A Virtual Environment for Industrial Control Systems: A Nonlinear Use-Case in Attack Detection, Identification, and Response

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Context

Problem – Attacks to critical infrastructures:

- Critical infrastructures interact with the real world
- Attacks have huge financial, economical, political and even military impact

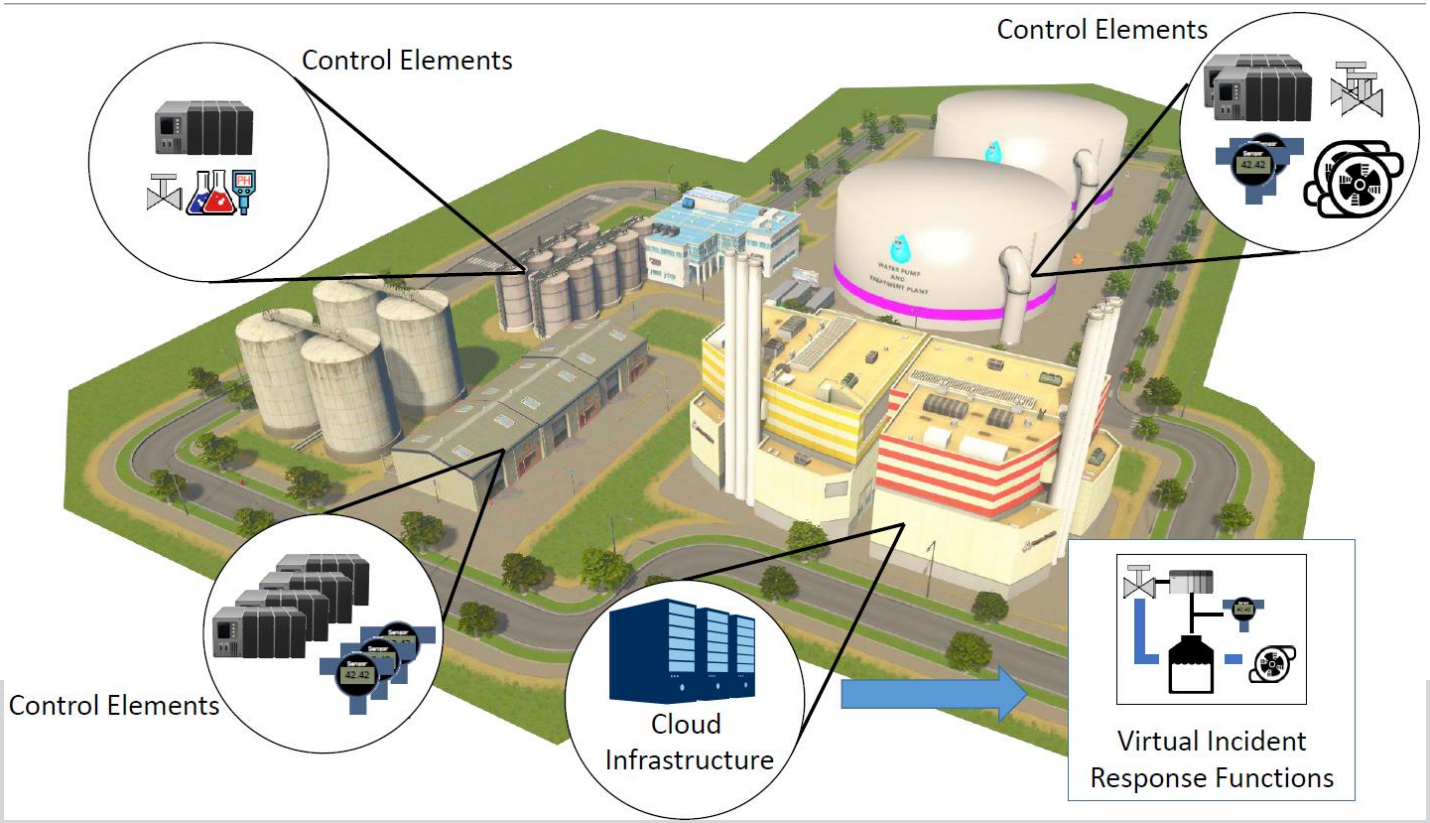
Credit: Office of the Presidency of the Islamic Republic of Iran

Credit: Steag/VGB Power Tech GmbH, CC BY-SA

Context

We need:

- Environments for testing security of industrial control systems
- Fidelity of testing environments is important



Proposal

Idea:

- Virtual environments offer a high fidelity environment without the cost associated to physical environments

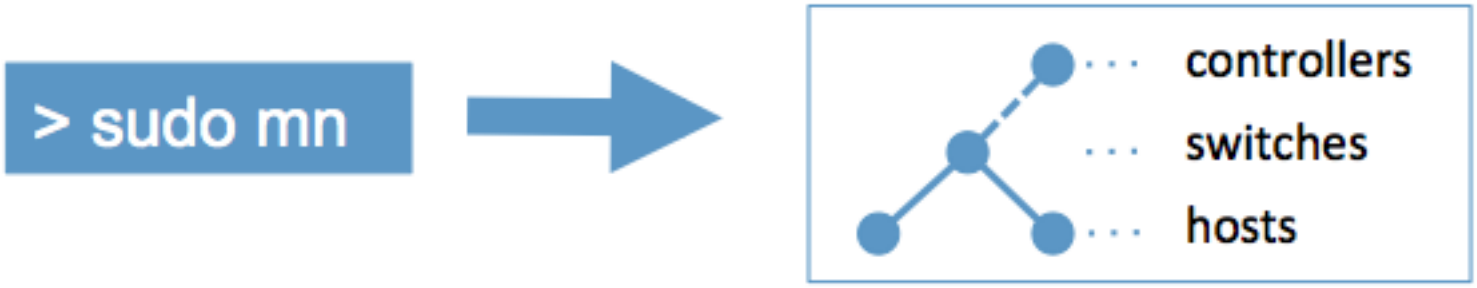
Proposal:

- Using a virtualized open source platform to test security approaches for Industrial Control Systems (ICS)

Virtual Environments for Industrial Control Systems

Previous work:

- Mininet: light virtualization tool to emulate communication networks (http://mininet.org/)



- Mininet enables to emulate network topologies, in which each host and switch is represented by a container

Virtual Environments for Industrial Control Systems

Previous work:

- MiniCPS: mininet extension that enables the emulation of industrial control systems (https://github.com/scy-phy/minicps)

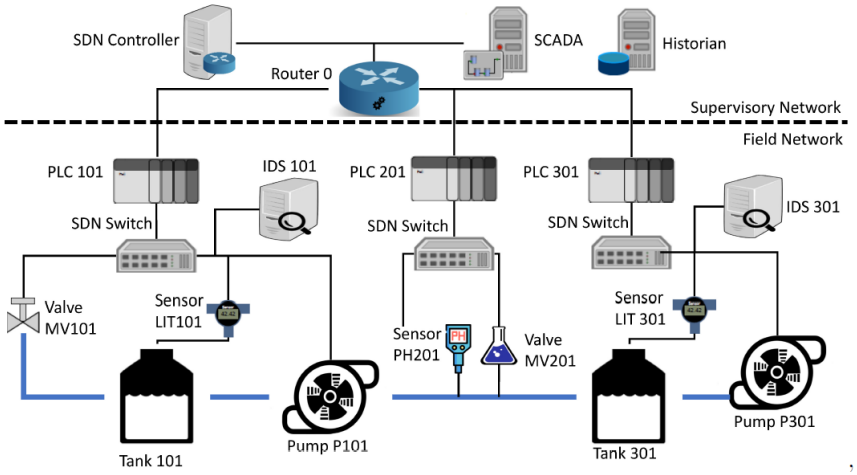
- MiniCPS emulated plants with very simplistic models
  - MiniCPS does not represent plant-sensor and actuator-plant behavior

Virtual Environments for Industrial Control Systems

Our previous work:

- Virtual Incident Response Functions in Control Systems

- Topology with three control loops
- Emulation of Sensor-PLC-Actuator communication



