Development of a Testbed to Demonstrate Attacks on Emulated PLC Networks

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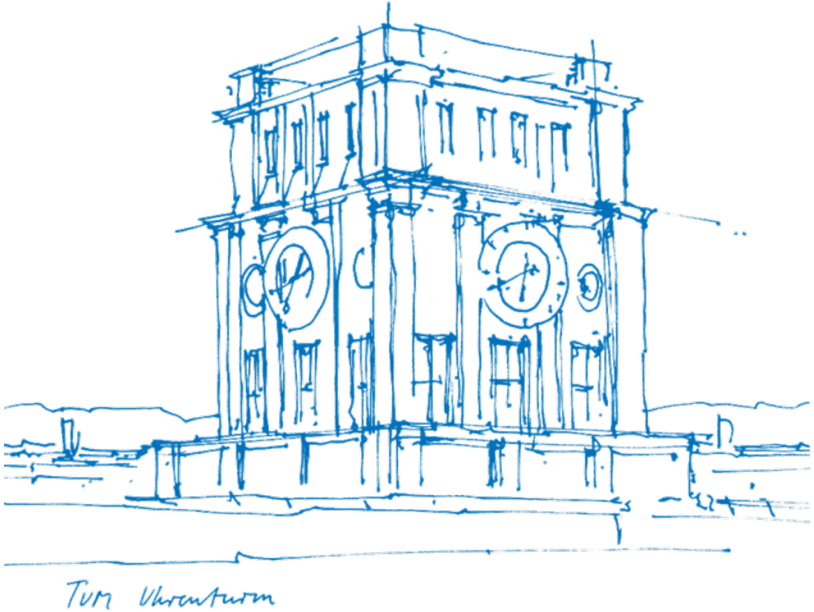

Outline

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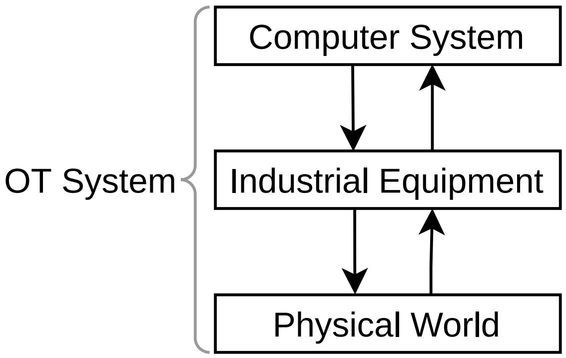
Introduction - Defining IT and OT

Information technology (IT): corporate systems that primarily process information

Operational Technology (OT):

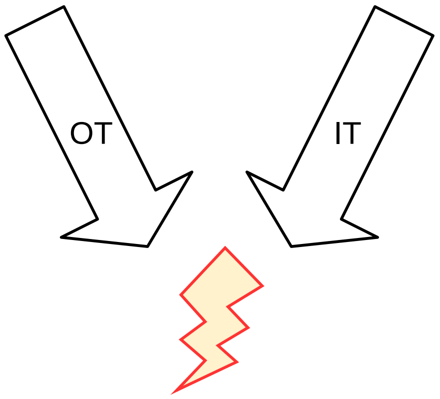
- directly interact with the physical world ⇒ **cyber-physical systems**
- control industrial components
- **industrial control systems (ICS)** are a common type of OT network. (more details later)



Introduction - Convergence of IT and OT

- IT and OT have become more connected to each other
  ⇒ **control networks previously were isolated**
  ⇒ but **now** are **connected to corporate networks or the Internet**
- IT hardware and software is now more frequent in OT systems
  ⇒ systems are now vulnerable to "general-purpose" malware
- previously **unaddressed problems become more apparent**:
  - insecure protocols
  - weak authentication
  - lack of attention towards network security

⇒ **OT networks receive more attention from attackers** . . .
. . . but from security researchers as well.



Growing Pains

Introduction - Motivation and Objectives

- ICS's (and other OTs) are essential to the functioning of society ⇒ **critical infrastructure**
- Pre-existing testing environments commonly do not address programable logic controllers (PLCs) in-depth

⇒ **Observation:** we require a **safe and realistic testbed** that . . .

