

CPDY: Extending the Dolev-Yao Attacker with Physical-Layer Interactions

Marco Rocchetto^{1*} and Nils Ole Tippenhauer²

¹ SnT, University of Luxembourg

² ISTD, Singapore University of Technology and Design

Abstract. We propose extensions to the Dolev-Yao attacker model to make it suitable for arguments about security of Cyber-Physical Systems. The Dolev-Yao attacker model uses a set of rules to define potential actions by an attacker with respect to messages (i.e. information) exchanged between parties during a protocol execution. As the traditional Dolev-Yao model considers only information (exchanged over a channel controlled by the attacker), the model cannot directly be used to argue about the security of cyber-physical systems where physical-layer interactions are possible. Our Dolev-Yao extension, called Cyber-Physical Dolev-Yao (CPDY), allows additional orthogonal interaction channels between the parties. In particular, such orthogonal channels can be used to model physical-layer mechanical, chemical, or electrical interactions between components. In addition, we discuss the inclusion of physical properties such as location or distance in the rule set. We present an example set of additional rules for the Dolev-Yao attacker, using those we are able to formally discover physical attacks that previously could only be found by empirical methods or detailed physical process models.

1 Introduction

In recent years, security of Cyber-Physical systems (CPS) has received increasing attention by researchers from the domain of computer science, electrical engineering, and control theory [20,29]. We use the term CPS to refer to systems that consist of networked embedded systems, which are used to sense, actuate, and control physical processes. Examples for such CPS include industrial water treatment facilities, electrical power plants, public transportation infrastructure, or even smart cars. All those systems have seen a rapid increase in automation and connectivity, which threatens to increase vulnerability to malicious attacks.

Security analysis of any system relies on well-defined attacker and system models [16,3]. While the system model provides an appropriate abstraction of the system under attack, the attacker model ideally fully defines the possible interactions between the attacker and the attacked system. In particular, the model will also define constraints for the attacker (e.g. finite computational resources, no access to shared keys).

In contrast to the domain of information security, where the Dolev-Yao attacker model [16] (DY) is widely used for protocol analysis, the state-of-the-art for CPS security does not have a common terminology for attacker models. Even if the topic has been

* The work was carried out while Marco was with iTrust at Singapore University of Technology and Design

broadly discussed in the CPS research community, e.g., in [12], only a small number of tentative works (e.g., [35,18]) have addressed that problem. The DY model used by the information security community represents a very strong attacker, who can access and manipulate all network traffic arbitrarily. One could directly translate this attacker to CPS by allowing the attacker to intercept any communication in a real system (e.g. local fieldbus communication), or to be within physical proximity of all (unprotected) devices. However, such an attacker would only be capable of finding attacks on the network level of the CPS. Since the network traffic of CPS does not contain information about all interactions possible in a CPS, it is not sufficient for comprehensive analysis. As a result, there likely are (physical-layer) interactions between the attacker and the system that cannot be captured by the DY paradigm.

In this paper, we investigate the application of the DY attacker model for security analysis of CPS. We present a set of extensions to allow for a more general attacker model for CPS, that we named CPDY (Cyber-Physical Dolev-Yao) [24]. The CPDY attacker model allows us to consider the interaction of an attacker on the communication network, the physical presence of attackers, and the physical interaction with the mechatronics component of the CPS.

We summarize our contributions as follows:

- We discuss the general limitations of the DY attacker model for analysis of CPS, and physical layer interactions between the attacker and the attacked system.
- We propose a number of rule extensions to analyze CPS using the DY model.
- We implement these rule extensions in the ASLan++ [37] formal language, and present use case examples.

Structure. In Section 2, we summarize the DY attacker model. We discuss the use of the DY model in the context of CPS in Section 3, and show that the traditional attacker and system model is only able to represent a subset of possible interactions. We propose extensions to the DY attacker model in Section 4, and show our results on a real word water treatment plant use case in Section 5. We summarize the related work in Section 6 and we conclude the paper in Section 7.

2 Background

2.1 Modeling Systems and Communications

Level of Modeling Detail. Formal languages, e.g. HLPSL [36] and ASLan++ [37], permit a modeler to define not only the exchanged messages but also the behavior of entities involved in the communication. Some of the security validation tools allow a modeler to benefit of some algebraic properties (e.g., [27,8]) but these are typically represented symbolically by a set of constraints. Intuitively, a high level of details (e.g., a concrete highly detailed representation of the behavior of an agent) may result in non-termination problems while performing the analysis. In addition, even if we could afford such a level of details, it might not be useful to analyze security protocols against security properties at that level of detail. Some of the most common attacks (such as man-in-the-middle and replay attacks) that violate confidentiality or authentication can be found without the need of detailing the encryption scheme in the protocol.

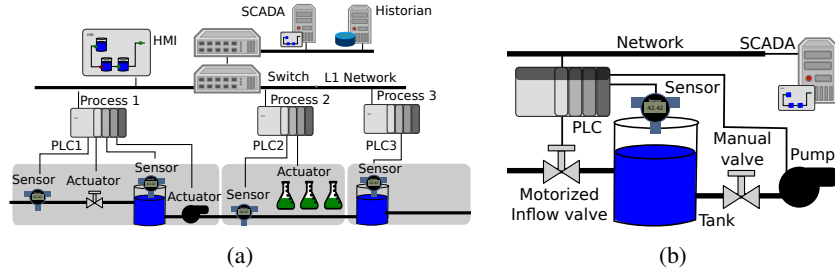


Fig. 1: (a) Example CPS architecture. (b) Use case scenario of water tank with motorized valve and pump controlled by a PLC. A level meter reports to the PLC. A manual valve is placed between tank and pump.