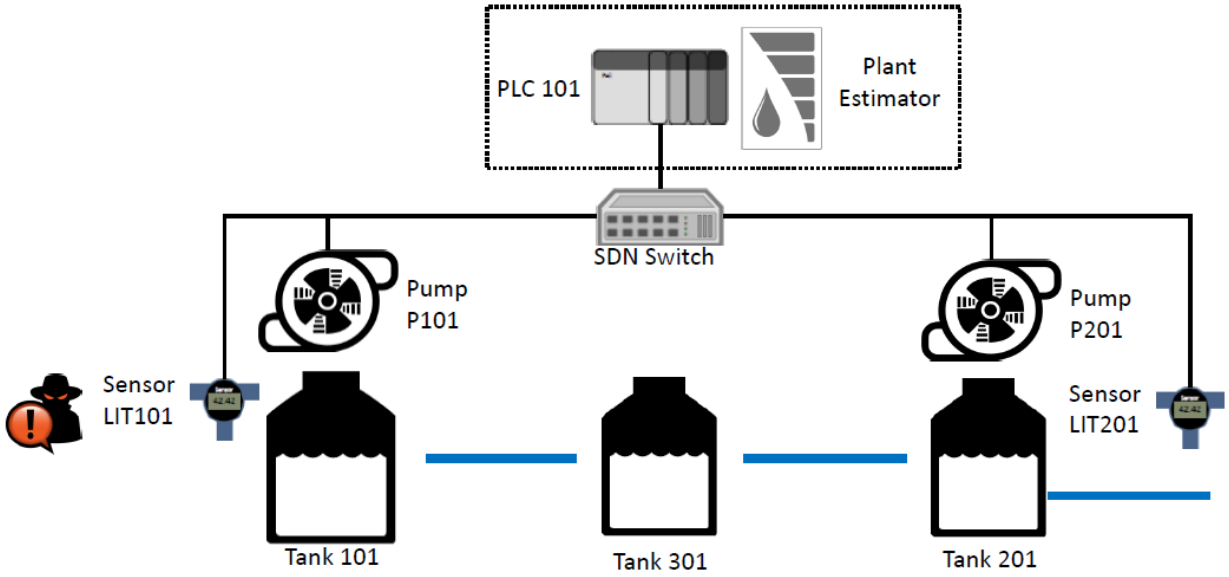
Plant model was still too simple.

- In such systems is difficult to grasp network impact in security attacks

In this paper,

We extend our previous work by using a non-linear plant for experiments

- One control loop
- Behavior of the three tanks is interdependent,
- Non-linear
- Tank 301 is not controlled



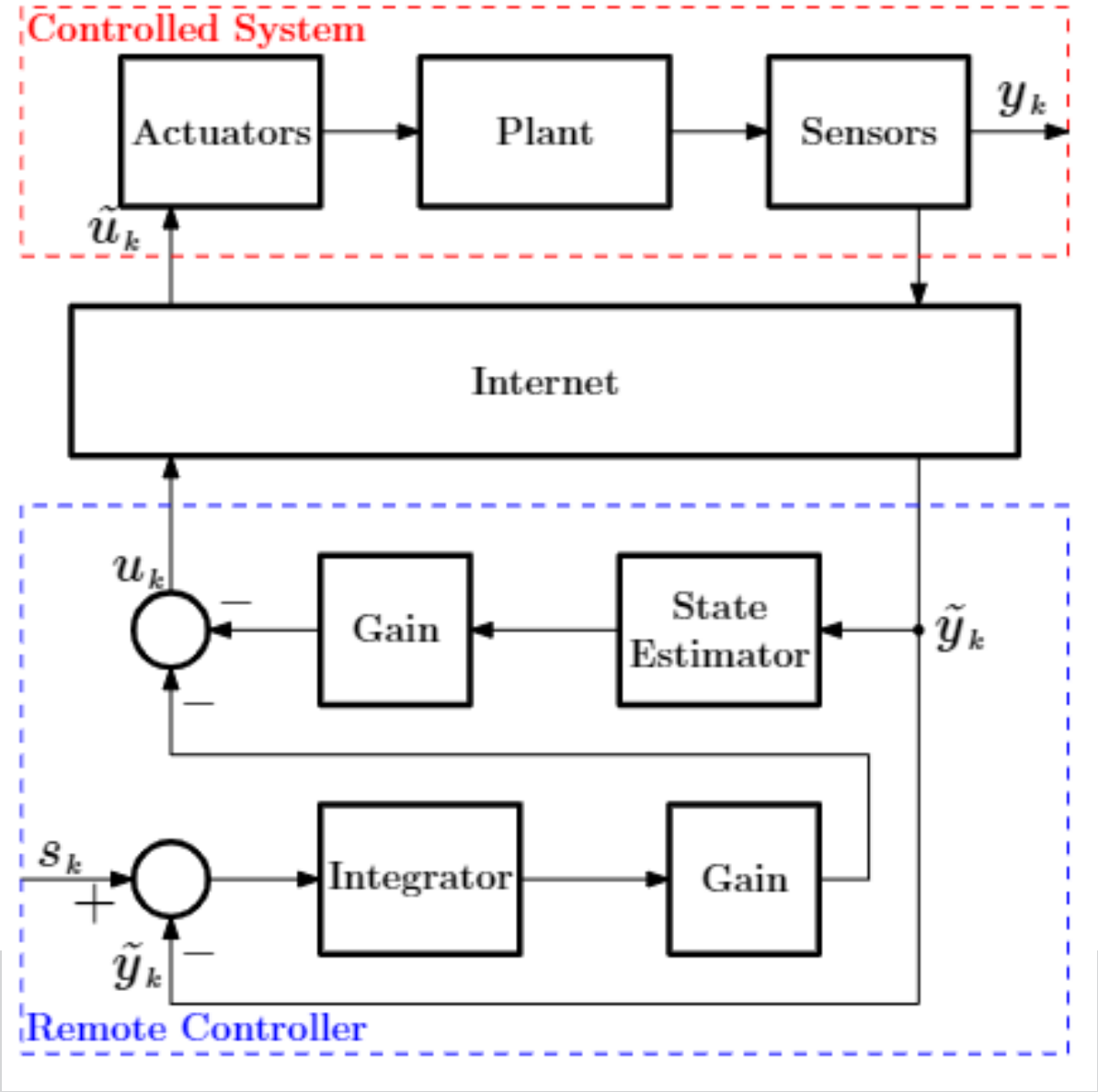
Basics - ICS Model

Objective:

- Keep the plant at a desired setpoint

Flow:

1. Controller receives reading from sensor
2. Controller calculates action control
3. Controller sends commands to actuators



Basics - ICS Model

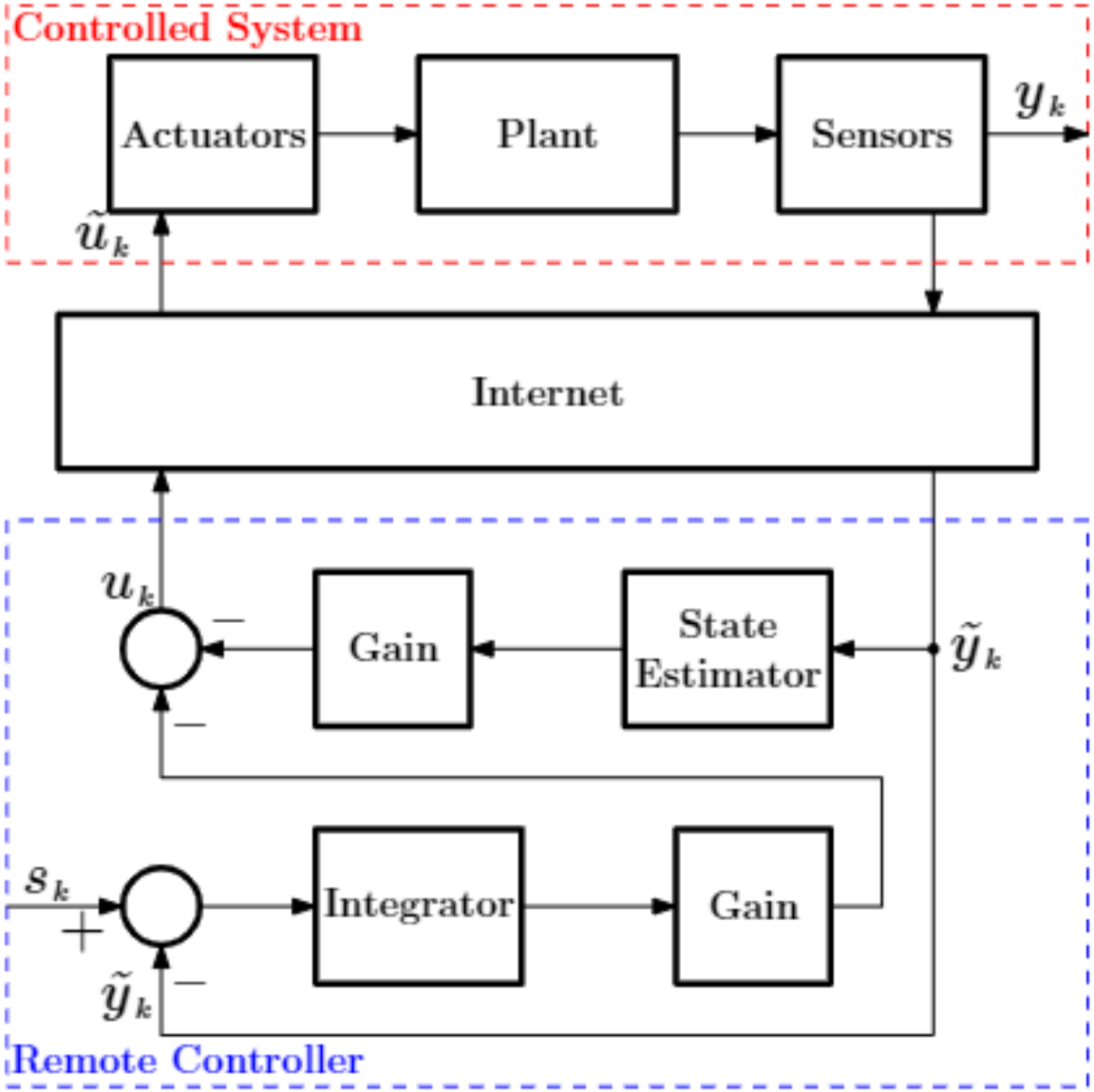
Plant is represented by:

$$X_{k+1} = AX_k + Bu_k$$
$$Y_k = CX_k$$

X → Plant State
Y → Sensor Output

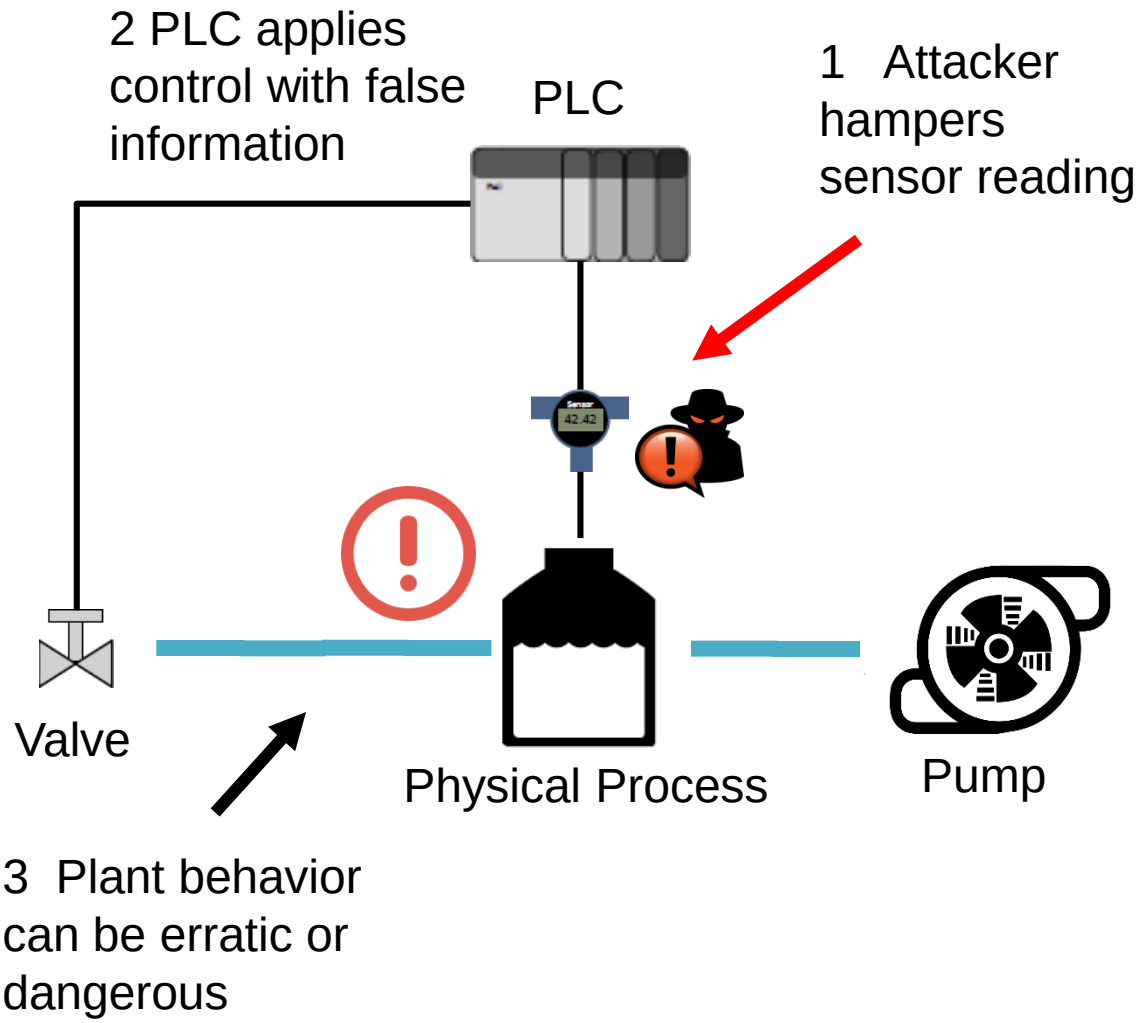
Sensor reading might not represent accurately plant state!

- Malfunction
- Attack



Integrity Attacks

Integrity Attacks:
An integrity attack tampers sensor readings



Integrity Attacks – Malware Attacks

- Integrity attacks on ICS networks are akin to malware on traditional IT environment

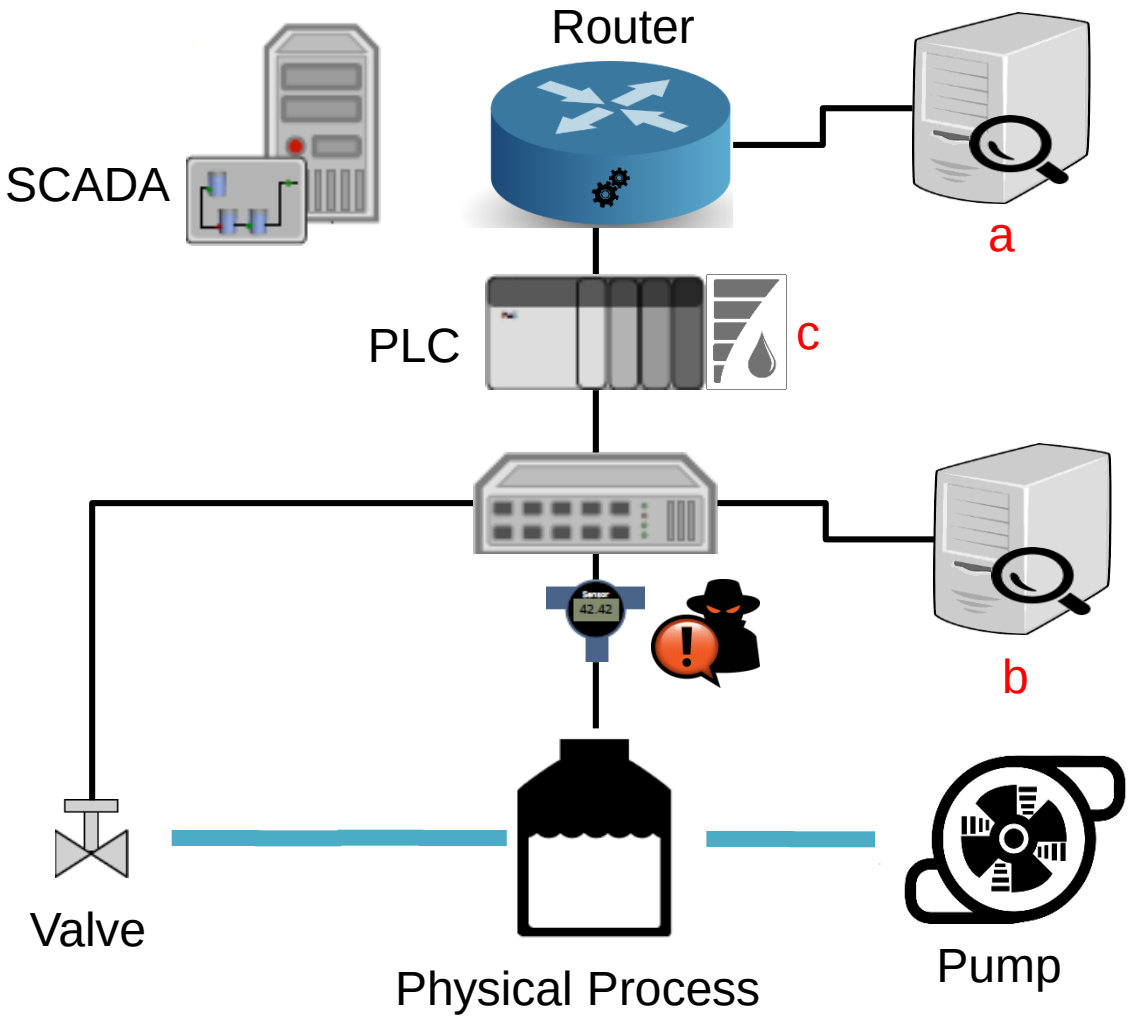
- In both cases, the message can be authentic and have integrity
  - Payload is designed with deep knowledge of application
  - Payload “tricks” main application to perform desired behavior