- focuses on PLCs
- **can educate both IT and OT personnel** on known issues or attacks
- **enables security research**

Background - Industrial Control Systems

- ICS is a generic term for a wide array of **cyber-physical systems**.
- used to automate and control processes in industry and critical infrastructure.
- different ways to structure ICS networks:
  - **Distributed Control Systems (DCS)**: decentralized, local and a flat hierarchy
    $\Rightarrow$ e.g. **power plant**
  - **Supervisory Control and Data Acquisition (SCADA) Systems:** centralized, multiple regions, tall hierarchy
    $\Rightarrow$ e.g. **power grid**
  - **single PLC** controlling an industrial process

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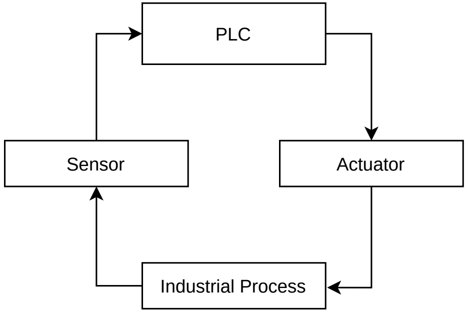
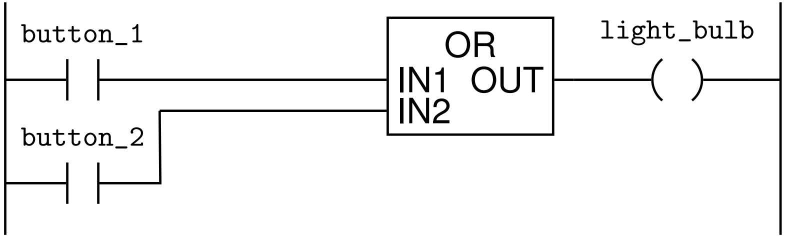
Background - Programable Logic Controllers

- devices used to **control processes**, used in **both SCADA systems and DCS's**
- designed for **rough environments** (low/high temperatures, vibration, etc.)
- **Run a loop:**
  1. read inputs (usually sensors, e.g. a thermometer)
  2. run PLC program
  3. write instructions to outputs that affect the physical world (actuators, e.g. servo)
- **PLC programs can be written in five languages** (standardized in IEC 61131-3)
  ⇒ we are only using Ladder Diagrams (LD)





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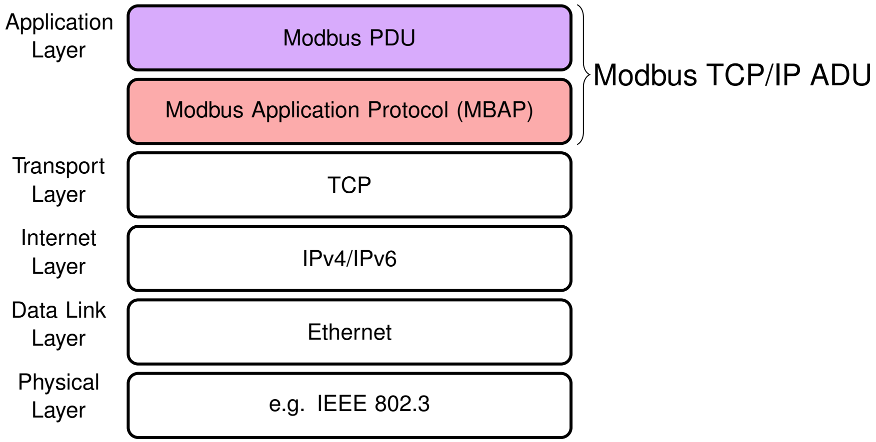
Background - Modbus Protocol

- commonly used in ICS networks, especially with PLCs to communicate with other ICS components.
- open protocol, standardized by the Modbus Organization.
- **originally** used asynchronous **serial** connections, **evolved to support TCP/IP**
- client-server protocol with request-response pairs.



