industrial system as an output. As mentioned, the script makes no provision to choose the individual PLCs to be analyzed, nor to decide on a temporal range over which to perform the analysis: in fact, it may happen that during the period of scanning and data gathering there is a so-called *transient*, i.e., a general state in which the industrial system is still initializing before actually reaching full operation; or, more simply, there is the need to analyze the process of only a specific part of the industrial system in a certain period of interest: whatever the motivation, the lack of elasticity and options to provide to the user makes the analysis much more complex than it might be, affecting even the later phases, as the number of variables to be analyzed becomes enormously higher.
In addition, it is not possible to specify an output CSV file where to save 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

- **-n** or **--nrows:** reference temporal period in seconds (rows) for the analysis from the beginning of the dataset or from the point specified in the `-s` option or in the corresponding setting in *config.ini*.
  This option makes a **selection** on the data of the dataset.

- **-p** or **--plcs:** PLCs to be merged and enriched. The user can specify the desired PLCs by indicating the CSV file names of the associated datasets with no limitations on number.
  This option makes a **projection** on the data of the dataset.

- **-d** or **--directory:** performs the merge and enrichment of all CSV files contained in the directory specified by user, overriding the default setting in *config.ini*. It is in fact the old functionality of the previous tool, maintained here to give the user more flexibility and convenience in case he wants to perform the analysis on the whole system.
  This is also the default behavior in case the `-p` option is not specified.

- **-o** or **--output:** specifies the name of the file in which the obtained dataset will be saved. It must necessarily be a file in CSV format.

- **-g** or **--granularity:** specifies a granularity that will be used to calculate the measurement slope during the dataset enrichment phase. We will discuss this later in Section 4.2.1.2.

4.2.1.2 Dataset Enrichment

After a step in which a function is applied to each PLC-related dataset that eliminates its registers that have not been used within the system (this is especially true if the Modbus register scan has been performed, in which ranges of registers are scanned: it is assumed that unused registers have constant value zero), the **dataset enrichment operation** is performed.

This operation differs from the previous version not only in the fact that it is performed on each individual dataset and not on the resulting dataset, but also in the additional attributes: not only are they greater in number, but they are automatically calculated and inserted by the `mergeDatasets.py` script into the dataset and, most importantly, it is possible to decide through the parameters in the *config.ini* configuration file under the `[DATASET]` section to which registers these attributes should be assigned.
In Listing 4.3 we can see the list of additional attributes and how they should be associated with the registers of the dataset:

```
[DATASET]
timestamp_col = Timestamp
max_prefix = max_
min_prefix = min_
max_min_cols_list = lit|ait|dpit
prev_cols_prefix = prev_
prev_cols_list = mv[0-9]{3}|p[0-9]{3}
trend_cols_prefix = trend_
trend_cols_list = lit
trend_period = 150
slope_cols_prefix = slope_
```

```
slope_cols_list = lit
```

Listing 4.3: `config.ini` *parameters for dataset enriching*

Following is a brief explanation of the parameters just seen:

`timestap_col` indicates the name of the column that contains the data timestamps. This parameter is used not only in this phase, but is also referred to in the Process Mining phase. In the previous work, this parameter was hardcoded and not configurable (and thus causing errors if the system being analyzed changed)

`max_prefix`, `min_prefix`, `max_min_cols_list` refer to any relative maximum or minimum values (*relative setpoints*) of one or more measures and that can be found and inserted as new columns within the dataset. The first two parameters indicate the prefix to be used in the column names affected by this additional attribute, while the third specifies of which type of registers we want to know the maximum and/or minimum value reached (several options can be specified using the logical operator `|` - or).
If, for example, we want to know the maximum value of the registers associated with the tanks, indicated in the iTrust SWaT system by the prefix `LIT`, we only need to specify the necessary parameter in the *config.ini* file, so `max_min_cols_list = lit`.
The result will be to have in the dataset thus enriched a new column named `max_P1_LIT101`.

`prev_cols_prefix`, `prev_cols_list` refer to the values at the previous step of the registers specified in `prev_cols_list`. It is possible to specify registers using *regex*, as in the example shown. It may be useful in some cases to have this value available to check, for example, when a change of state of a single given actuator occurs. The behavior of these parameters is the same as described in the point above.

`slope_cols_prefix`, `slope_cols_list` are related to the calculation of the slope of a specific register (usually a measure), that is, its trend. The slope can be ascending (if its value is greater than zero), descending (if less than zero) or stable (if approximately equal to zero).I will discuss the slope calculation in more detail in the next paragraph, as it is related to the attributes `trend_cols_prefix`, `trend_cols_list` and `trend_period`

Initially, the parameters for registers to be associated with each additional attribute may be left blank, assuming that we do not know the system at all and therefore do not know which registers may be actuators, which measures, and which further. This information can be obtained from the **brief analysis** following the datasets merging operation: this analysis, performed at the user's choice, indicates which may be likely sensors, which actuators, and further information of various kinds: these indications allow the user to be able to set the desired values in *config.ini* file and hence refine the enrichment process by re-launching the `mergeDatasets.py` script again.

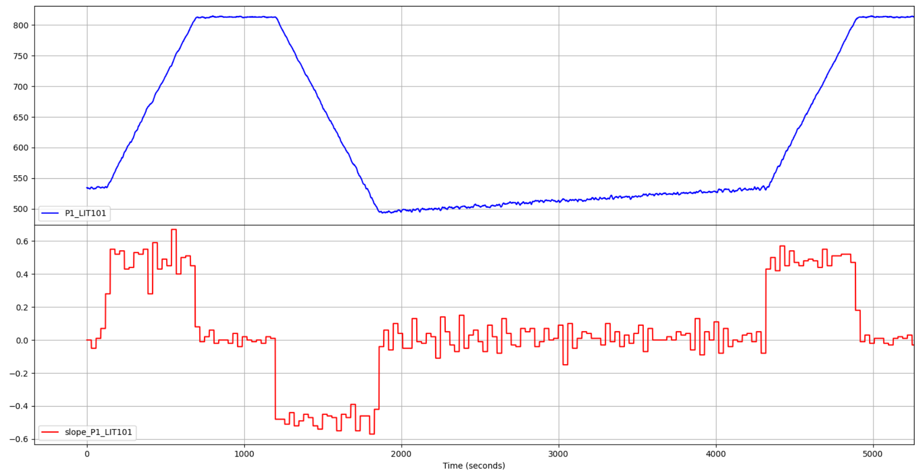
Slope Calculation The *slope* is an attribute that indicates the trend of the measurement we are considering and is useful, in our context, during the inference and invariant analysis phase in order to derive information about this trend given specific conditions: this trend can be, in general, increasing (slope > 0), decreasing (slope < 0) or stable (slope = 0).
Normally, the slope is calculated through a simple mathematical formula: given an interval a, b relative to the measurement l, the slope is given by the difference of these two values divided by the amount of time t that the measurement takes to reach b from a:

$$slope = \frac{l(b) - l(a)}{t(b) - t(a)}$$

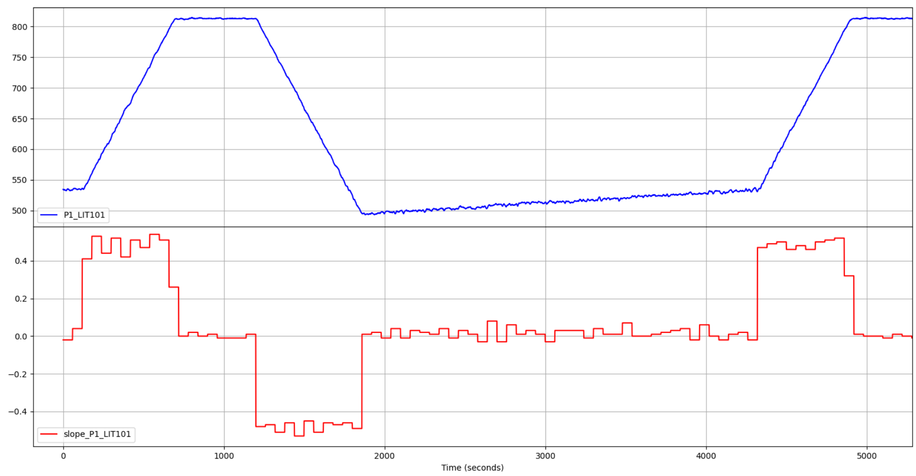
In the novel framework as in the old tool, this time interval (also called ***granularity***) can be either long or short, depending on the accuracy desired on the slope: the lower the granularity, the more the slope will reflect the actual measurement trend; the higher the granularity, on the other hand, the more the slope data will be flattened. Each time interval into which the measure is divided corresponds to a slope, the set of which inserted as an additional attribute in the dataset will later be used to define the trend of the measure itself in specific situations.

Calculating the slope directly from the raw measurement data may be an acceptable solution for those systems whose measurements are not significantly affected by **perturbations** (such as the oscillations of the liquid inside a tank during the filling and emptying phases, leading to fluctuating level readings): in this case, granularity can be kept low and thus obtain a very accurate overall trend calculation close to the actual measurement trend. This is the case, for example, with the tanks of the testbed used by Ceccato et al.
However, in the case where these perturbations significantly afflict the detections on the measurement, the slope calculation on the individual time intervals of the measurement may lead to an erroneous result in trend definition, regardless of the granularity used.

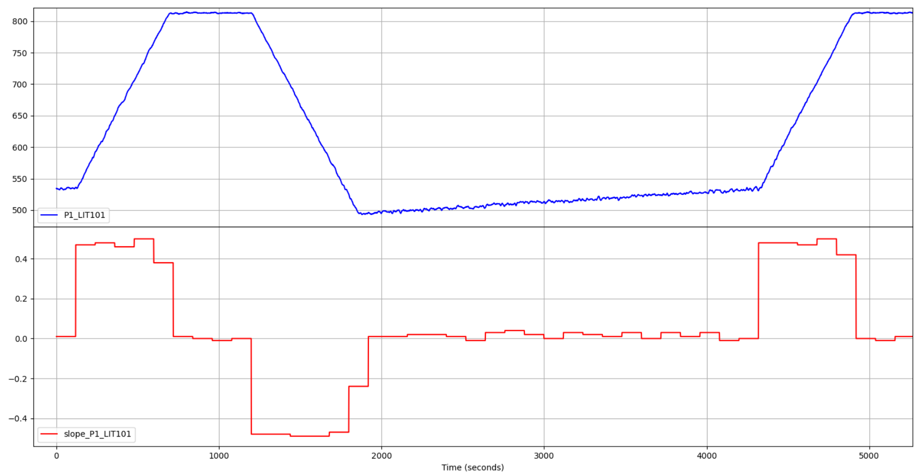
Figure 4.1 demonstrates this assertion: the measurement, in blue, refers to the LIT101 tank of the iTrust SWaT system; in red, the slope calculation related to the measurement with three different granularities: 30 (Figure 4.1a), 60 (Figure 4.1b) and 120 seconds (Figure 4.1c). It can be seen that in addition to the flattening of slope values as the granularity increases, in the time interval between seconds 1800 and 4200 the level of LIT101 has a generally increasing trend, but the slope values vary from positive to negative: the result is that in the invariant analysis the general increasing trend will not be detected thus losing the information.
The possibility of a having (strongly) perturbed data was not considered in the previous tool, so I was faced with this issue to solve.



(a)



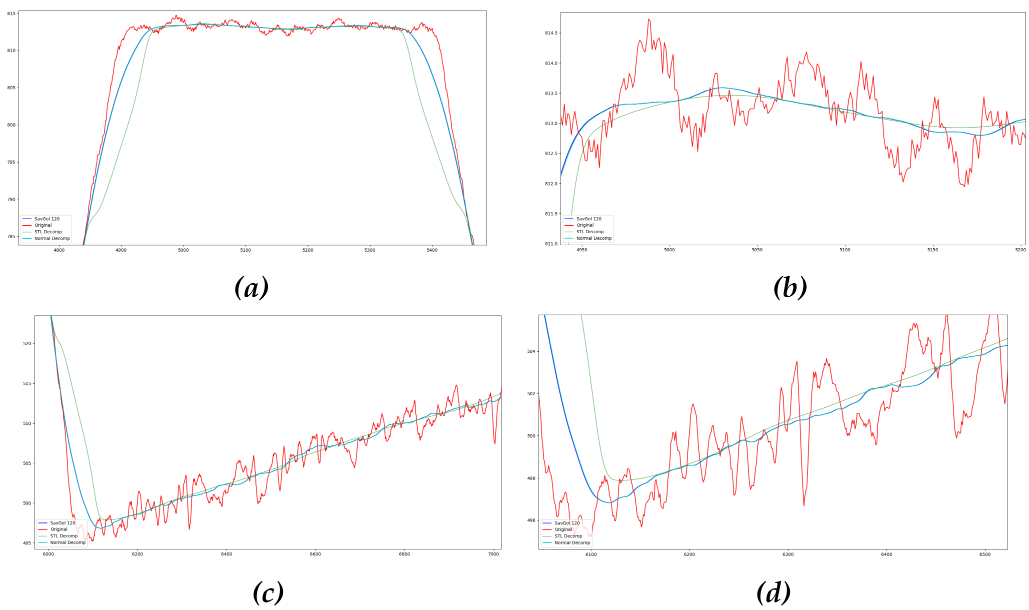
(b)



(c)

Figure 4.1: *Slope comparison with granularity 30 (a), 60 (b) and 120 seconds (c)*

The solution to this problem is trying to remove as much "noise" as possible from the data, in order to get a more linear trend in the curve representing the measurement and consequently be able to calculate slopes more accurately.
There are several ways to smooth out the noise, but two of them seemed to me to be the most suitable and that I considered and evaluated: using **polynomial regression**, thus creating a filter on the noise, or a **seasonal decomposition**, and more specifically the part concerning the **trending**.
With regard to polynomial regression, I evaluated the *Savitzky-Golay* algorithm [50], and with regard to seasonal decomposition, I evaluated *Seasonal-Trend decomposition using LOESS* (STL) [51].
For reasons of the length of this paper I cannot describe these two solutions in detail (for this, I refer to the bibliographical notes): Figure 4.2, however, shows a quick graphical comparison of them compared with the original data. The solution chosen is the STL decomposition, which is more effective in attenuating noise than the Savitzky-Golay filter although at the cost of more delay (still present in all algorithms of this kind) in some parts.