- In both cases, defenses require to inspect the packet payload

Integrity Attacks - Defenses

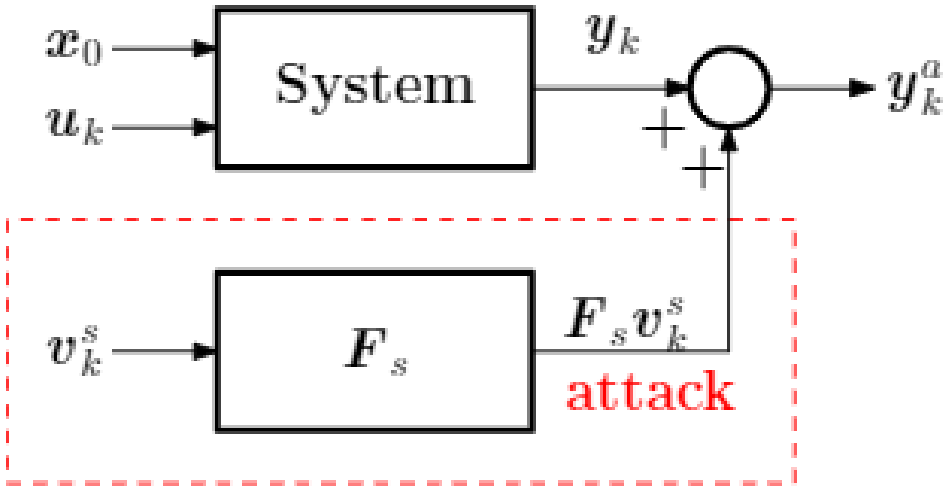
Defenses to this type of attacks could be applied at different network points

a) IDS at supervisory level
b) IDS at field level
c) IDS integrated into the PLC



Bias Attacks

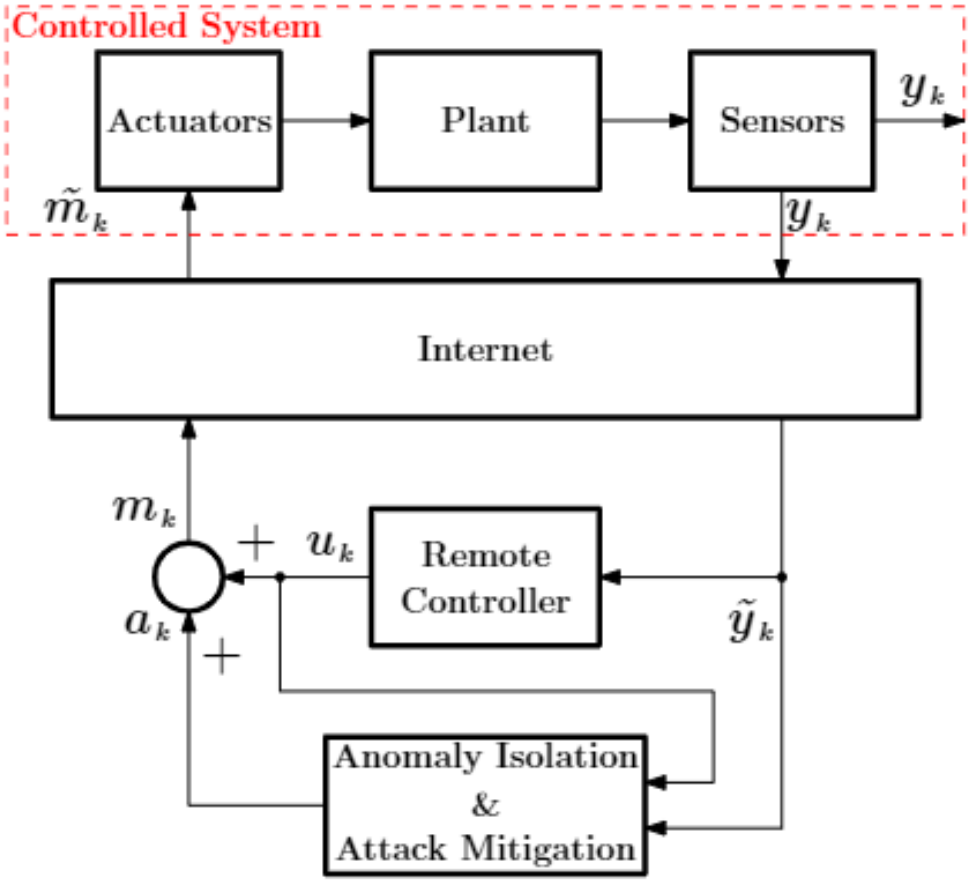
- Also an integrity attack
- A bias attack adds an F value to the original sensor reading



Detection

Anomaly Detection:
Unknown Input Observer (UIO)

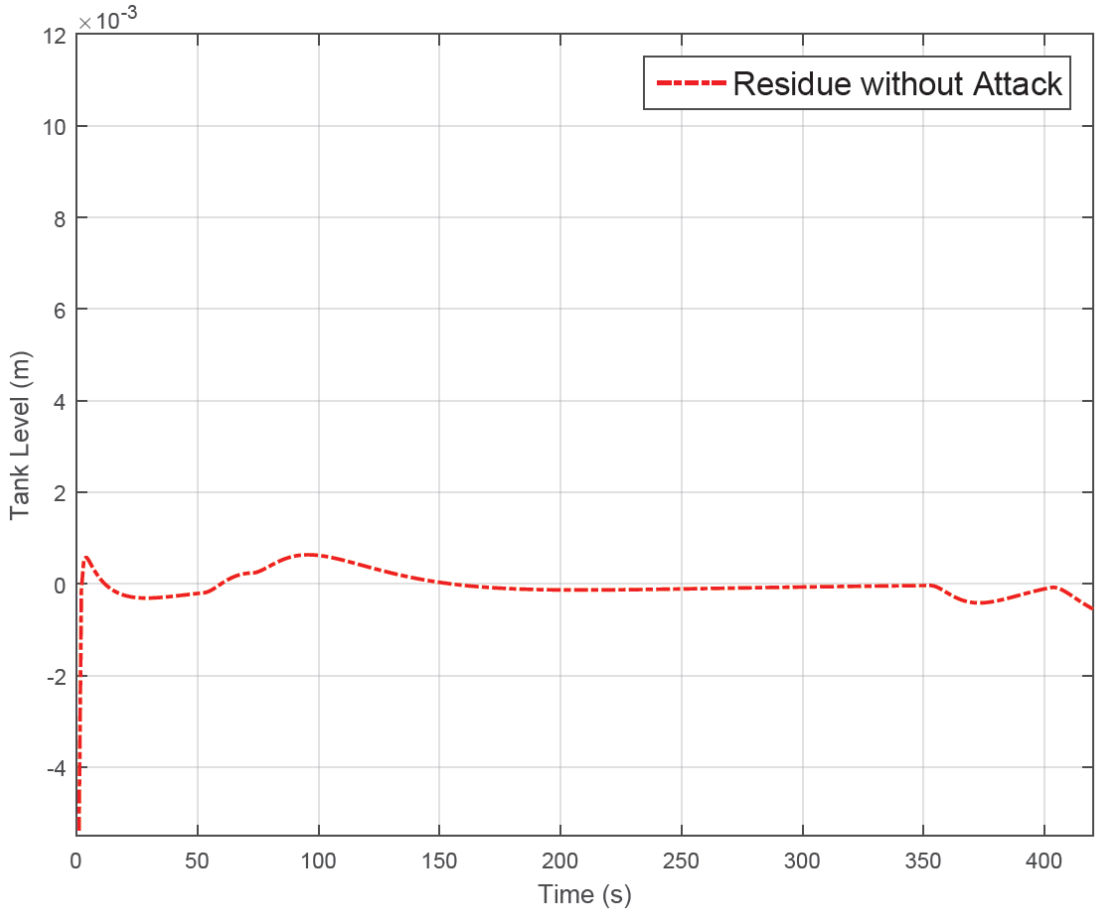
- Known plant behavior
- Plant behavior must follow physical laws
- Anomaly detection can be performed using physical laws
- If at time k, the systems deviate from expected physical model, an anomaly is detected