Modbus TCP/IP in the five-layer Internet model

Background - ICS and PLC Attacks

ICS attacks:

- ICS's are also vulnerable to many attacks known from IT
- many attacks are made possible by bad practices
  - protocols lacking encryption, authentication and integrity protection
  - passwords are insecure or hardcoded
  - legacy OS's

PLC attacks:

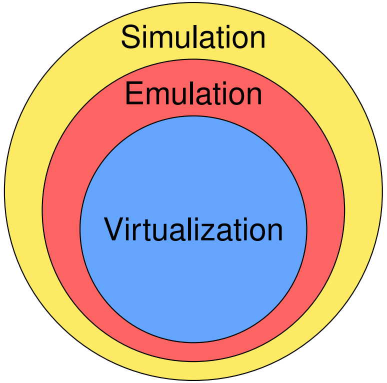
- modification of communicated sensor and actuator values
- upload a malicious PLC program

$\Rightarrow$ **only a small selection!**

Background - Simulation, Emulation and Virtualization

- **Simulation:** replication of a real-world system over time
- **Emulation:** replace hardware components with software
- **Virtualization:** decouple relationship between physical hardware and abstractions of it

Relationship of the three techniques:



Related Work (1)

I found the following relevant testbed surveys . . .

- *Holm et al.* (2015)
  - analyzes requirements posed to ICS testbeds and how they are adhered to ⇒ affected conceptualization
  - note that many testbeds do not address the requirement “fidelity”
  - **most important ICS testbed related survey**
- *Qassim et al.* (2017) and *Geng et al.* (2019)
  - both analyze the advantages and disadvantages of different realization techniques
  - assess hybrid techniques and virtualization as best ⇒ should be utilized whenever possible

Related Work (2)

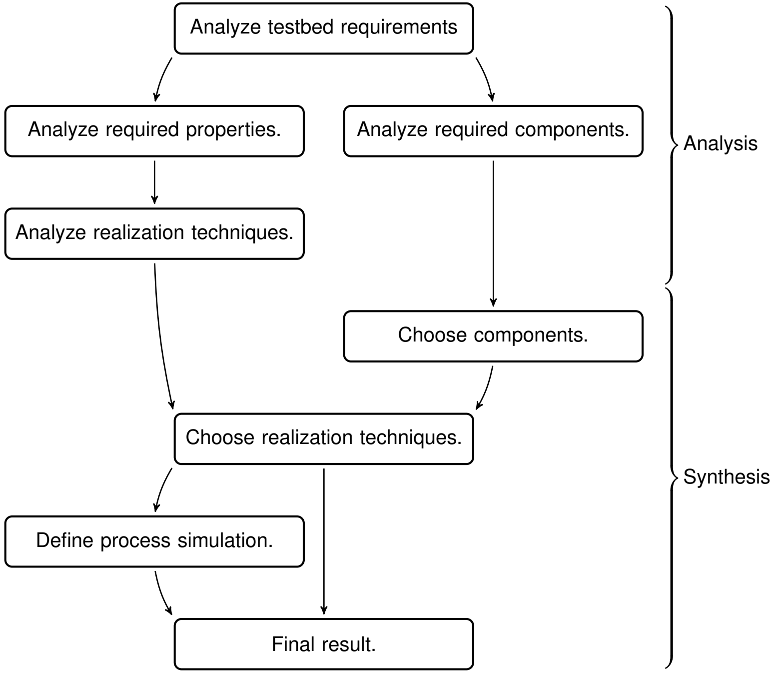
. . . and the following more concrete papers.

- *Formby et al.* (2018) developed an ICS testbed
  - does not include all components we include
  - partially uses proprietary software
- *Alves et al.* (2018)
  - **general approach** to SCADA testbeds **instead** of a **specific testbed** that can be used by readers
  - discuss a number of case studies using their testbed approach

⇒ **this thesis introduces**:

- **an exhaustive, high fidelity testbed** with a largely automated setup,
- **that only uses free and open-source components**,
- and is **shown to be able to demonstrate attacks and find new vulnerabilities**.