Modeling Simplifications. In the so called *perfect cryptography* assumption, the security encryption scheme is supposed to be “perfect”, without any exploitable flaw, and so the only way for the attacker to decrypt a message is by using the proper key. That assumption is widely accepted in the security protocol community, and most of the formal reasoning tools for the analysis of security protocols abstract away the mathematical and implementation details of the encryption scheme [32,8,4,25].

Modeling Architectures. Following the same line of reasoning, when one considers more complicated architecture representation, such as web applications or Service Oriented Architecture (SOA), some of the components are commonly assumed to be “perfect”, in the same way as encryption schemes. Several examples are shown by the case studies of the AVANTSSAR and SPaCIoS projects [3,34] where researchers have developed several abstract models of SOAs and web applications using the ASLan++ language, e.g. in [5]. In order to give some specific examples, databases in SQLi analysis in [10], CSRF token generation in [23] are assumed to be “perfect”. This is due to the fact that (as the security of security protocols is not guaranteed only by encryption schemes) the security of web applications is not guaranteed only by store procedures or perfect random generation of token. Another example has been presented in [11], where authors search for attacks in zero-knowledge proof systems abstracting away some of the mathematical and implementation details of the zero-knowledge algorithms.

2.2 Cyber-Physical Systems

In this work, we use the term Cyber-Physical System (CPS) to refer to systems that consist of networked embedded systems, which are used to sense, actuate, and control physical processes. Examples for such CPS include industrial water treatment facilities, electrical power plants, public transportation infrastructure, or even smart cars. All those systems have seen a rapid increase in automation and connectivity, which threatens to increase vulnerability to malicious attacks. While details on network topology, protocols, and control differ between engineering domains, the fundamental architecture is similar. We now explain that architecture using an industrial control system (ICS).

A modern industrial control system typically consists of several layers of networks. An example industrial control network is illustrated in Fig. 1a. The physical process is

$$\begin{array}{c}
\frac{M_1 \in M}{M_1 \in DY} G_{\text{axiom}} \quad \frac{M_1 \in DY \quad M_2 \in DY}{[M_1, M_2] \in DY} G_{\text{pair}} \quad \frac{M_1 \in DY \quad M_2 \in DY}{\{M_1\}_{M_2} \in DY} G_{\text{crypt}} \\
\frac{M_1 \in DY \quad M_2 \in DY}{\{|M_1|\}_{M_2} \in DY} G_{\text{scrypt}} \quad \frac{[M_1, M_2] \in DY}{M_i \in DY} A_{\text{pair}_i} \quad \frac{\{|M_1|\}_{M_2} \in DY \quad M_2 \in DY}{M_1 \in DY} A_{\text{scrypt}} \\
\frac{\{M_1\}_{M_2} \in DY \quad \text{inv}(M_2) \in DY}{M_1 \in DY} A_{\text{crypt}} \quad \frac{\{M_1\}_{\text{inv}(M_2)} \in DY \quad M_2 \in DY}{M_1 \in DY} A_{\text{crypt}}^{-1}
\end{array}$$

Fig. 2: The system of rules of the Dolev-Yao attacker

measured by distributed sensors, and manipulated by actuators. These sensors and actuators operate by receiving and sending analog signals. The analog signals are converted into digital signals by Programmable Logic Controllers (PLCs). The digital signals are then exchanged between PLCs and a central supervisory control system (SCADA) using industrial communication protocols (e.g. Modbus/TCP).

Modeling CPS. CPS can also be seen as a set of communicating agents [12] (often with one node acting as a controller), and related work focuses on the representation of the concrete behavior of the CPS [31,2,1,33]. This is believed to help the discovery the new attacks specific for CPS, e.g. resonance attacks [12]. However, that can lead researchers to over-complicating the system models even when searching for security attacks.

2.3 The Dolev-Yao Model

The DY attacker model [16] is a de-facto standard for the formal analysis of information security. The usage of such an attacker model is usually employed for the identification of cyber-related attacks, e.g. Web applications and Service-Oriented architectures as proposed in [3,23]. Attacker models à la DY have been proposed [30,26] to reason on CPS. In this work, we consider the standard DY [16] model of an active attacker who controls the network but cannot break cryptography.

The attacker can intercept messages and analyze them if he possesses the corresponding keys for decryption, and he can generate messages from his knowledge and send them under any agent name. As usual, for a set M of messages, we define DY (for “Dolev-Yao” knowledge) to be the smallest set closed under the *generation* (G) and *analysis* (A) rules of the *system* given in Fig. 2. The G rules express that the attacker can compose messages from known messages using pairing, asymmetric and symmetric encryption. The A rules describe how the attacker can decompose messages.

The *algebra of messages*, which tells us how messages are constructed, is defined following [8], in the standard way. In this paper, we consider the following operations:

- $\{M_1\}_{M_2}$ represents the *asymmetric encryption* of M_1 with public key M_2 ;
- $\{M_1\}_{\text{inv}(M_2)}$ represents the *asymmetric encryption* of M_1 with private key $\text{inv}(M_2)$ (the mapping $\text{inv}(\cdot)$ is discussed below);
- $\{|M_1|\}_{M_2}$ represents the *symmetric encryption* of M_1 with symmetric key M_2 ;
- $[M_1, M_2]$ represents the *concatenation* of M_1 and M_2 .
- $\text{inv}(M)$ gives the private key that corresponds to public key M

3 The Dolev-Yao Model is not Enough

Although the classic DY model can be applied to CPS security analysis straight away, we argue that it will not be able to detect a large set of attacks possible in that context (i.e. those that involve physical-layer interactions). To illustrate that argument, we now provide three example scenarios. For the sake of simplicity, we start by presenting the intuition behind the model and the goal. Further details on the ASLan++ prototype of these scenarios along with our results are provided in Section 5 and [24].

