Gamifying Education and Research on ICS Security: Design, Implementation and Results of S3

Daniele Antonioli  Hamid Reza Ghaeini  Sridhar Adepu

Martín Ochoa  Nils Ole Tippenhauer

{daniele_antonioli, sridhar_aedepu, martin_ochoa, nils_tippenhauer}@sutd.edu.sg, ghaeini@acm.org

Singapore University of Technology and Design

ABSTRACT

In this work, we consider challenges relating to security for Industrial Control Systems (ICS) in the context of ICS security education and research targeted both to academia and industry. We propose to address those challenges through gamified attack training and countermeasure evaluation.

We tested our proposed ICS security gamification idea in the context of the (to the best of our knowledge) first Capture-The-Flag (CTF) event targeted to ICS security called SWaT Security Showdown (S3). Six teams acted as attackers in a security competition leveraging an ICS testbed, with several academic defense systems attempting to detect the ongoing attacks. The event was conducted in two phases. The online phase (a jeopardy-style CTF) served as a training session. The live phase was structured as an attack-defense CTF. We acted as judges and we assigned points to the attacker teams according to a scoring system that we developed internally based on multiple factors, including realistic attacker models. We conclude the paper with an evaluation and discussion of the S3, including statistics derived from the data collected in each phase of S3.

1. INTRODUCTION

Industrial Control System (ICS) security is a major challenge because it requires specific knowledge about domain-specific devices, industrial protocols and general knowledge about traditional IT security threats [18, 19, 36]. A common trend in ICS is the shift towards commodity computing platforms and communication channels, e.g., TCP/IP based communication using Ethernet instead of RS-485 [18]. That shift if motivated by increased functionality, together with cost savings. In addition, even smaller devices are increasingly connected to networks (e.g., as part of the Industry 4.0 paradigm [32]), and use access to the Internet to report data or obtain updates.

Recently, it has been widely argued that one of the fundamental issues in securing ICS lies in the cultural differences between traditional IT security and ICS engineering [25, 26]. Therefore, education has been advocated as a means of bridging the gap between these cultures [25, 26]. However, recent surveys indicate that although general IT security education efforts have risen in ICS, there is still need for more targeted education combining both security and ICS specific knowledge [19].

ICS testbeds constitute a convenient environment to study ICS security, however their deployment is rare because of many reasons, such as cost and manpower [10, 11]. Researchers are usually not able to get access to such testbeds, and those willing to do research on ICS security are facing many problems, such as lack of understanding of a real ICS and the inability to test (new) attacks and countermeasures in a realistic setup. Another common issue in ICS security is resulting from the intrinsic inter-disciplinary nature of the subject, namely it is difficult to bring together people from different expertise domains, such as control theory, information security, and engineering.

In this work, we propose a number of solutions to those problems, and we elaborate one of them based on gamification in the context of ICS security education and research targeted both to academia and industry. We strongly believe that gamification combined with access to real and simulated ICS is a key driver for ICS security progress at all levels (from beginner to expert) and among different professional communities (both academia and industry).

We implemented our ideas as part of the (to the best of our knowledge) first Capture-The-Flag style event on a productive Industrial Control System held at our institution in the summer of 2016. The experiment leveraged a realistic water treatment testbed that is available for security research [3], together with a simulation environment for some of the proposed challenges.

Our experiment involved six attacker teams from academia and industry worldwide. Attackers were provided with the documentation of the target systems, and the CTF composed of two phases: an online qualifier and a live-phase. During the online phase the attackers were exposed to simulations and remote-access to a physical water treatment plant. On the live-phase of the experiment, teams deployed a wider range of attacks during two days, with two academic attack detection systems in place. In this work we describe the setup in detail, and comment on insights and lessons learned.

We summarize our contributions as follows:

- We identify several issues that currently hinder the adoption of security in industrial control systems, and likewise prevent security researchers from becoming familiar with ICS.
- We propose a set of solutions to mitigate those issues, with a particular focus on gamified interactive Capture-The-Flag events using simulated and real infrastructure.
- We present the design and implementation of a two-part CTF event in detail, and analyze its results.

This work organized as follows: in Section 2, we provide brief background on Industrial Control Systems (ICS), the Secure Wa-
ter Treatment, and Capture-The-Flag (CTF) events. In Section 3, we present our problem statement and solution ideas. One of those proposed ideas was implemented by us in two phases, which are presented in detail in Section 4 and Section 5. We present an analysis of the two events together with lessons learned in Section 6. Related work is summarized in Section 7 and we conclude the paper in Section 8.

2. BACKGROUND

In this section, we will introduce the relevant information about Industrial Control Systems (ICS), the Secure Water Treatment a real water treatment testbed and Capture-The-Flag (CTF) events.