Conceptualization - Steps



Conceptualization - Required Properties

The ICS testbed survey from **Holm et al. (2015)** poses four properties to such an environment:

1. **Fidelity**
   - accuracy of mirroring real systems
   - addressed either by replicating a real system or based on standards
2. **Repeatability**
   - results need to be verified $\Rightarrow$ repetition is one way
   - **tests should have consistent results**
3. **Measurement Accuracy**
   - measuring should not affect the outcome of tests
   - **Comparison:** observer effect from physics
4. **Safe Execution of Tests**
   - no harm to living beings, environment, or equipment
   - testbed should not be damaged

Conceptualization - Additional Properties and Goal Conflicts

Furthermore, we have to address the following properties:

- **real-time properties**: e.g. low networking delays
- **affordability/low cost**: reduce financial barriers, make it affordable for everyone
- **open-source** components
- **reduced manual set-up**, use automation

However, some goals partially **conflict**:

- highest fidelity vs. open-source
- highest fidelity vs. low cost

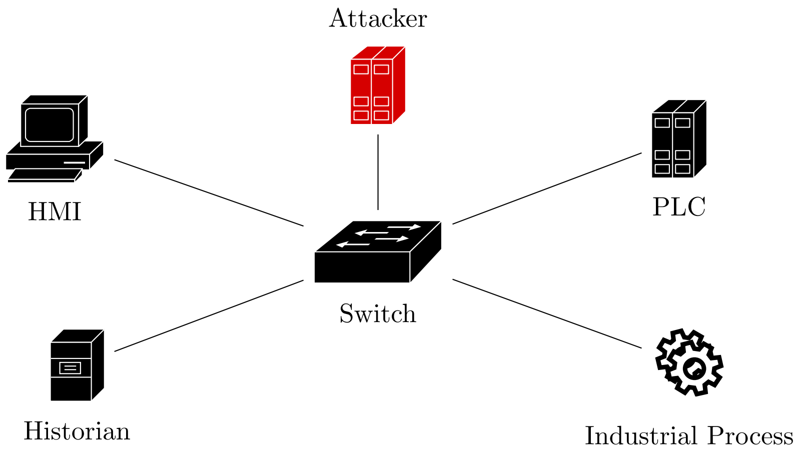
some **compliment** others:

- open-source $\Rightarrow$ low cost
- safe execution $\Rightarrow$ repeatability

Conceptualization - Required and Included Components

The ICS testbed survey from **Holm et al. (2015)** names a number of **required components**, we include:

- **control center:** HMI, data historian
- **field devices:** PLC
- **physical/industrial process:** an industrial process controlled by a single PLC
- **communication architecture:** switched ethernet network
- **used protocols:** (later slides)



Conceptualization - Realization Techniques: Pros and Cons

- **Physical replication** of the system
  - not an option for our entirely virtual testbed
  - High fidelity and accuracy, repeatability, but can be unsafe and expensive!
- **Simulation**
  - safe, scales well, affordable, but low fidelity, accuracy
  - **not the best option to research cybersecurity threats** $\Rightarrow$ does not use real hard or software
- **Emulation:**
  - **good to replace hardware components with software** (avoid cost and damage)
  - high fidelity, safety, repeatability, accuracy
  - however accuracy depends on the quality of the emulation
- **Virtualization:**
  - high fidelity, repeatability, accuracy, safety, lower cost, scales well
  - usually the best approach, but **not always possible**
- **Hybrid approach:**
  - choose best approach for each component $\Rightarrow$ best overall properties
  - however, can be expensive if physical hardware is used

Conceptualization - Choosing the Correct Approach

- **HMI & data historian ⇒ real software + virtualization**
  - easy to virtualize
  - usually software running on x86 architecture + commodity OS (Windows, Linux, etc.)
- **PLC ⇒ emulation via software PLC**
  - simulation would be too inaccurate, limits ability to research cybersecurity of PLCs
  - we can use real PLC programs and protocols
- **industrial process ⇒ software simulation**
- **communication architecture ⇒ network virtualization**
  - use real network stacks and protocols ⇒ **examine real network based attacks**
  - **no major drawbacks**