Detection

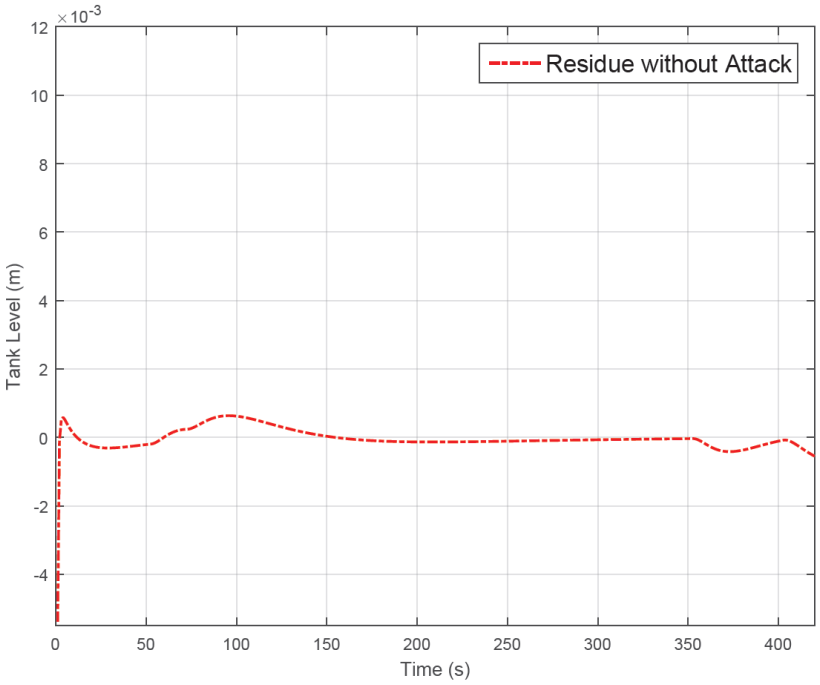
Anomaly Detection:
Unknown Input Observer (UIO)

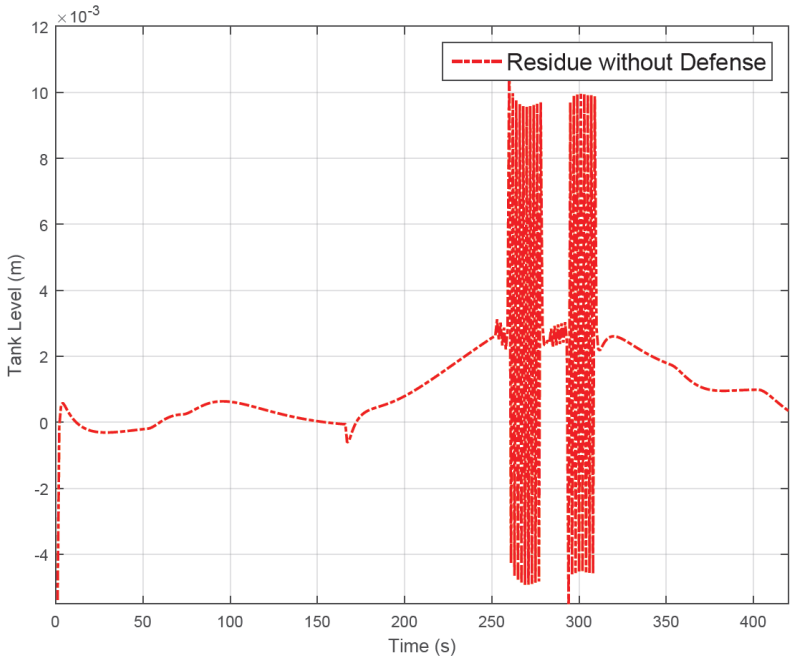
- Plant behavior must follow physical laws
- The residue of the plant without an attack is measured, this is used as a base value
- If at time k, the systems deviate from expected physical model, an anomaly is detected



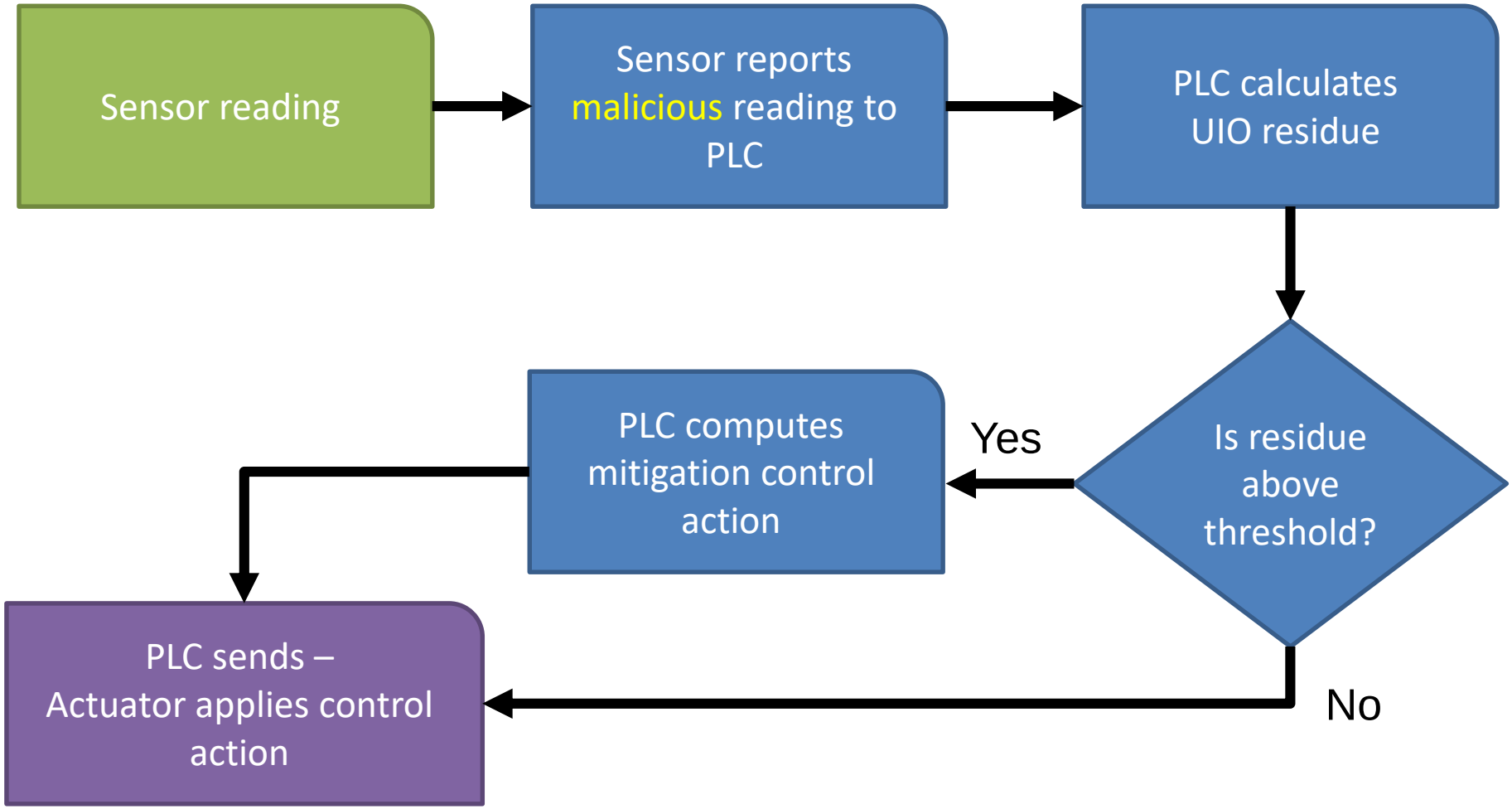
Detection

Anomaly Detection:
Unknown Input Observer (UIO)