3.1 Application of Dolev-Yao for CPS

We base our example on a minimal setup in a water treatment system (see Fig. 1b). In particular, we use a subprocess of a real water treatment testbed depicted in Fig. 6 (the SWaT testbed [1,33]). A similar scenario has been considered in [21,22]. The scenario we considered contains five different components and a PLC:

1. A *motorized inflow valve*, initially open, let water flows into a tank through a pipe
2. A *tank* is equipped with a *sensor* which checks the level of the water inside the tank
3. The sensor communicates its reading of the level of the water inside the tank to a *PLC*
4. When the level of the water reaches a certain upper threshold, the PLC communicates to the motorized inflow valve to close and to the *pump* to start
5. Symmetrically, when the water reaches a certain lower threshold, the PLC communicates to the inflow valve to open and to the pump to stop
6. A *manual valve* (placed between the tank and the pump) can be manually opened/closed, e.g., to prevent the water to flow into the rest of the testbed in case the water in the tank is contaminated or the pump broken
7. A central *SCADA* control that communicates with the PLC over the network

In the following, we assume that the attacker’s goal is to cause a water spillage (or burst) in the tank component. The abstract messages exchanged over the network are quite simple (see Fig. 3a). The valve controls the inflow of the water to the tank. The sensor of the tank reports the current fill state to the PLC as analog signals. The PLC converts the analog signals into digital messages (value in the picture) that it sends to the SCADA. If the water level in the tank has crossed certain high/low thresholds, the SCADA sends a close/open message to the inflow valve and on/off to the pump. We note that in this setting, there is no distinction between the tank and the sensor. Nothing prevents us in considering them as two separate entities, but this would complicate the model without benefit in terms of attacks.

We analyzed the ASLan++ model using the AVANTSSAR platform, and found a simple attack (as expected). In that attack, the attacker drops the messages from the PLC to the SCADA. As result, the tank will overflow and the attacker will achieve his goal. Even if the attack is simple, it shows that one can easily use state-of-the-art verification tools and the standard DY attacker model to search for attacks on a CPS model. This basic example demonstrates that it is possible to reason on similar scenarios without considering the (fluid) mechanics of the process under attack. In particular, even in such a simple example the equations describing the flow of the water are far from trivial and are usually considered when reasoning on similar scenarios. In the remainder of

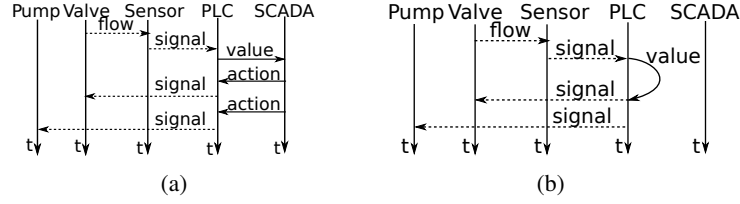


Fig. 3: (a) Physical interaction (dashed line) and digital interaction (solid line) between components in the first example. (b) Example interactions, with direct (out-of-band) communication between PLC, sensor, and actuator.

this section, we consider a modification of this scenario in which the network-only DY attacker model cannot find the attack.

3.2 Limitations of Dolev-Yao for CPS

The previous examples demonstrate that the DY attacker model can be used to reason on network-related security aspects of CPS. We now consider a scenario in which the agents also interact through physical-layer interactions. In particular, in real-world CPS the communication between PLCs, sensors and actuators usually uses analog signals. When a distributed control scheme is used, the logic of the system is usually integrated directly into the PLC, instead of relying on the SCADA component. In addition, components can interact through the physical layer directly (e.g. by exchanging water from a pipe into a tank). To reflect such a setting, we modify the system in the previous example as follows: the inflow valve and the pump are now directly controlled by the PLC based on analog signals from the sensor. In other words, the valve and the pump operate without interrogating the SCADA. As a result, the messages on the network and SCADA are not directly involved in the operations of the valve and the pump. We can consider the setting as one in which there is just one entity whose internal behavior encapsulate the behaviors of the valves, sensor, tank, pump and PLC (see Fig. 3b). Since there is no communication over the network related to the opening/closing of the valve or to the level of the water, there is no way for the DY attacker model to achieve the goal, i.e., overflowing the tank. We confirmed this intuition with a related model in ASLan++ and evaluation in the AVANTSSAR platform. No successful attack is found.

Nevertheless, it could be expected that attacks by a physically present attacker are possible in the given setting, in particular if a physically present attacker can manually open or close the valves. Our ASLan++ model does not find such an attack because potential malicious physical-layer interactions with the system have not been considered.

3.3 Proposed Approach

We claim that, (so far) the related work generally models the operation of a CPS as a set of messages exchanged between entities over a network (see Section 6). For that reason, we consider prior work as limited modification of the DY attacker model. However, consideration of the physical actions is often crucial to find real-world attacks on CPS

(e.g. attacks such as Stuxnet [38]). For that reason, we propose an extension of the DY attacker model with new physical interaction rules to support reasoning on the physical-layer security of CPS. We will introduce those rules in Section 4. Before that, we briefly discuss two aspects of our proposed approach in more detail: abstraction of physical process behavior, and whether verification tools or model checkers are better suited.

Abstraction of Physical Processes. In our proposed approach, physical layer interactions will be modeled as abstract interactions between components. In particular, we do not model all the details of the behavior of an agent for CPS. We believe that it will be very challenging for a security verification tool (or a model checker in general) to consider all details of the behavior of an agent for CPS. For example, differential equations that model the behavior of an ultra-filtration process will be difficult to consider by the DY model or verification tool.