⇒ **we use an hybrid approach**

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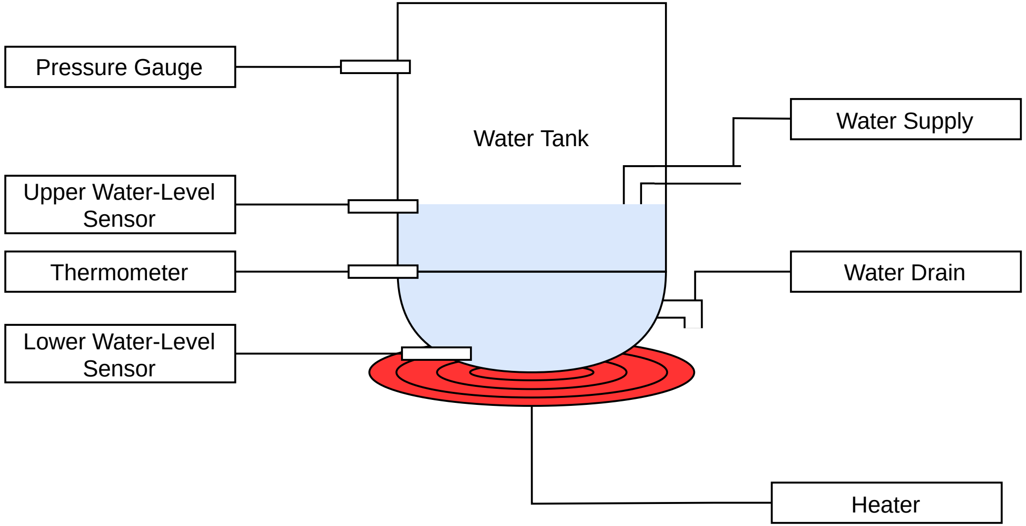
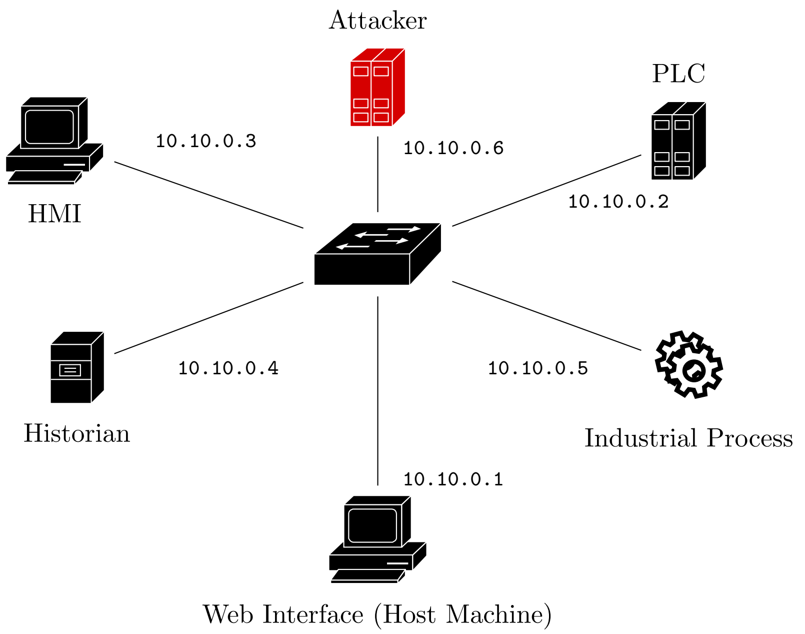
Conceptualization - Process Simulation Model



⇒ **behavior will become clear in the demo!**

Implementation - Virtualizing the Hosts and Network

- use **libvirt** as our virtualization management framework
  $\Rightarrow$ **provides virtualized networking and VMs**
- **hosts** run Ubuntu cloud images + cloud-init
- we automate the installation of dependencies and configuration as much as possible with libvirt and cloud-init
- communication between hosts uses the Modbus protocol



Implementation - Testbed ICS Components

- **PLC ⇒ OpenPLC**
  - only open-source PLC
  - supports all IEC 61131-3 programming languages
- **HMI ⇒ ScadaBR**
  - gathers data from the PLC and industrial process
  - can be used to build graphical views (control and monitor)
- **data historian ⇒ TICK stack**
  - based on **T**elegraf, **I**nfluxDB, **C**hronograf and **K**apcitor
  - a lot more powerful than just using the HMI for some limited record keeping
- **industrial process** ⇒ next slide!