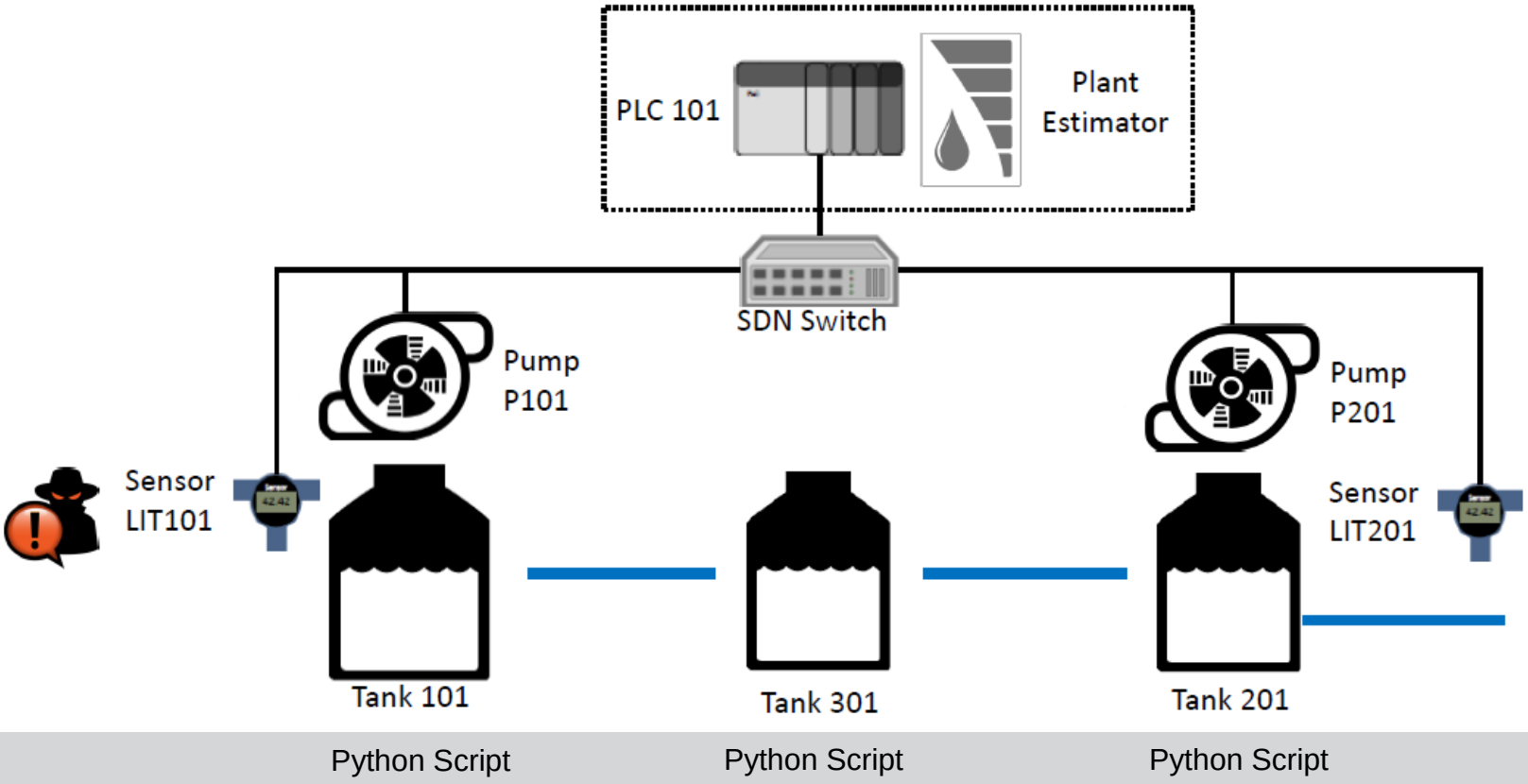
Response


Sensor reading
Sensor reports malicious reading to PLC
PLC calculates UIO residue
Is residue above threshold?
Yes
PLC computes mitigation control action
No
PLC sends – Actuator applies control action

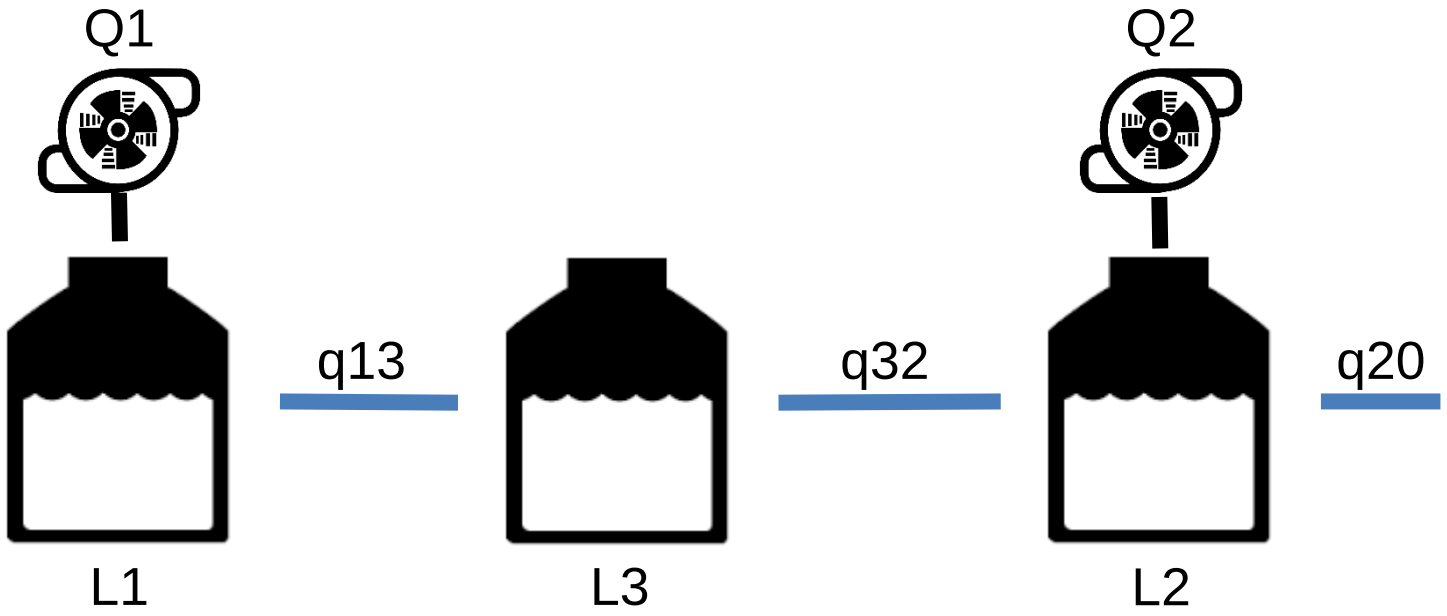
Evaluation

Setup:

- Mininet - MiniCPS
- Physical plant
  - Three tank water plant
  - Python odeint differential equation system solver



Evaluation



Setup:

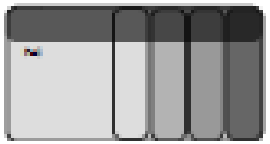
- Plant equations:

$$
\begin{aligned}
S\frac{d}{dt}L_1(t) &= Q_1(t) - q_{13}(t),\\
S\frac{d}{dt}L_2(t) &= Q_2(t) + q_{32}(t) - q_{20}(t),\\
S\frac{d}{dt}L_3(t) &= q_{13}(t) - q_{32}(t),\\
q_{13}(t) &= \mu_{13}S_n\,\mathrm{sgn}[L_1(t) - L_3(t)]\sqrt{2g|L_1(t) - L_3(t)|}\\
q_{32}(t) &= \mu_{32}S_n\,\mathrm{sgn}[L_3(t) - L_2(t)]\sqrt{2g|L_3(t) - L_2(t)|}\\
q_{20}(t) &= \mu_{20}S_n\sqrt{2gL_2(t)},
\end{aligned}
$$