In this work, we abstract away all these details, similar to the way that perfect cryptography is used for security protocols analysis where we abstract from cryptographic primitives (see [15] for more details). In security protocols, that abstraction is justified by the observation that most of the attacks rely on the logical aspects of the protocol. Encryption schemes are treated as black box and the attacker cannot learn any useful information from an encrypted message without the proper decryption key. As such, a generic predicate over a term defines the encryption as $\{M_1\}_{M_2}$ in Section 2. In CPS, we assume that all the physical processes can be abstractly represented.

Verification Tools vs. Model Checkers. In particular, we propose to use a DY verification tool, and not a general model checker. Our argument for that is the following: in order to model a CPS to formally validate it against an attacker model, CPS (or subparts) are often modeled with languages supported by tools which do not implement the DY attacker model, e.g. NuSMV, SPIN [14]. However, it has been shown [7] that an ad-hoc implementation of the DY is more advanced in terms of efficiency and coverage than using a “general purpose” model checker with the DY model-hard coded in the specification. That is particularly evident when considering the numerous amount of verification tools developed specifically to reason on the security aspects of various systems, e.g., [9,8,4,32,17].

4 Physical-Layer Interactions for the Dolev-Yao Attacker

In this section, we present our proposed extensions of the DY model in order to make it suitable to argue about security of Cyber-Physical Systems. In particular, we discuss the introduction of additional rules for the DY attacker model to describe physical-layer interactions.

4.1 New Rules for the DY Attacker and System

New Rules for the System. The new rules for our system model aim to capture the diverse physical-layer interactions between components in the system under attack. The interactions are usually constrained by the laws of physics, which will never be violated. A very exhaustive coverage of all kinds of physical layer interactions and laws

$$\begin{array}{c}
\frac{\text{Tank}(\text{level}, \text{value}) \in \text{Sys} \quad \text{Pump}(\text{status}, \text{off}) \quad \text{InflowValve}(\text{status}, \text{open}) \in \text{Sys}}{\text{Tank}(\text{level}, \text{value}') \in \text{Sys} \wedge (\text{value}' > \text{value})} \text{raise}_1(\text{Tank}) \\
\frac{\text{Tank}(\text{level}, \text{value}) \in \text{Sys} \quad \text{ManualValve}(\text{status}, \text{close}) \in \text{Sys} \quad \text{InflowValve}(\text{status}, \text{open}) \in \text{Sys}}{\text{Tank}(\text{level}, \text{value}') \in \text{Sys} \wedge (\text{value}' > \text{value})} \text{raise}_2(\text{Tank}) \\
\frac{C(\text{status}, \text{damaged}) \in \text{Sys} \quad C(\text{contains}, \text{water}) \in \text{Sys} \quad C(\text{level}, \text{value}) \in \text{Sys}}{C(\text{level}, \text{value}') \in \text{Sys} \wedge (\text{value}' < \text{value})} \text{damaged}(C) \\
\frac{C(\text{operate}, \text{manual}) \in \text{Sys} \quad C(\text{status}, \text{open}) \vee C(\text{status}, \text{close}) \in \text{Sys}}{C(\text{status}, \text{close}) \in \text{Sys}} \text{close}(C) \\
\frac{C(\text{operate}, \text{manual}) \in \text{Sys} \quad C(\text{status}, \text{open}) \vee C(\text{status}, \text{close}) \in \text{Sys}}{C(\text{status}, \text{open}) \in \text{Sys}} \text{open}(C)
\end{array}$$

Fig. 4: Examples of rules that represent physical-layer interactions in the system

$$\begin{array}{c}
\frac{\text{DYProp}(\text{distance}, \text{physical_access}) \quad \text{DYProp}(\text{tool}, \text{damage})}{C(\text{status}, \text{damaged}) \in \text{Sys}} \text{damage}_{DY} \\
\frac{\text{DYProp}(\text{distance}, \text{physical_access}) \quad C(\text{operate}, \text{manual}) \in \text{Sys} \quad C(\text{status}, \text{open}) \in \text{Sys}}{C(\text{status}, \text{close}) \in \text{Sys}} \text{manualClose}_{DY} \\
\frac{\text{DYProp}(\text{distance}, \text{physical_access}) \quad C(\text{operate}, \text{manual}) \in \text{Sys} \quad C(\text{status}, \text{close}) \in \text{Sys}}{C(\text{status}, \text{open}) \in \text{Sys}} \text{manualOpen}_{DY}
\end{array}$$

Fig. 5: Examples of rules that represent physical-layer capabilities of attacker

of physics would potentially result into a large set of additional rules (potentially automatically extracted from a system specification, e.g., [28]). In the following, we will consider only few additional rules to model specific interactions. In Fig. 4, we present rules that represent laws of physics related to our example (Fig. 1b). With a slightly abuse of notation, each rule represents a modification of the system status *Sys* from preconditions (top) to postconditions (bottom). *Sys* is a set collecting all the physical properties of the systems (e.g., water level, temperature, pressure) for each component in the system (e.g., tank). The properties are expressed with the predicate $C(\text{property}, \text{value})$ ($C(\cdot)$ as short form of $\text{Component}(\cdot)$). In Fig. 4, $\text{raise}_1(\text{Tank})$ and $\text{raise}_2(\text{Tank})$ relates a system configuration with its physical effects, i.e., the increase of the water level in the tank. $\text{damaged}(C)$ expresses the effect of the burst of the tank, and $\text{close}(C)$ and $\text{open}(C)$ defines the effect of physical interactions with a component (e.g., a valve) which can be manually operated to change its status.

Rules for DY Attacker. The new rules for our attacker model aim to capture the diverse physical-layer interactions between the attacker and the system (see Fig. 5). Similar to the system specification rules, the interactions between attacker and system are usually constrained by the laws of physics—even a strong attacker would not be able to create or consume arbitrary amounts of energy, move at infinite speed, or similar.