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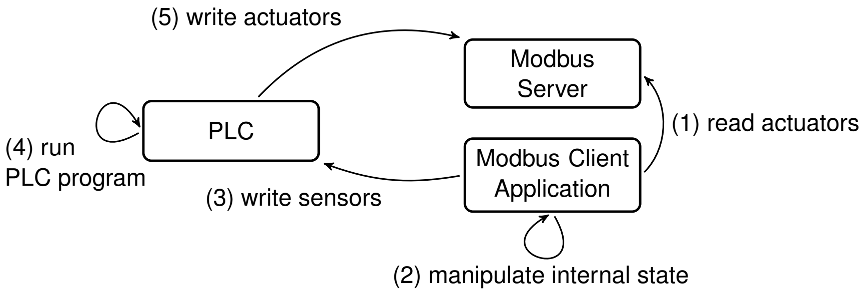
Implementation - Simulator

- implements the simulation model we defined in the conceptualization part
- written in Python using the PyModbus library for Modbus communication
- consists of a Modbus server and a application using a Modbus client



Tech Demo

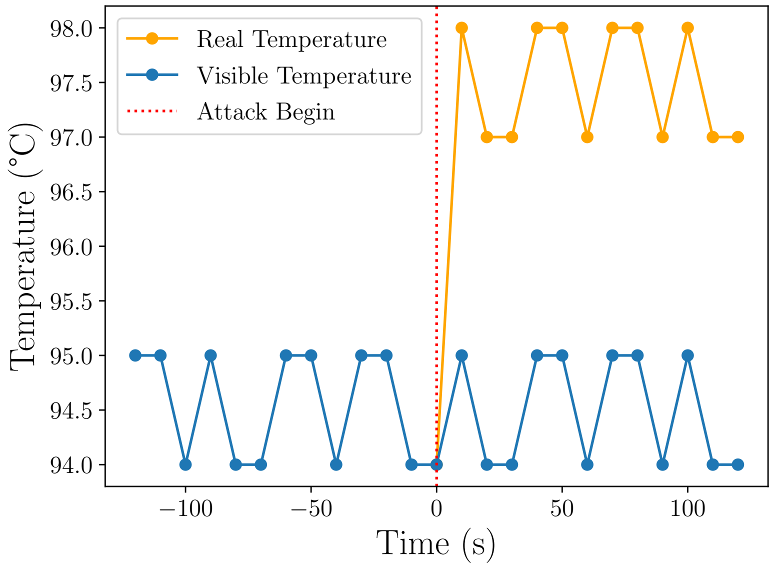
Attack Demonstration - Adversary

- **Before discussing attacks how could an adversary have gotten access?**
  - propagate from a corporate network to a field network ⇒ inadequate firewalls or DMZs
  - exploitation of a remote access point
- **What information does an attacker require to launch these attacks?**
  - all necessary information publicly avoidable (e.g Modbus specification)
  - no need for complicated reverse engineering tasks, that might require purchasing hardware

  ⇒ **required know-how is reasonable!**
- **Immediately before the attack:** attacker gains a MitM position via ARP cache poisoning

Attack Demonstration - Manipulating the Thermometer (1)

- **Background:** Modbus traffic is not secured at all
- **Idea:** alter sensor values communicated via Modbus
  - under report temperature
  - PLC receives false information and behaves accordingly
  - temperature reaches unsafe levels and system becomes damaged



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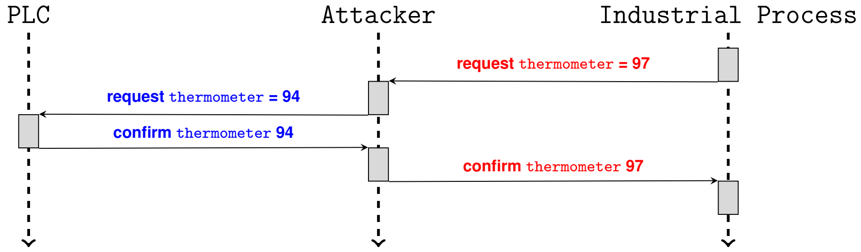
Attack Demonstration - Manipulating the Thermometer (2)

How does the attack work?