(a) *(b)* *(c)* *(d)*

Figure 4.2: *Savitzky-Golay filter (blue line) and STL decomposition (green) comparison*

The application of the STL decomposition results in a significant improvement in slope calculation even when using low granularity: in Figure 4.3 it can be seen that, with the same granularity used for the example in Figure 4.1a, the slope values, although with unavoidable fluctuations, remain within the same trend, corresponding to the trend of the data curve net of the introduced lag caused by the periodicity set for the decomposition.

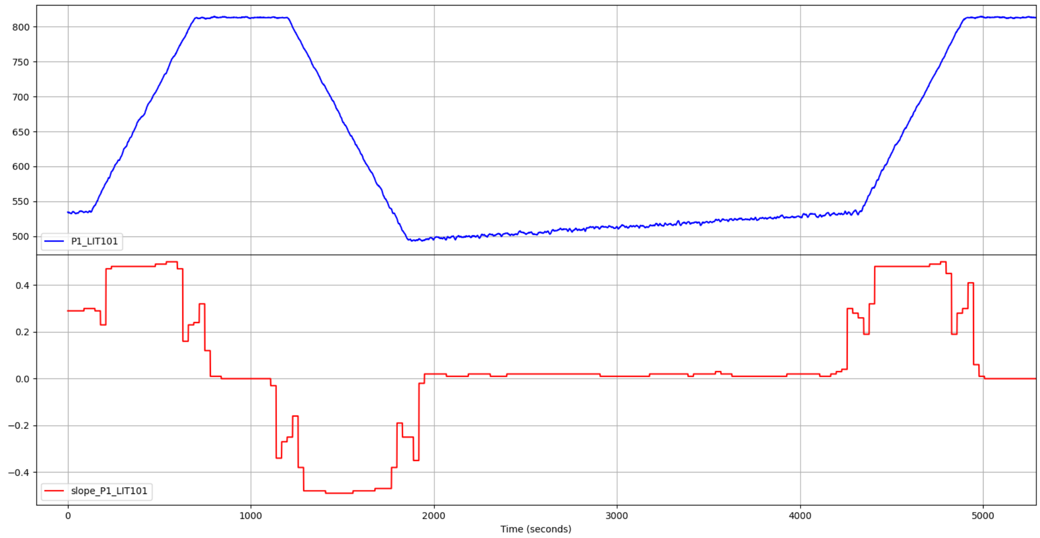


Figure 4.3: *Slope after the application of the STL decomposition*

This periodicity, which indicates the sampling time window for decomposition and thus the level of noise smoothing, can be set in the *config.ini* configuration file in the `trend_period` directive.
The slope calculation will then be performed on the data from the additional measurement trend attributes specified in the `trend_cols_list` directive in the configuration file, and no longer on the original unfiltered data.

Finally, to enable Daikon to correctly interpret the slope data, the decimal values corresponding to each calculated slope are converted into three numerical values -1, 0, and 1, which correspond to the decreasing (if the slope is less than zero), stable (if it is equal to zero), and increasing (if it is greater than zero) trends, respectively. In Figure 4.4, the new slope can be seen, along with the curve obtained from the STL decomposition:

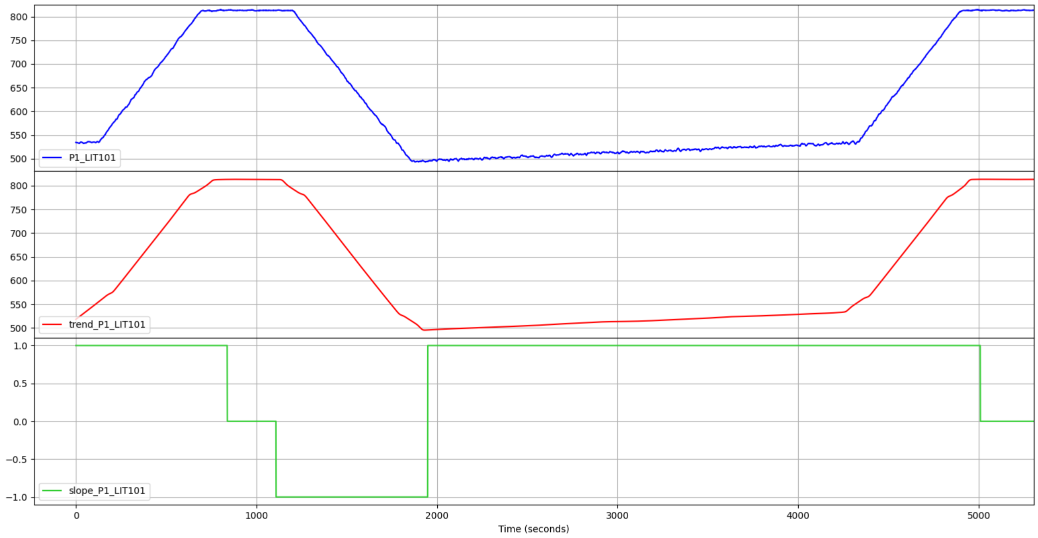


Figure 4.4: *The new slope representation (green line) and the smoothed measurement data obtaind with the STL decomposition (red)*

4.2.1.3 Datasets Merging

In this step the individual datasets are merged, obtaining two new distinct datasets: one without the enrichment and that will be use in the process mining phase, and the other, containing the additional attributes but with the timestamp column removed, intended for inference and invariant analysis.

The first of the two datasets obtained will be saved in CSV format by default in the `$(project-dir)/process-mining/data` directory while the second one in the `$(project-dir)/daikon/Daikon_Invariants` directory (both paths are however configurable via *config.ini*).
The dataset name is specified in *config.ini* or via the `-o` command-line option: in the case of the dataset intended for process mining, the script will automatically add a `_TS` suffix to the filename, indicating the fact that the dataset includes the timestamp.

The opportunity for the user to specify a different filename for the output each time allows the user to save the execution trace of the selected subsystem without overwriting the previous ones and thus to use all of them in the subsequent phases of the analysis.