4.2 Implementation of New Rules for DY

We base our attacker model on a review of related work that aims to profile attackers for CPS [12,13,33,18]. We found that they all share the idea of defining the attacker by means of a set of *dimensions*. These dimensions can be seen as *properties of the attacker*, e.g., distance with respect to the CPS, knowledge of the physics of the components of the system, tools (software and hardware) available to the attacker, financial support, and preference to stay hidden. We can use dimensions together with *physical properties of the system* to define new rules for the attacker as follows.

$$\frac{\text{attacker_property} \quad \text{system_property}}{\text{result of action}} \quad \text{action}$$

where one or more attacker's properties along with the knowledge of one or more system property (that might be related to the knowledge of some physical laws connected to the system property) are the precondition to perform an action *action* which results are expressed as postconditions. In other words, an attacker is a malicious agent that can take advantage from the improper use of some device of the system.

In our first example, we can add the *damage_{DY}* in Fig. 5 which express that an attacker who has physical access to the CPS could damage or manually operate a component, for example, a tank. Other examples are rules expressing that if the attacker has physical access to the CPS can (as we will discuss in Section 5.3) heat the tank and increase its pressure. In Section 5, we will show how we can leverage those attacker rules to find new attacks on a CPS which involve physical-layer interactions.

4.3 DY Rule Extension Using Horn Clauses

In order to apply our idea to a concrete example, we require a verification tool such that: (i) allows modification to the DY rules, and (ii) provides a language expressive enough to model a CPS. It is not easy to find a security verification tool with such constraints and, to the best of our knowledge, there is no tools in the literature.

In this work, we propose the following two workarounds that allow us to implement our additional rules even without a tool that satisfies the mentioned requirements: (i) we have used Horn Clauses (HC) to add extra rules to the DY attacker model, and (ii) we have used databases (shared memories) to store the state of the components the system, e.g., the level of the water of a tank. Using both ideas, we require only a tool that supports Horn Clauses and Shared Memories. We chose the ASLan++ specification language [37] which supports both HC and shared memories. Using ASLan++, we have implemented several case studies and obtained preliminary results that support our proposed approach.

5 Case Studies

In this section, we first show that a DY verification tool can be used to check security goals in CPS models. We have used the ASLan++ specification language [37] to define our examples which are based on a process of the SWaT testbed [19] depicted in Fig. 6



Fig. 6: Process P1 (raw water treatment) – SWaT testbed

Table 1: Summary of the analysis on the use cases

	attack found		timing	
	DY	CPDY	analysis	total
Network (Section 5.1)	✓	✓	220ms	1.7s
Manual (Section 5.2)		✓	8ms	1.3s
Heating (Section 5.3)		✓	4ms	1.0s

total includes time for translation, analysis and attack trace generation

(see Fig. 3a for the message sequence chart). We start by providing more details on the example summarized in Section 3. In particular, we present a network-only modeling of the CPS and potential attacks, which shows that the DY model can be used to find attacks similar to ones discussed in related work (e.g., man-in-the-middle attacks in [2,33]). For that analysis, we abstract away the implementation details of the CPS and detect the same (network related) security flaw of most of the approaches we have found in the literature. We then modify the specification (as depicted in Fig. 3b) to show that when some physical operations (which are the at very core of a CPS) are involved in the process, the standard DY attacker model might not be able to find all attacks. To mitigate this, we modify the DY model to let him physically interact with the system under certain constraints. This allows the attacker to detect new attacks which involves physical interaction with the system. We show that almost all the attacks which relay on attackers' physical actions cannot be found. We propose a first investigation on how to extend the DY model in order to capture both cyber and physical attacks. Our results, along with timing, are summarized in Table 1.

5.1 Network-Based Communication Use Case

This section briefly summarizes an implementation of the scenario proposed in Section 3.1. We focus on three aspects:

- The *status* of the system (e.g., the level of water and measurements of sensors)
- The *behavior* of each entity (i.e., tank, valves, pump, PLC and SCADA)
- The *communication* between various entities (analog and network channels)

In this example, the PLC converts the analog signals to digital messages and sends them to the SCADA control. To be coherent with the example, we model an analog channel (e.g., by using a database) between the inflow valve, the tank, the pump, and the PLC. The PLC then translates and communicates the tank/valve/pump status over a network channel with the SCADA. For the sake of readability, we assume the PLC automatically converts and sends the tank/valve/pump status. As a result, the valve, the tank, and the pump directly communicate with the SCADA over a network channel. The full implementation is reported in [24].

System Status. CPS can be seen as communicating over two channels: one is the network channel (maybe itself divided into several layers or regions) and the other is the physical flow of the events, e.g., electricity in power grids or water in water treatment or distribution CPS. We believe that an understanding on how to model the physical flow of a CPS, integration of that with the network (in such a way that an attacker model can concretely find new attacks) is still not well defined in the literature.

In this work, the status of the system is defined by a database *systemStatus*, shared between all the entities (but hidden to the DY attacker). The database is defined as a set of pairs (*agent*, *status*) that keeps track of the status of all entities of the specification.

Inflow Valve/Pump. The valve/pump specification describes a scenario where a SCADA changes the status of the valve/pump, e.g., from open/on to close/off, by sending to the valve a message through the PLC.

Manual Valve. The behavior of the manual valve is the same as the inflow valve. The only difference is that the manual valve can only be manually operated (e.g. to change its status from open to close), i.e., cannot be operated using network messages.

Tank. In the real testbed the PLC interrogates the sensor of the tank in order to obtain the level of the water inside the tank. For simplicity, we do not distinguish between the tank as a container and its sensors. We also assume that the sensor sends the sensed data of the level of the water whenever the level is above or below a certain threshold. We can obviously consider the more complicated and realistic tank specification containing a sensor that waits for the PLC to interrogate it. This complicates the analysis but the performance of the validation phase does not change order of magnitude (there is a variation of some milliseconds) and the result of the analysis remains the same. We recall that messages are directly sent to the SCADA instead of PLC for readability.