- we match specific write requests and their responses
- use a NetfilterQueue + ScaPy based application to modify packets in real-time
- both PLC and industrial process are oblivious to the manipulation
- **correct sensor values do not appear in any of the logs ⇒ stealthy**
- **attack principle can be applied to all other Modbus connections in our setup**



MitM modification

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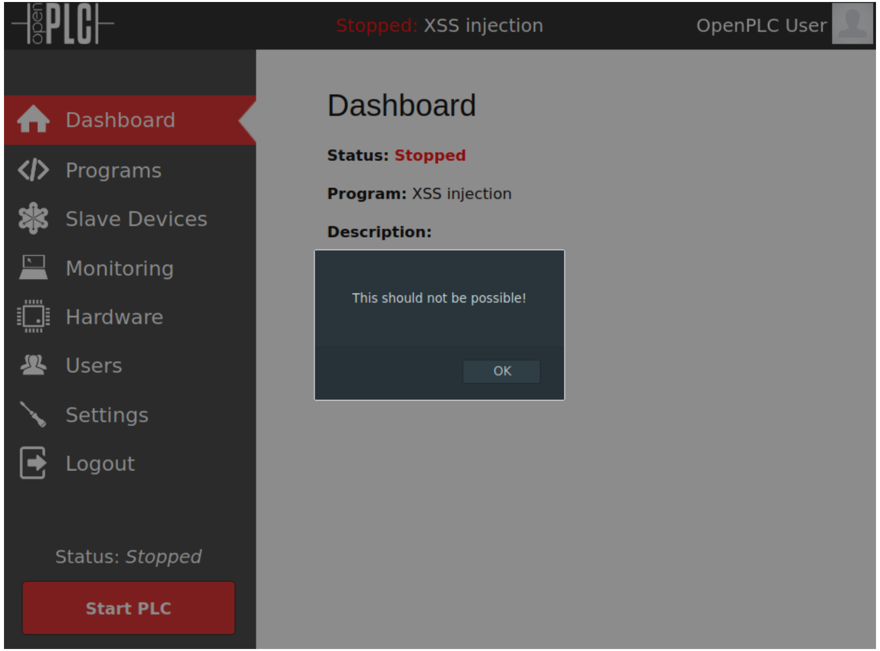
Attack Demonstration - Other Possible Attacks

- **variation of the previous attack**
  - redirect requests to a malicious server, instead of manipulating the traffic directly
  - choose what sensor or actuator values are passed on
- **sniff password to the OpenPLC web interface and upload a malicious PLC program**
- **most trivial attack:** write falsified values to any of the Modbus servers **(no authentication)**
- Exploit an **injection vulnerability** I discovered in the **OpenPLC web interface**
  - lack of input sanitation in multiple POST forms
  - **requires access to web interface** credentials (can be sniffed)
  - **consequences:** able to launch persistent XSS attacks



Attack Demonstration - Discussion

We observe that:

- the testbed is suitable to implement and demonstrate cyber-attacks
- ARP cache poisoning is an important factor in MitM attacks
- **lack of** attention towards security goals (e.g. integrity) in ICS software
- **attacks could be avoided**
  - lack of HTTPS support (OpenPLC, ScadaBR)
  - lack of TLS support in Modbus implementations $\Rightarrow$ TLS variant exists, but seems to lack common support
- confirm that PLCs are desireable attack targets

Conclusion - Status

- we succeeded in building a PLC testbed that can be used for attack demonstration and cybersecurity research

- **Strengths:**
  - good at examining network/communication based attacks $\Rightarrow$ virtualized networking
  - address common requirements (properties, components)
  - affordable/free
- **Weaknesses:**
  - strictly open-source components $\Rightarrow$ less used in industry, reduces fidelity, codebase-specific attacks
  - cannot examine more physically based attacks (e.g. those targeting I/O pins)

- **Realized Goals:** complete testbed suited for attack demonstration and research
- **Open Goals:** focus on real-time requirements, more realistic simulation

Conclusion - Future Work

- examine real-time behavior of our system and how it is affected by attacks
- improve testbed in collaboration with OT personnel ⇒ **cross-sectional teams can be very important**
- examine the applicability of the TICK stack for intrusion/anomaly detection
- explore the potential of lightweight virtualization techniques such a containerization (e.g. Docker) ⇒ might decrease fidelity

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Thank you for your attention!