4.2.1.4 Brief Analysis of the Obtained Subsystem

At the end of the datasets merging and saving step, the user is asked whether to perform a brief optional analysis of the final resulting dataset to extract preliminary data, with the purpose of obtaining basic information about the (sub)system and possibly refining the enrichment.
If the user responds affirmatively to the request, `mergeDatasets.py` launches within it a further Python script located in the same `$(project-dir)/pre-processing` directory, called `system_info.py`. This script, using a combination of Daikon and Pandas analysis, performs a quick analysis of the dataset contents trying to **recognize**, however roughly, **the register types**, with possible maximum and minimum values and hardcoded setpoints. In addition, using the additional attribute `prev_`, it is capable of deriving measurement values in correspondence with state changes of individual actuators.
Listing 4.4 shows an example of this brief analysis elated to PLC1 of the iTrust SWaT system (for brevity, only one measurement is reported in the analysis of actuator state changes):

```
Do you want to perform a brief analysis of the dataset? [y/n]: y

Actuators:
P1_MV101 [0.0, 1.0, 2.0]
P1_P101 [1.0, 2.0]

Sensors:
P1_FIT101 {'max_lvl': 2.7, 'min_lvl': 0.0}
P1_LIT101 {'max_lvl': 815.1, 'min_lvl': 489.6}

Hardcoded setpoints or spare actuators:
```

```
P1_P102 [1.0]

Actuator state changes:
       P1_LIT101  P1_MV101  prev_P1_MV101
669     800.7170         0             2
1850    499.0203         0             1
4876    800.5992         0             2
6052    498.9026         0             1
9071    800.7170         0             2
10260   499.1381         0             1
13268   801.3058         0             2
14435   498.4315         0             1
17423   801.4628         0             2
18603   498.1567         0             1

P1_LIT101  P1_MV101  prev_P1_MV101
677     805.0741         1             0
4885    805.7414         1             0
9079    805.7806         1             0
13276   805.1133         1             0
17432   804.4068         1             0

P1_LIT101  P1_MV101  prev_P1_MV101
1858    495.4483         2             0
6060    497.9998         2             0
10269   495.9586         2             0
14443   495.8016         2             0
18611   494.5847         2             0

       P1_LIT101  P1_P101  prev_P1_P101
118     536.0356        1             2
4322    533.3272        1             2
8537    542.1591        1             2
12721   534.8581        1             2
16883   540.5890        1             2

P1_LIT101  P1_P101  prev_P1_P101
1190    813.0031        2             1
5395    813.0031        2             1
```

```
9597    811.8256        2            1
13776   812.7283        2            1
17938   813.3171        2            1

Actuator state durations:
P1_MV101 == 0.0
9  9  10  9  9  10  9  9  10  9

P1_MV101 == 1.0
1174  1168  1182  1160  1172

P1_MV101 == 2.0
669  3019  3012  3000  2981

P1_P101 == 1.0
1073  1074  1061  1056  1056

P1_P101 == 2.0
118  3133  3143  3125  3108
```

Listing 4.4: *Example of preliminar system analysis*

From these results we can see that:

- the probable actuators are `P1_MV101`, which assumes three states identified by the values 0, 1 and 2, and `P1_P101`, which instead assumes two states identified by the values 1 and 2
- there are two probable measures: `P1_FIT101` whose values range from 2.7 to 0.0, and `P1_LIT101` whose values range from 815.1 to 489.6. One conjecture could already be made about the topology of the system: `P1_LIT101` represents a tank
- apparently there are no related *hardcoded setpoints*, but a probable spare actuator, `P1_P102`, whose value is always 1. From this data, another conjecture can be made: the value 1 is the close state for that particular type of actuators, while 2 represents the open state
- from the analysis of state changes, in summary, we derive some *relative setpoints*: for example, we know that `P1_P101` changes state from

value 1 to value 2 when the level of P1_LIT101 is about 813, while it changes from value 2 to 1 when the level of P1_LIT101 is about 535. We can deduce that P1_P101 is responsible for emptying the tank

- as the last information we have duration of actuator states for each cycle of the system: this information can be useful for making assumptions and conjectures about the behavior of an actuator in a specific state or, by observing the duration values of each cycle, highlighting anomalies in the system.
  In the specific case, the very short duration of P1_MV101 in state 0 is observable: since we are unable, at this preliminary stage, to make assumptions about this, we will try to understand the behavior of the system in this actuator state in the next stages of the analysis

The information obtained here can be used, as mentioned above, to refine the enrichment of the dataset by setting directives in the [DATASET] section of the *config.ini* file, should this be empty or only partially set, or to make the first conjectures about the system, as we have just seen.

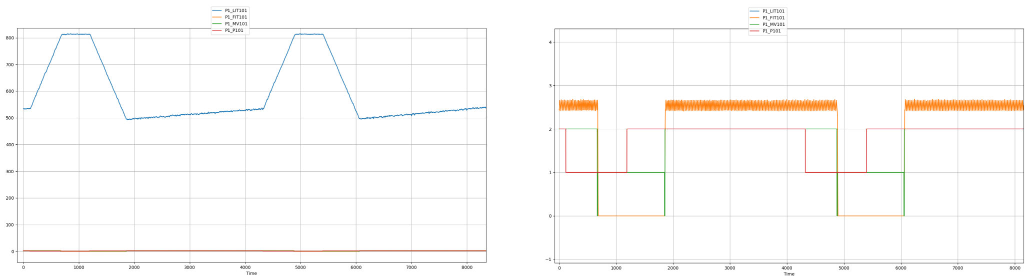
The system_info.py file can also run in standalone mode if needed: it takes as command-line arguments the dataset to be analyzed, a list of actuators, and a list of sensors. For analysis related to state changes, the dataset must mandatorily be of the enriched type.

4.2.2 Phase 2: Graphs and Statistical Analysis

The new *graph analysis* arises from the need to give the user an overview of the (sub)system obtained in the previous pre-processing phase, identifying more easily the typology of the registers and grasping more effectively the relationships and the dynamics that may exist between the registers controlled by one or more PLCs, confirming the initial conjectures if the brief analysis described in the previous section has been performed, or making new ones thanks to the visual graph support.

In the previous tool, as already pointed out in Section 3.2.7, it is possible to view the chart of one only register at a time: this certainly makes it possible to identify, or at least to hypothesize, the type of that register, but it makes it very complicated to be able to relate it to the other components of the system and thus to derive conjectures about the behavior of the latter, conjectures to be possibly confirmed in the later phases. Hence the need to create a tool that was better than the previous one and that provided more information in an easier way.

The first thing I thought was that an approach similar to Figure 3.5, with all the graphs contained within a single plot, might be the most suitable one: unfortunately, I quickly realized that this solution presented several issues, which are highlighted in figure 4.5.