Evaluation

Setup:

- Mininet - MiniCPS
- PLC – Sensors – Actuators
    - Each one a mininet node, running a python script



PLC101

LIT101

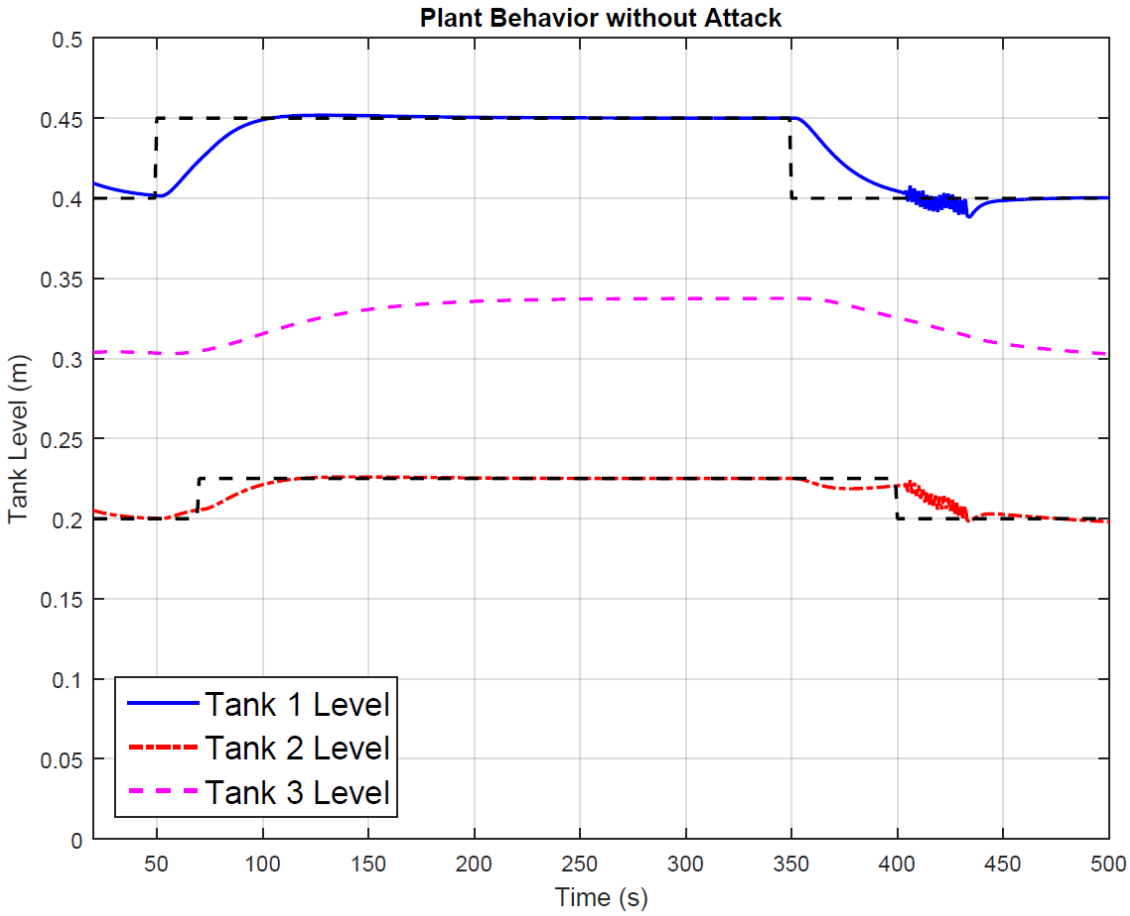
LIT102

Q101

Q102

Experiment

Set point
(expected behavior)

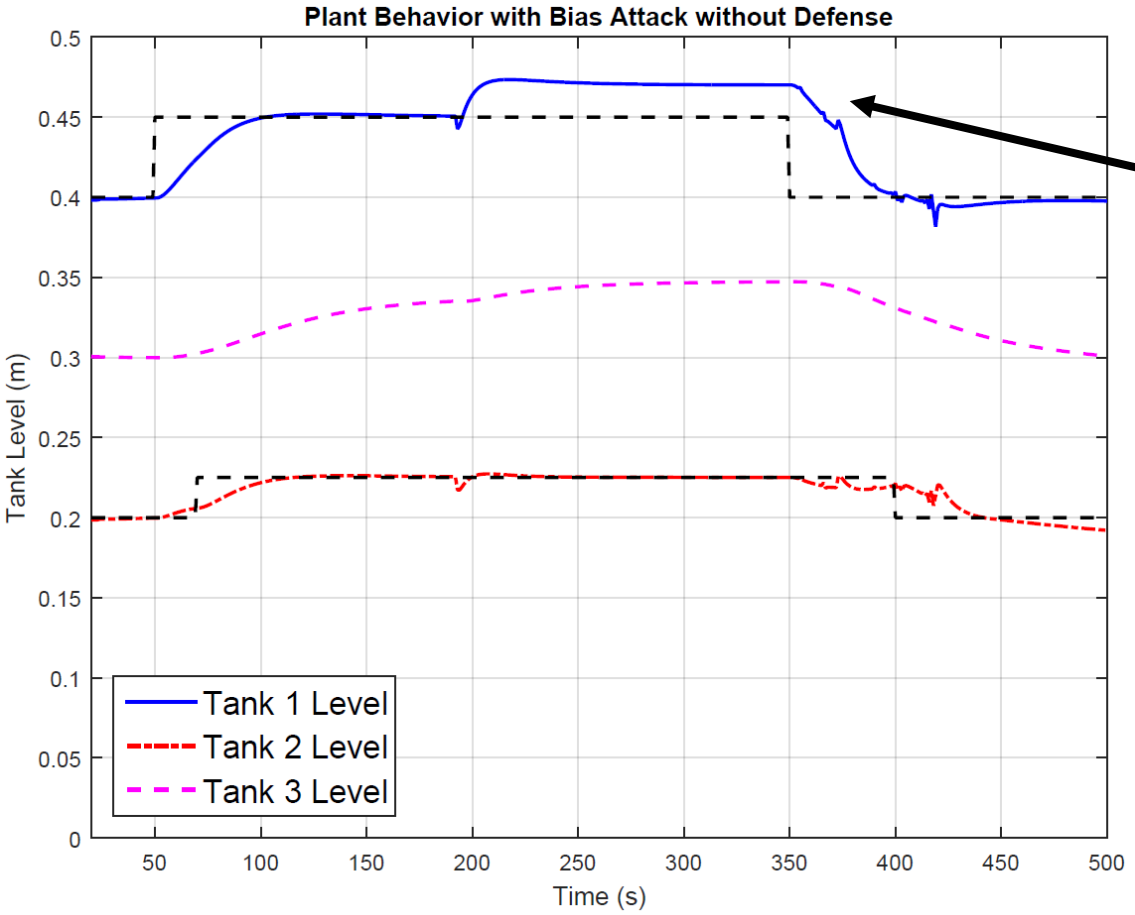


Experiment

Bias Attack:

1. Time k=200. Attacker starts the attack
2. Attack value: 0,02m
3. Controller thinks that the plant level is below the desired setpoint and applies the control algorithm
4. Attack ends at k=350