The tank model checks for two, mutually exclusive, status of the tank.

- If the level of the water has reached an upper threshold *overT*, the inflow valve is closed, the pump is on, and the manual valve is open, the *systemStatus* database is updated as if the water level had lowered to a lower threshold *underT*. After the status update, the tank communicates its new status *underT* to the SCADA.
- Symmetrically, if the level of the water has reached a threshold *underT*, the inflow valve is open, and either the manual valve is closed or the pump is off, the *systemStatus* database is updated as if the water level had reached the upper threshold *overT*.

SCADA. As for the valve entity, we have defined the behavior of the SCADA waiting for incoming messages from the tank entity. When the tank communicates to the SCADA that the water has reached the upper threshold *overT*, the SCADA closes the inflow valve and turns on the pump. Symmetrically, when the tank reaches the lower threshold, the SCADA opens the inflow valve and turns off the pump.

Initial Status of the System. The initial status of the specification is defined with the tank empty (i.e., the level of the water is *underT* in the *systemStatus* database), the inflow and the manual valve are open, and the pump is off.

Goal. The goal is to overflow the tank and in ASLan++ we can define our goal as the following LTL (Linear Temporal Logic) formula.

$$\Box(\text{inflowValve}(\text{status}, \text{open}) \in \text{Sys} \Rightarrow \text{manualValve}(\text{status}, \text{open}) \in \text{Sys} \wedge (\text{tank}(\text{status}, \text{underT}) \in \text{Sys} \vee \text{pump}(\text{status}, \text{on}) \in \text{Sys}))$$

In the formula, we define that whenever the inflow valve is open, i.e. the *systemStatus* database contains *valve(status, open)*, then the manual valve is open, and either the tank must be empty or the pump turned on. In other words, if we find a configuration of the system such that the inflow valve is opened, the tank is full of water, and the pump is off, then the tank is overflowing. The \Box at the beginning of the goal states that the goal must hold in every state of the system (i.e., LTL global operator).

Security Analysis. The AVANTSSAR platform finds a violation of the goal (i.e., a states where the goal does not hold). The goal is violated because there is a state of the system in which the tank has reached the *overT* but the valve is still open and the pump is switched off. In order to achieve the goal, an attacker have to drop the packet, communicating the *overT* status, sent from the tank to the SCADA.

5.2 Physics-Based Interaction Use Case

We now modify the scenario by removing the communication of the level of the water between the PLC and the SCADA, i.e., between tank/valve/pump and SCADA in the previous specification. For that reason, we assume that the PLC automatically close the inflow valve when the level of the water inside the tank reaches the threshold level *overT*. The DY attacker cannot spoof or eavesdrop the communication between entities anymore since there is no more network communication with the SCADA.

Security Analysis. Against the DY model, the AVANTSSAR platform does not report any attack on the specification with respect to the goal defined in Section 5.1. This result is straightforward since the attacker does not receives any message and there is no interactions over network between various entities.

As we are considering a CPS, an attacker who could have physical access to the system could most likely find a number of ways to overflow the tank. Being in close proximity of the CPS could give to the attacker an advantage with respect to a cyber-attacker who can only access the system through the network. For example, an attacker

$$\begin{array}{c}
\frac{C(\text{status}, \text{heating}) \in \text{Sys} \quad C(\text{contains}, \text{water}) \in \text{Sys} \quad C(\text{temperature}, \text{Level}) \in \text{Sys}}{C(\text{temperature}, \text{Level}') \in \text{Sys} \wedge \text{Level}' > \text{Level}} \text{heat}_1(C) \\
\frac{C(\text{status}, \text{heating}) \in \text{Sys} \quad C(\text{contains}, \text{water}) \in \text{Sys} \quad C(\text{pressure}, \text{Level}) \in \text{Sys}}{C(\text{pressure}, \text{Level}') \in \text{Sys} \wedge \text{Level}' > \text{Level}} \text{heat}_2(C) \\
\frac{C(\text{status}, \text{heating}) \in \text{Sys} \quad C(\text{contains}, \text{water}) \in \text{Sys} \quad C(\text{temperature}, \text{TLevel}) \in \text{Sys} \quad C(\text{pressure}, \text{PLevel}) \in \text{Sys}}{C(\text{temperature}, \text{TLevel}') \in \text{Sys} \wedge C(\text{pressure}, \text{PLevel}') \in \text{Sys} \wedge (\text{PLevel}' > \text{PLevel}) \wedge (\text{TLevel}' > \text{TLevel})} \text{heat}_3(C)
\end{array}$$

Fig. 7: Rules that represent physical laws in use case of Section 5.3

could manually operates the valves to increase the level of the water in the tank and burst the tank. In this perspective, it is fair to assume that there are some attacker properties, e.g., distance, that can be exploited by an attacker to perform some actions (or even attacks) that leads to some physical consequences in the CPS. As a simple motivating example, the following rule has been added to the specification (as a Horn clause as discussed in Section 5).

$$\frac{DYProp(\text{distance}, \text{physical_access}) \wedge C(\text{status}, \text{open}) \in \text{Sys} \wedge C(\text{operate}, \text{manual}) \in \text{Sys}}{C(\text{status}, \text{close}) \in \text{Sys}}$$

The clause states that whenever the attacker has physical access to the CPS, he can close any valve which can be manually operated. We also modeled the opening of a valve.

When we run the AVANTSSAR platform searching for a state of the system in which the level of the water in the tank has reached the upper threshold *overT* (defined as a goal), we (unsurprisingly) find an attack. To perform the attack, the attacker manually opens the inflow valve and closes the manual valve.