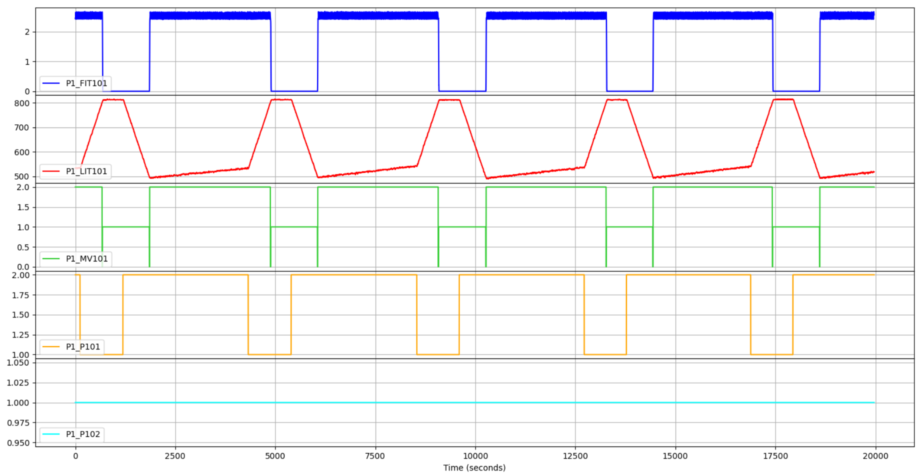


(a) *(b)*

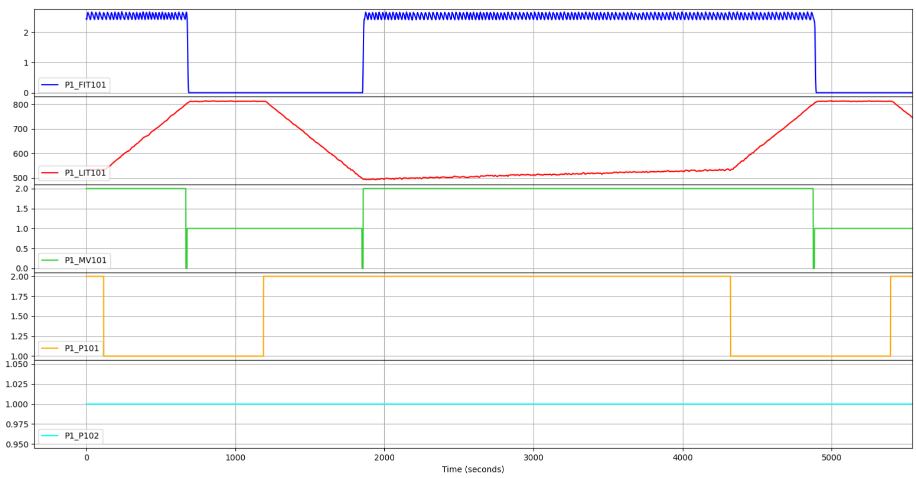
Figure 4.5: *Plotting registers on the same y-axis*

In figure 4.5a it can be seen that the biggest issue is the use of the same y-axis, related to the values of the individual registers, for all charts: if the range between register values is wide, the risk of some charts resembling a single flat line, or at any rate being in fact indistinguishable and very difficult to read immediately; furthermore, as shown in Figure 4.5b, if registers have similar values to each other, the respective graphs may be confusing to each other, making them more difficult to understand.

The solution to this issue is simple and effective: the use of **subplots**. Basically, each register corresponds to a subplot of the graph that shares the time axis (the x-axis) with the other subplots, but keeps the y-axis of the values of each register independent. This maintains the readability and comprehensibility of the charts, while simultaneously being able to immediately grasp the relationships between them. In addition, by sharing the time axis, it is possible to zoom in on a particular area of one of the charts and automatically the other ones will be zoomed in as well, thus not losing any information and no connection between registers. Figure 4.6 illustrates more clearly what has just been explained: the charts refer to the PLC1 registers of the iTrust SWaT system.



(a) *Example of plotting charts of a PLC registers using subplots*



(b) *Zooming on a particular zone of the charts*

Figure 4.6: *Example of the new graph analysis*

To demonstrate the behavior and effectiveness of the new graph analysis process, we observe in particular, Figure 4.6b: we can already have some validation on the conjectures made in the brief analysis from the previous step:

- the chart of `P1_FIT101` seems to confirm that this register can be associated with a **measurement**; moreover, we can see that the trend of this register is closely related to the periods in which `P1_LIT101` has an increasing trend and to the evolution of `P1_MV101`. Its values, between about 0 and 2.5, are too narrow to say that this register represents the tank, and the general trend also leads in that direction: we can therefore assume that it is a **pressure or flow sensor**
- `P1_LIT101`, because of the above, would therefore seem to **represent a tank**, as already assumed in the brief analysis
- `P1_MV101` assumes value 2 at the beginning of the ascending trend of `P1_LIT101`, while it has value 1 in correspondence with the *plateau* that is seen when the measurement is about 800 and when the trend of it is descending. Thus, we can have a confirmation of the initial conjecture: 1 represents the OFF state of the sensor, 2 the ON state, and `P1_MV101` is the **actuator responsible for the rising level** of `P1_LIT101`
- in the brief analysis we observed the short duration of `P1_MV101` in state 0, but we were not able to speculate on the reason for this. Graph analysis shows that P1_MV101 switches and stays in the 0 state acting as a kind of "transient" between states 1 and 2. It can be assumed that that is the period of time it actually takes for the actuator to change state
- `P1_P101` assumes value 2 at the beginning of the descending trend of `P1_LIT101`, after the *plateu*, and returns to value 1 at the change of slope of the (likely) tank increase: taken by itself this fact is not very clear, so it needs to be compared with `P1_LIT101` and `P1_MV101` to understand its behavior: it can be seen that when `P1_101` and `P1_MV101`

are in state 1 the water level remains stable, whereas, when `P1_P101` changes to state 2 the level of the measurement drops rapidly; when `P1_MV101` then also returns to state 2, the level of the measurement slowly starts rising again and then has a sudden rise at the change of state of `P1_P101` from 2 to 1. We can therefore infer that `P1_P101` is the **actuator responsible for emptying** the (presumed) tank: state 1 represents the OFF state, while state 2 represents the ON state

- `P1_P102` seems to play no role in the system, since its state remains at 1 all the time. It seems improbable that it could be a relative setpoint, so it can be assumed, according to the brief analysis, that it may be a **spare actuator**

As you have probably already noticed, the vast majority of the graphs shown in the previous sections and chapters were generated precisely using the new graph analysis script.
The script that performs the new graph analysis is `runChartsSubPlots.py`, located in the `$(project-dir)/statistical-graphs` directory, which is written in Python and makes use, like the previous one, of the *matplotlib* libraries to generate the graph plots.
The script accepts the following command-line parameters:

- **-f** or **--filename**: specifies the dataset, in CSV format, from which to read the data. The dataset must be located within the directory containing the enriched datasets for the invariant analysis phase. If subsequent parameters are not specified, the script will show all registers in the dataset, except for additional attributes

- **-r** or **--registers**: specifies one or more specific registers to be displayed

- **-a** or **--addregisters**: adds one or more registers to the default visualization. This option is useful in case an additional attribute such as slope is to be analyzed

- **-e** or **--excluderegisters**: excludes one or more specific registers from the default visualization. This option is useful to avoid displaying hardcoded setpoints or spare registers

This script, like the previous ones, is designed to provide the maximum flexibility and ease of use for the user, combined with greater power and effectiveness in deriving useful information about the analyzed system.