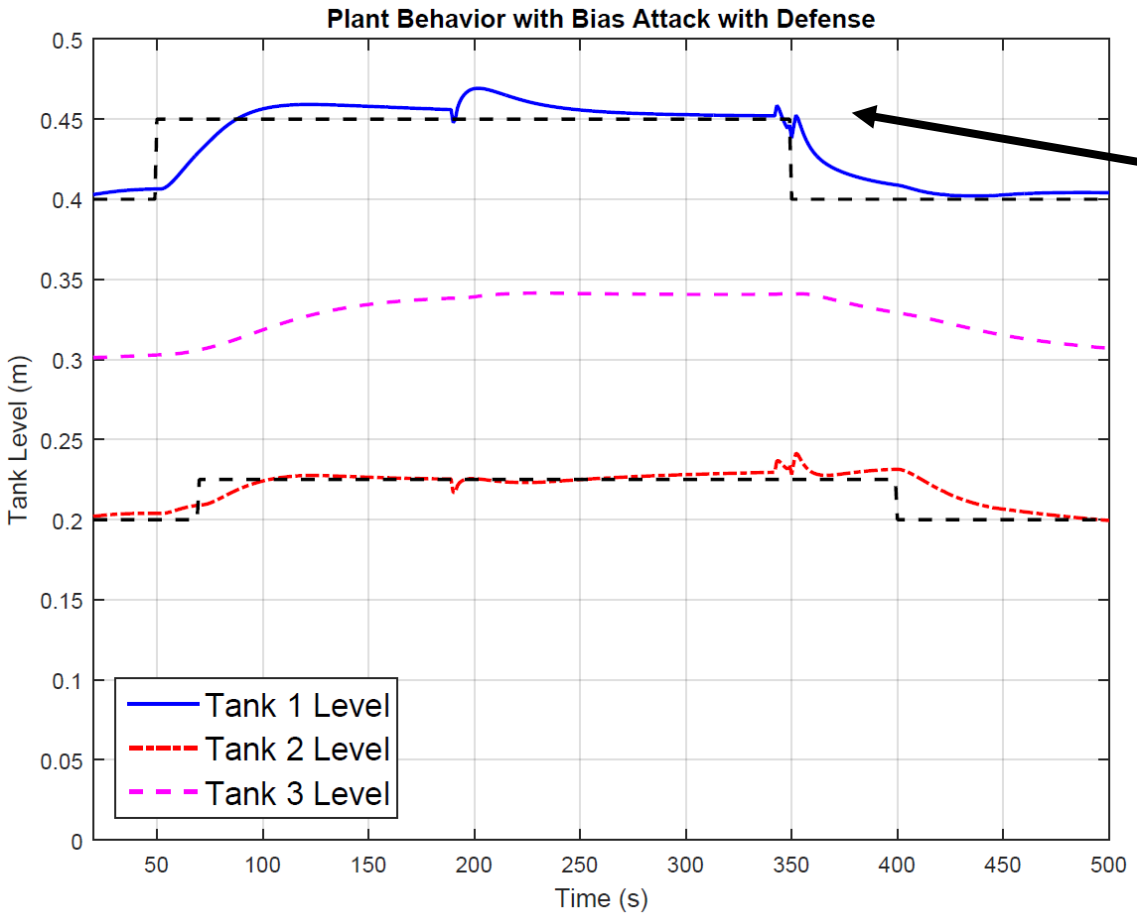
Experiment



Tank overflows

(Damaged product – Physical Harm)

Experiment



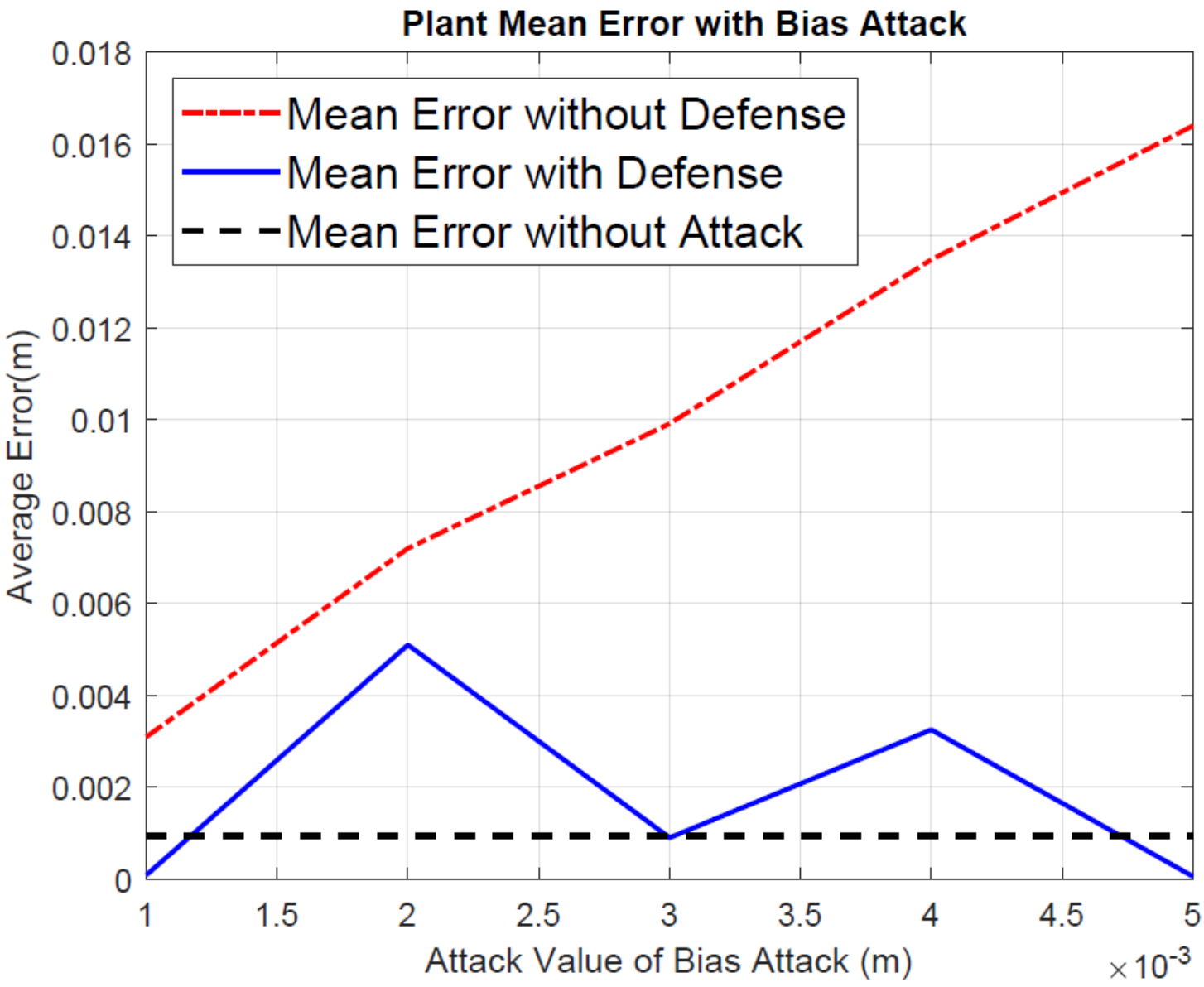
Defense mitigates impact

Experiment

Bias Attack:

- Other experiments to further test behavior of our defense
- Five experiments
  - All of them: with and without defense
  - Duration: 500 seconds
  - Attacks start at 200 and ends at 350
- Change bias attack from 0,01m to 0,05m
- Calculate mean error between desired behavior and current behavior of the tank

Experiment


Plant Mean Error with Bias Attack
Mean Error without Defense
Mean Error with Defense
Mean Error without Attack
Average Error(m)
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1
1.5
2
2.5
3
3.5
4
4.5
5
Attack Value of Bias Attack (m)
×10-3

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Related Work

Testbed	Controlled Plant	Industrial Equipment	Network Representation	Considerations
Pipeline virtual testbed	Simulation (Simulink)	Emulation (Open PLC)	Physical	Physical network is difficult to scale
Lancaster ICS Testbed	Physical Equipment	Physical Equipment	Physical Equipment	Expensive testbed and difficult to scale
Emulab ICS Testbed	Simulation (Matlab)	Simulation (PLC Code)	Emulation (Emulab Network)	Uses proprietary software

Conclusions

- Virtual environments may be used to emulate the behavior of a non-linear plant and a networked control loop (*better scalability*)
- Emulating and controlling a non-linear plant is much more challenging than emulating a linear plant (*more testing setups – and more interesting*)
- Unknown Input Observer (UIO) can be used on Networked Industrial Control Systems to protect the plant from harmful behavior (*in the same way that anti-malware software is used today*)

Future Work

- Extend our virtual environments to consider Real-Time Operating Systems
  - Enables to evaluate real time constrains (RTOSs are actually used in ICS environments)
- Deploy environment in a cloud environment
  - Offers a testbed that more closely resembles a virtualized industrial control system

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Thanks
Questions and comments are always welcome

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