5.3 Physics-Based Interaction Use Case – a Stronger Attacker

This use case is a variation of the one in Section 5.2, where we add extra rules to the attacker. In particular, we have modeled that whenever the attacker has physical access to the CPS, he can physically interact with the system and heat up the water in tank (e.g., through microwave or fire).

$$\frac{DYProp(\text{Distance}, \text{physical_access}) \quad DYProp(\text{Tool}, \text{heating})}{C(\text{status}, \text{heating}) \in \text{Sys}} \text{heat}_{DY}$$

Note here that some system properties should hold, e.g., the tank should contain a liquid but for the sake of simplicity we abstract away system properties in this example.

We have modeled the corresponding physical laws and we report three examples in Fig. 7. *heat*₁(*C*) and *heat*₂(*C*) express the temperature and pressure increase when heating a generic component containing water respectively. *heat*₃(*C*) defines the direct proportionality between temperature and pressure in the presence of water inside a component.

Goal. We check if the attacker can burst the tank, increasing the pressure of the tank.

$$\Box(\text{Tank}(\text{pressure}, \text{overT}) \notin \text{Sys})$$

Security Analysis. The AVANTSSAR platform reports a violation of the goal. The two clauses $heat_2$ and $heat_{DY}$ have been used to heat the tank component and then to raise its pressure, bursting the tank.

6 Related Work

The formal verification of security properties of CPS is a non trivial task, as CPS introduce physical properties to the system under analysis. SAT/SMT solvers used by security analysis tools (e.g., [3]) do not support such properties. In order to overcome this limitation, one could simulate the process (e.g., [2]) or adapt the level of abstraction of CPS components. In [35], the author presents a formal definition of an attacker model for CPS. The attacker is defined as a set of pairs representing locations and capabilities. Capabilities are defined as a set of tuples expressing actions, cost (energy/time) and range (with respect to the topology) of the attacker. The attacker is assumed to perform two types of attacks: *physical*, against a device and *cyber* against the communications; where the first requires physical access while the second proximity to the node. The actions of the attacker are *WSN actions* (remove, read/write, reveal, reprogram, starve) and *cyber actions* (block, eavesdrop, inject).

In [26,6], the authors present a formalization to reason on security properties of wireless networks (including a considerations of physical properties related to those networks). The authors present an attacker model as a variation of the DY attacker model. The attacker is a malicious agent of the network who cannot break cryptography. He has a fixed location, while the usual DY controls the entire network, a set of transmitters and receivers, an initial knowledge with his private/public keys which can use to create and analyze messages. The authors also consider constraints on the distance of communicating parties. An attacker can only intercept messages at his location and colluding attackers do not instantaneously exchange knowledge, they are constrained by the network topology.

7 Conclusions and Future Work

In this paper, we argued that (to the best of our knowledge) current approaches for the formal reasoning on the security of CPS do not consider most of the physical interaction between the attacker and the system. Instead, the works we reviewed only focus on the network interaction between components of a CPS, which is indeed important but not sufficient for an extensive security analysis. One of the main difficulties of considering physical interaction of the CPS is that usually this leads to the definition of the physical processes of various components of the CPS.

We proposed several basic uses cases in which the physical behavior of both the CPS and the attacker can be used to produce attacks that rely on physical actions of the attacker that are outside the normal behavior of the CPS. To alleviate that problem, we presented the idea of extending the DY attacker to a CPDY attacker model that allows to include physical-layer interaction. We implemented that CPDY model in ASlan++ and used the AVANTSSAR platform to show that our extended attacker model is indeed able to discover the physical-layer attacks in CPS.

Acknowledgments. This work was supported by the National Research Foundation of Singapore under grant NRF2014NCR-NCR001-40.

References

1. S. Adepu and A. Mathur. An investigation into the response of a water treatment system into cyber attacks. In *IEEE Symposium on High Assurance Systems Engineering (HASE)*, 2015.
2. D. Antonioli and N. O. Tippenhauer. MiniCPS: A toolkit for security research on CPS networks. In *Proceedings of Workshop on Cyber-Physical Systems Security & Privacy (SPC-CPS)*, co-located with CCS, 2015.
3. A. Armando, W. Arsac, T. Avanesov, M. Barletta, A. Calvi, A. Cappai, R. Carbone, Y. Chevalier, L. Compagna, J. Cuéllar, G. Erzse, S. Frau, M. Minea, S. Mödersheim, D. von Oheimb, G. Pellegrino, S. E. Ponta, M. Rocchetto, M. Rusinowitch, M. T. Dashti, M. Turuani, and L. Viganò. The AVANTSSAR platform for the automated validation of trust and security of service-oriented architectures. In *Tools and Algorithms for the Construction and Analysis of Systems (TACAS)*, pages 267–282, 2012.
4. A. Armando and L. Compagna. SATMC: a SAT-based model checker for security protocols. In *JELIA*, LNAI 3229. Springer, 2004.
5. AVANTSSAR. Deliverable 5.3: AVANTSSAR Library of validated problem cases. www.avantssar.eu, 2010.
6. D. Basin, S. Capkun, P. Schaller, and B. Schmidt. Formal reasoning about physical properties of security protocols. *Transactions on Information and System Security (TISSEC)*, 14(2):16, 2011.
7. D. Basin, C. Cremers, and C. Meadows. Model checking security protocols. *Handbook of Model Checking*, 2011.
8. D. Basin, S. Mödersheim, and L. Viganò. OFMC: A symbolic model checker for security protocols. *Journal of Information Security*, 4(3):181–208, 2005.
9. B. Blanchet. An efficient cryptographic protocol verifier based on prolog rules. In *Computer Security Foundation Workshop (CSFW)*. IEEE, 2001.
10. M. Buchler, K. Hossen, P. Mihancea, M. Minea, R. Groz, and C. Oriat. Model inference and security testing in the spacios project. In *IEEE Conference on Software Maintenance, Reengineering and Reverse Engineering (CSMR-WCRE)*, 2014.
11. J. Camenisch, S. Mödersheim, and D. Sommer. A formal model of identity mixer. In *Formal Methods for Industrial Critical Systems FMICS*, 2010.
12. A. A. Cárdenas, S. M. Amin, B. Sinopoli, A. Giani, A. Perrig, and S. S. Sastry. Challenges for securing cyber physical systems. In *Workshop on Future Directions in Cyber-physical Systems Security*. DHS, July 2009.
13. A. A. Cárdenas, T. Roosta, and S. Sastry. Rethinking security properties, threat models, and the design space in sensor networks: A case study in SCADA systems. *Ad Hoc Networks*, 7(8):1434–1447, 2009.
14. Y. Choi. From nusmv to SPIN: experiences with model checking flight guidance systems. *Formal Methods in System Design*, 30(3):199–216, 2007.
15. V. Cortier, S. Delaune, and P. Lafourcade. A survey of algebraic properties used in cryptographic protocols. *Journal of Computer Security*, 14(1), 2006.
16. D. Dolev and A. C. Yao. On the security of public key protocols. *IEEE Transactions on Information Theory*, 29(2):198–207, 1983.
17. S. Escobar, C. Meadows, and J. Meseguer. Maude-NPA: Cryptographic protocol analysis modulo equational properties. In *Foundations of Security Analysis and Design*. 2009.