Statistical Analysis A quick mention of the statistical analysis part: after careful evaluation, I decided **not to include this aspect** of the previous tool within the framework, because I saw no real practical use for it. The actual statistical information can be easily integrated into the brief analysis immediately following the pre-processing phase, while the histogram has relative utility and, in my opinion, is outdated by the new graph analysis I implemented.
However, the Python `histPlots_Stats.py` script remains in the directory, essentially unchanged from the one developed by Ceccato et al., in case future use is needed.

4.2.3 Phase 3: Invariant Inference and Analysis

The phase of invariant inference and analysis has undergone a redesign and improvement to offer the user a more comprehensive and effortless approach to identify invariants. This has been achieved through the application of new criteria to analyze and reorganize the Daikon analysis results. The outcome of this is a more compact presentation of information that highlights the possible relationships among invariants.
The new design not only enables the identification of undiscovered aspects of the system behavior but also confirms the hypotheses made during the earlier stages of analysis. This step is now semi-automated, unlike before, and allows for the analysis of invariants on individual actuator states and their combinations.

4.2.3.1 Revised Daikon Output

To streamline the process of identifying invariants quickly and efficiently, it is necessary to revise the output generated by standard Daikon analysis. The goal is to create a more compact and readable format for the output.

The current Daikon results consist of three sections:

1. the first section containing generic invariants, i.e., valid regardless of whether a condition is specified for the analysis
2. the second section containing invariants obtained by specifying a condition for the analysis in the *.spinfo* file
3. a third section containing the invariants that are obtained from the negations of the condition possibly specified in the .spinfo file

In each section only a single invariant per row is shown, without relating it in any way to the others: this makes it difficult to identify significant invariants and any invariant chains that might provide much more information about the behavior of the system than the single invariant.
A brief example of the structure and format of this output related to `PLC1` of the iTrust SWaT system is shown in Listing 4.5, where a condition was specified on the measurement `P1_LIT101` and on actuator `P1_MV101`:

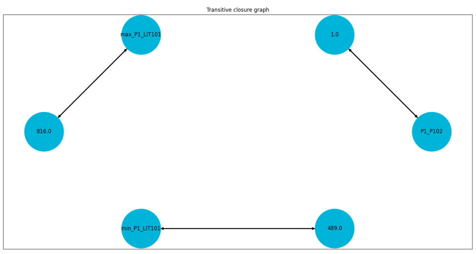
```
aprogram.point:::POINT
P1_P102 == prev_P1_P102
P1_FIT101 >= 0.0
P1_MV101 one of { 0.0, 1.0, 2.0 }
P1_P101 one of { 1.0, 2.0 }
P1_P102 == 1.0
max_P1_LIT101 == 816.0
min_P1_LIT101 == 489.0
slope_P1_LIT101 one of { -1.0, 0.0, 1.0 }
[...]
P1_LIT101 > P1_MV101
P1_LIT101 > P1_P101
```

```
P1_LIT101 > P1_P102
P1_LIT101 < max_P1_LIT101
P1_LIT101 > min_P1_LIT101
[...]
P1_MV101 < min_P1_LIT101
P1_MV101 < trend_P1_LIT101
P1_P101 >= P1_P102
P1_P101 < max_P1_LIT101
[...]
===============================================
aprogram.point:::POINT;condition="P1_MV101 == 2.0 &&
 ↪ P1_LIT101 < max_P1_LIT101 - 16 && P1_LIT101 >
 ↪ min_P1_LIT101 + 15"
P1_MV101 == prev_P1_MV101
P1_P102 == slope_P1_LIT101
P1_MV101 == 2.0
P1_FIT101 > P1_MV101
P1_FIT101 > P1_P101
P1_FIT101 > P1_P102
P1_FIT101 > prev_P1_P101
P1_MV101 >= P1_P101
P1_MV101 >= prev_P1_P101
P1_P101 <= prev_P1_P101
===============================================
aprogram.point:::POINT;condition="not(P1_MV101 == 2.0 &&
 ↪ P1_LIT101 < max_P1_LIT101 - 16 && P1_LIT101 >
 ↪ min_P1_LIT101 + 15)"
P1_P101 >= prev_P1_P101
Exiting Daikon.
```

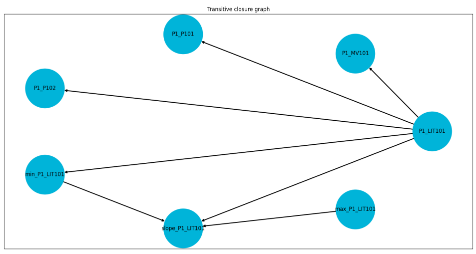
Listing 4.5: *Standard Daikon output for* `PLC1` *of the iTrust SWaT system*

In the framework I am presenting, this output is reduced to two sections, the general one and the elated to the user-specified condition, eliminating the one related to the negated condition because it is not useful in this context and a source of potential misinterpretation; moreover, the relationships between invariants will be highlighted instead by using **transitive closures**: transitive closure of a relation R is another relation, typically denoted R^+ that adds to R all those elements that, while not necessarily related directly to each other, can be reached by a *chain* of elements related to each other. In other words, the transitive closure of R is the smallest (in set theory sense) transitive relation R such that $R \subset R^+$ [52].

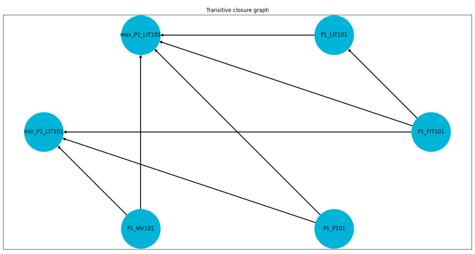
To implement the transitive closure of the invariants generated by Daikon, I first divided the invariants in each section by type according to their equivalence relation, not considering all those invariants that refer to additional attributes except for the slope, and for each of them I generated a **graph** using the NetworkX libraries, connecting with an arc the registers (represented by nodes) that have a common endpoint in the invariant through the transitive property. To reconstruct the individual invariant chains, then, I used a simple *Depth-first Search* (DFS) on each of the graphs, thus obtaining the desired outcome. Figure 4.7 shows some examples of these graphs:



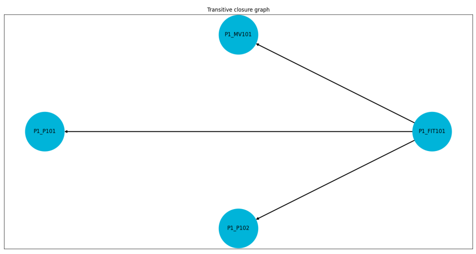
***(a)** Transitive closure graph for "=="*



***(b)** Transitive closure graph for ">"*



***(c)** Transitive closure graph for "<"*



***(d)** Transitive closure graph for ">" cond.*

***Figure 4.7:** Example of transitive closure graphs for invariants in PLC1 of iTrust SWaT system*

At the end of this process, still applied to `PLC1` of the iTrust SWaT system and with the same analysis condition, we get the following complete output:

```
1  ===========================
2  Generic
3  ===========================
4  P1_MV101 one of { 0.0, 1.0, 2.0 }
5  P1_P101 one of { 1.0, 2.0 }
6  slope_P1_LIT101 one of { -1.0, 0.0, 1.0 }
7  P1_FIT101 != P1_P101, P1_P102
8  P1_P102 == 1.0
9  max_P1_LIT101 == 816.0
10 min_P1_LIT101 == 489.0
11 P1_LIT101 > P1_MV101
12 P1_LIT101 > P1_P101
13 P1_LIT101 > P1_P102
14 P1_LIT101 > min_P1_LIT101 > slope_P1_LIT101
15 P1_FIT101 >= 0.0
16 P1_P101 >= P1_P102 >= slope_P1_LIT101
17
18 ===========================
19 P1_MV101 == 2.0 && P1_LIT101 < max_P1_LIT101 - 16 &&
     ↪ P1_LIT101 > min_P1_LIT101 + 15
20 ===========================
21 slope_P1_LIT101 == P1_P102
22 P1_MV101 == 2.0
23 P1_FIT101 > P1_MV101
24 P1_FIT101 > P1_P101
25 P1_FIT101 > P1_P102
26 P1_MV101 >= P1_P101
```

Listing 4.6: *Revised Daikon output with transitive closures for* PLC1 *of the iTrust SWaT system*

Transitive closures can be appreciated in lines 7, 14 and 16 of Listing 4.6. In general, the output has been reduced in the number of effective rows (19 versus the 61 in the output of Listing 4.5, making it certainly better to read and identify significant invariants) and the invariant chains make it more immediate to grasp the relationships between registers.

4.2.3.2 Types of Analysis

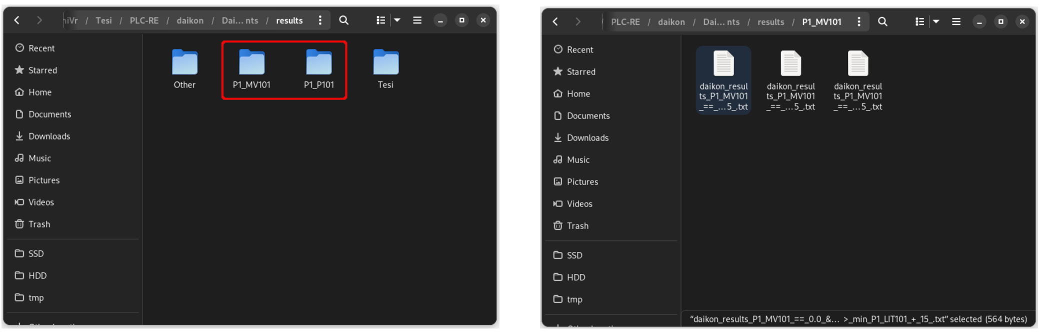
Compared to Ceccato et al.'s solution, in which individual analyses are performed manually, my proposal is to implement two types of semi-automated analysis: the first performs an analysis of all states for each individual register, while the second performs the analysis on the current system configuration based on the actual states of the actuators.
Both analyses refer to a specific measurement, selected by the user.

These two types of analysis will be handled by the Python script `daikonAnalysis.py`, contained in the default directory `$(project_dir)/daikon`. The script accepts the following command-line arguments:

- **-f** or **--filename**: specifies the enriched dataset, in CSV format, from which to read the data. The dataset must be located within the directory containing the enriched datasets specified in the *config.ini* file (by default `$(project_dir)/daikon/Daikon_Invariants`).
- **-s** or **--simpleanalysis**: performs the analysis on the states of individual actuators
- **-c** or **--customanalysis**: performs the analysis on combinations of actual states of the actuators
- **-u** or **--uppermargin**: defines a percentage margin on the maximum value of the measurement
- **-l** or **--lowermargin**: defines a percentage margin on the minimum value of the measurement

One or both types of analysis can be selected. The last two parameters set a condition on the value of the measurement that is meant to bypass the transient periods between the actuator state change and the actual trend change at the maximum and minimum values: this expedient is especially useful for the first type of analysis, allowing for generally more accurate data on measurement trends.

Analysis on single actuator states Analysis on the states of individual actuators is the simplest: after the user is prompted to input the measurement, chosen from a list of likely available measurements, the script recognizes the likely actuators and the relative states of each, using the same mixed Daikon/Pandas technique adopted in the brief analysis during the pre-processing phase.
For each actuator and each state it assumes, a single Daikon analysis is performed, eventually placing the condition on the maximum and minimum level of the measurement.
The result of these analyses are saved in the form of text files in a directory having the name corresponding to the analyzed actuator and contained in the default parent directory `$(project_dir)/daikon/Daikon_Invariants/results`: each file generated by the analysis is identified by the name of the actuator, the state and the condition, if any, on the measurement (see Figure 4.8).



(a) *(b)*

Figure 4.8: *Directory (a) and outcome files (b) for the single actuator states analysis*

An example of the outcome of this analysis is Listing 4.6, where the actuator analyzed is `P1_MV101` in state 2: from the generic invariants we can observe that `P1_P101` is a likely actuator (line 5), assuming binary values; from line 8, however, we note that `P1_P102` is permanently equal to 1, so it can be confirmed that it is a spare actuator rather than a setpoint; furthermore, lines 9 and 10 show the maximum and minimum values reached by `P1_LIT101`, which we have assumed to be the register connected to the tank. The most interesting information, however, comes from the condition-generated invariants: at line 21 we notice that the slope of `P1_LIT101` is 1 (thus increasing) when `P1_MV101` is set to 2: this confirms what we assumed in the previous steps, namely, that `P1_MV101` represents the ON state of the actuator and is responsible for filling the tank `P1_LIT101`; moreover, at line 23 we see that `P1_FIT101` is greater than `P1_MV101`: this means that when the actuator assumes the value 2 the sensor `P1_FIT101` detects data (in contrast, if `P1_MV101` is 1 `P1_FIT101` is 0, detecting nothing), confirming the original hypothesis made that this may be a pressure or flow sensor.