18. E. LeMay, M. D. Ford, K. Keefe, W. H. Sanders, and C. Muehrcke. Model-based security metrics using adversary view security evaluation (ADVISE). In *Proceedings of Conference on Quantitative Evaluation of Systems, QEST*, 2011.
19. A. Mathur and N. O. Tippenhauer. A water treatment testbed for research and training on ics security. In *Proceedings of Workshop on Cyber-Physical Systems for Smart Water Networks (CySWater)*, Apr. 2016.
20. Y. Mo, T.-H. Kim, K. Brancik, D. Dickinson, H. Lee, A. Perrig, and B. Sinopoli. Cyber-physical security of a smart grid infrastructure. *Proc. of the IEEE*, 100(1):195–209, 2012.
21. T. Morris, A. Srivastava, B. Reaves, W. Gao, K. Pavurapu, and R. Reddi. A control system testbed to validate critical infrastructure protection concepts. *Journal of Critical Infrastructure Protection*, 4(2):88 – 103, 2011.
22. B. Reaves and T. Morris. An open virtual testbed for industrial control system security research. *Journal of Information Security*, 11(4):215–229, 2012.
23. M. Rocchetto, M. Ochoa, and M. Torabi Dashti. Model-based detection of CSRF. In *ICT Systems Security and Privacy Protection*, volume 428 of *IFIP Advances in Information and Communication Technology*. Springer Berlin Heidelberg, 2014.
24. M. Rocchetto and N. O. Tippenhauer. CPDY (Cyber-Physical Dolev-Yao), 2016. Available at <http://research.scy-phy.net/cpdy/>.
25. M. Rocchetto, L. Viganò, M. Volpe, and G. D. Vedove. Using interpolation for the verification of security protocols. In *Security and Trust Management STM*, 2013.
26. P. Schaller, B. Schmidt, D. A. Basin, and S. Capkun. Modeling and verifying physical properties of security protocols for wireless networks. In *Computer Security Foundations Symposium (CSF)*, pages 109–123, 2009.
27. B. Schmidt, R. Sasse, C. Cremers, and D. A. Basin. Automated verification of group key agreement protocols. In *Symposium on Security and Privacy (S&P)*, pages 179–194, 2014.
28. M. Schmidt and H. Lipson. Distilling free-form natural laws from experimental data. *science*, 324(5923):81–85, 2009.
29. SPaCioS. Deliverable 3.3.2: Methodology and technology for vulnerability-driven security testing (final version), 2014. Available at <http://www.spacios.eu>.
30. D. Steinmetzer, M. Schulz, and M. Hollick. Lockpicking physical layer key exchange: Weak adversary models invite the thief. In *Proc. ACM Conference Wireless Security (WiSeC)*, 2015.
31. R. Taormina, S. Galelli, N. O. Tippenhauer, E. Salomons, and A. Ostfeld. Simulation of cyber-physical attacks on water distribution systems with EPANET. In *Proceedings of Singapore Cyber Security R&D Conference (SG-CRC)*, Jan. 2016.
32. M. Turuani. The CL-Atse Protocol Analyser. In *RTA*, LNCS 4098, 2006.
33. D. Urbina, J. Giraldo, N. O. Tippenhauer, and A. Cardenas. Attacking fieldbus communications in ICS: Applications to the SWaT testbed. In *Proceedings of Singapore Cyber Security R&D Conference (SG-CRC)*, Jan. 2016.
34. L. Viganò. The spacios project: Secure provision and consumption in the internet of services. In *Software Testing, Verification and Validation (ICST)*, pages 497–498. IEEE, 2013.
35. R. Vigo. The cyber-physical attacker. In *Proceedings of Workshop of Conference on Computer Safety, Reliability, and Security (SAFECOMP)*, 2012.
36. D. von Oheimb. The high-level protocol specification language HLPSP developed in the EU project AVISPA. In *Proceedings of APPSEM 2005 workshop*, pages 1–17, 2005.
37. D. von Oheimb and S. Mödersheim. ASLan++ — a formal security specification language for distributed systems. In *FMCO*, LNCS 6957. Springer, 2010.
38. S. Weinberger. Computer security: Is this the start of cyberwarfare? *Nature*, 174:142–145, June 2011.