Analysis of the Current System Configuration The analysis of the current system configuration based on the actual states of the actuators is more complex, but at the same time offers more interesting outcomes as it provides better evidence of actuator behavior in relation to the selected measurement.

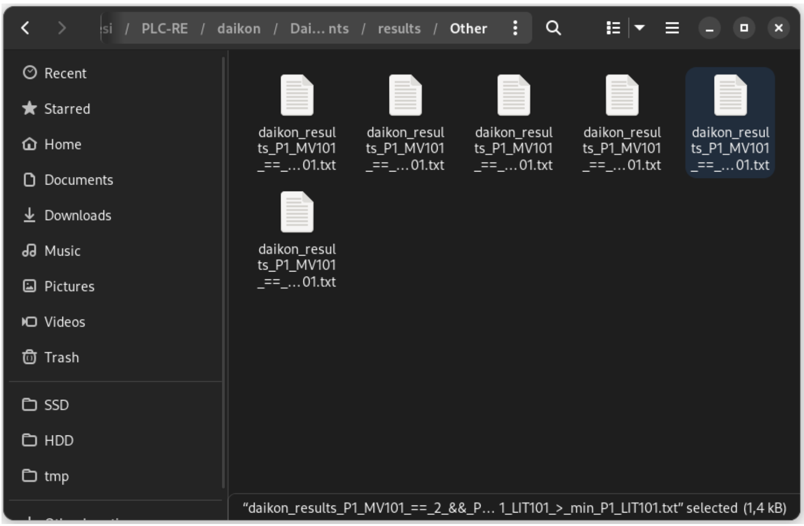


Figure 4.9: *Daikon outcome files for system configuration analysis. Each file represents a single system state*

For this analysis, the script automatically recognizes the actual configurations of the actuators (e.g., `P1_MV101 == 2, P1_P101 == 1`) that represent a system state, and for each of these configurations Daikon analysis is automatically run, after prompting the user for the measurement and eventually the actuators whose configurations are to be studied (If the user does not select any actuators, all those previously detected by the Python script will be considered): the analysis outcomes are saved, still in the text format, within a specific directory under the same parent directory of the previous type of analysis and, as before, their name is characterized by the rule used for the analysis (see Figure 4.9).

An example of the obtained outcomes can be seen in Listing 4.7:

```
===========================
Generic
===========================
P1_MV101 <= P1_P101  ==>  P1_FIT101 >= 0.0
P1_MV101 <= P1_P101  ==>  P1_MV101 one of { 0.0, 1.0, 2.0 }
P1_MV101 <= P1_P101  ==>  P1_P101 one of { 1.0, 2.0 }
P1_MV101 <= P1_P101  ==>  slope_P1_LIT101 one of { -1.0, 0.0, 1.0 }
P1_MV101 > P1_P101  ==>  P1_FIT101 > P1_MV101
P1_MV101 > P1_P101  ==>  P1_FIT101 > P1_P101
P1_MV101 > P1_P101  ==>  P1_FIT101 > P1_P102
P1_MV101 > P1_P101  ==>  P1_FIT101 > slope_P1_LIT101
P1_MV101 > P1_P101  ==>  P1_MV101 == 2.0
P1_MV101 > P1_P101  ==>  P1_MV101 > P1_P102
P1_MV101 > P1_P101  ==>  P1_MV101 > slope_P1_LIT101
P1_MV101 > P1_P101  ==>  P1_P101 == 1.0
P1_MV101 > P1_P101  ==>  P1_P101 == P1_P102
P1_MV101 > P1_P101  ==>  P1_P101 == slope_P1_LIT101
P1_MV101 > P1_P101  ==>  slope_P1_LIT101 == 1.0
[...]

===========================
P1_MV101 == 2 && P1_P101 == 1 && P1_LIT101 < max_P1_LIT101 && P1_LIT101 > min_P1_LIT101
===========================
slope_P1_LIT101 == P1_P102 == P1_P101 == 1.0
P1_MV101 == 2.0
P1_FIT101 > P1_MV101
```

```
27    P1_FIT101 > P1_P101
```

Listing 4.7: *Daikon outcomes for the system configuration* `P1_MV101 == 2, P1_P101 == 1` *on* `P1_LIT101`

Compared to Listing 4.6, this time we can observe in the general invariants section the presence of implications, which were previously absent (the remaining generic invariants have been omitted for reasons of space). Such implications can provide very useful information, as in this case: for example, the invariant on line 18 tells us that if the value of `P1_MV101` is greater than that of `P1_P101` then the value of the slope is 1, that is, the tank level is increasing. Consequently, we have further confirmation that the state `P1_MV101 == 2` is the ON state for that actuator and that it is the actuator responsible for filling the tank `P1_LIT101`. Comparing the other analysis outcomes, we will discover that `P1_P101` is instead responsible for emptying the tank and that its ON and OFF states are 2 and 1, respectively.
In addition, the invariant at line 8 also indicates that when the actuator `P1_MV101` is in state 2 and `P1_P101` is in state 1 then the value of `P1_FIT101` is greater than 2: consequently, it follows that the corresponding sensor is measuring something relative to the tank `P1_LIT101`.
The above is confirmed by the invariants related to the analysis condition: at line 24 we have that the slope is indeed equal to 1 (thus increasing) and that `P1_FIT101`, at line 26, takes values greater than 2 when `P1_MV101` is equal to 2.

Refining the Analysis In some cases, it may happen that the outcomes provided by the semi-automated analyses are not satisfactory to the user (e.g., the value of the slope may not emerge clearly) or simply the user wants to investigate a particular aspect of the system in more detail by trying to discover additional invariants that did not emerge previously: in this case, it is possible to run a new and more specific invariant analysis using the Python script `runDaikon.py`, which allows for more punctual analyses of the system.

The script, also contained in the default directory `$(project_dir)/daikon`, accepts three command-line parameters:

- **-f** or **--filename**: specifies the enriched dataset, in CSV format, from which to read the data. Even in this case, the dataset must be located within the directory containing the enriched datasets
- **-c** or **--condition**: specifies the condition for the analysis, which will be automatically overwritten in the *.spinfo* file. It is possible to specify more than one condition, but it is recommended to use the logical operator `&&`
- **-r** or **--register**: specifies the directory where to save the text file with the outcomes

Performing this single analysis will produce a single output file containing the invariants discovered, file that will be saved in the directory specified by the user via the `-r` command-line option (by default the file will be saved in the directory `$(project_dir)/daikon/Daikon_Invariants/results`) to be examined later by the user.

In conclusion, the two types of analysis presented, along with the possibility of allowing for more refined analysis at a later date and Daikon's redefined output, make this stage much more complete, clear, and powerful than before

4.2.4 Phase 4: Businness 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 Businness Process Analysis

Chapter 7

Conclusions

7.1 Discussions

7.2 Guidelines

7.3 Future work

List of Figures

List of Tables

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