2.1 Industrial Control Systems (ICS)

Industrial Control Systems (ICS) are complex autonomous systems involving different types of interconnected devices and an underlying physical process. ICS are deployed to monitor and control different types of industrial processes, such as critical infrastructure (water distribution and treatment), and transportation systems (airports and railways).

It is useful to categorize ICS devices according to their main role in an ICS. Control devices, such as Programmable Logic Controllers (PLC), and Human-Machine Interface (HMI), provide monitoring and programmable control capabilities to the ICS. Network devices, such as industrial switches and firewalls, provide the foundations to build a complex ICS network that may include different segments, protocols, and topologies. Typically, the ICS control network is (virtually) separated from other networks such as DMZ, and office networks. Physical-process devices, such as sensors and actuators, directly interface with the underlying physical process producing analog and digital signals that will be eventually converted and processed by other devices. Furthermore, an ICS might be viewed as a combination of OT (Operational Technology) and IT (Information Technology) devices, indeed it requires different expertise to be managed.

ICS security is a major challenge for many reasons. The complexity and diversity of devices involved in an ICS increases the attacker surface, namely an attacker can attack both the cyber-part and the physical-part of an ICS. Additionally, modern ICS are embracing standard Internet communication technologies, such as TCP/IP based industrial protocol, resulting in ICS that can be controlled (and attacked) from the Internet. Finally, the software of ICS devices may contain vulnerabilities for several common reasons, such as: un-patched or impossible to patch legacy code, the absence of standard security certifications for ICS devices, and lack of resources to keep the ICS updated. We note that ICS often run proprietary licensed Operating Systems, firmware, and management software.

Arguably, threats to ICS focus on impact to the physical world, instead of attacks on confidentiality or integrity of information. As such, the damage by such attacks is expected to cause financial cost due to destroyed property and decreased operational availability of commercial systems. Famous examples of attacks on ICS are Stuxnet [17] and the attack on a wastewater treatment facility in Maroochy [37].

2.2 Secure Water Treatment

In this work, we leverage the Secure Water Treatment (SWaT) for experimental work. SWaT is a state-of-the-art water treatment testbed opened at our institution in 2015 that comprises six stages or subsystems:

1. Supply and Storage: pumps raw water from the source to the Raw water tank.
two benefits: it allows a team to patch a service to be more resilient against adversarial attacks, and to attack other teams vulnerable service. Both jeopardy-style and attack-defense, CTF have time constraints (realistic scenario) and the team who scores most points wins the competition. The presented paper uses both online jeopardy-style and live attack-defense CTF styles to augment the learning experience.

Such events attract the attention of both industrial and academic teams and currently enjoy increasing popularity, as indicated by an established website in this community, listing CTF competitions worldwide [13]: this website lists 100 events being held worldwide, some of them with a long tradition such as the hacker-oriented DEFCON CTF [14] and the academic-oriented iCTF [11]. Of the 10,000 teams listed in CTF time in 2016, some are academic and others are composed of a heterogeneous mixture of security enthusiasts, many of them security professionals.

CTF-like gamified security competitions are expected to help the ICS security community in many ways [15][30][40]. A CTF is an hands-on learning experience and it can be used as an educational tool, research tool, and as an assessment tool. Ideally, both recruiters and candidates from academia and industry benefit participating in CTF events as they exercise key aspects of the ICS security domain such as knowledge of security (recent) threats, teamwork, analytical thinking, development of (new) skills, and working in a constrained environment. The gamification aspect of a CTF allows the participant to express his or her full potential, e.g., attack/defend without fear of consequences or bad marks. CTF events have already been proposed as a means to enhance security education and awareness [15][30][40]. Although such events cover a wide range of security domains, to the best of our knowledge they do not include so far the security of ICS.

3. GAMIFYING EDUCATION AND RESEARCH ON ICS SECURITY

We start this section by summarizing current challenge statements from academia and industry, and we leverage them to set the problem statement of this work. Then, we propose number of solution approaches. We focus on one of them, and discuss how it could be implemented.

3.1 ICS Current Security Challenges

In recent years, experts have argued extensively about the criticality of securing Industrial Control Systems (ICSs). Many have pointed out that one fundamental challenge in achieving this task lies in cultural and educational differences between the fields of (traditional) information security and ICS security. According to Schoenmakers [35]: “Differences in perspectives between IT and OT specialists can cause security issues for control systems. It is important for organizations to keep in mind that different values between groups can influence the perception of issues and solutions.”, which emphasizes the cultural clash exists still existing between traditional IT security and ICS specialists.

Education and training have been advocated to bridge this gap, but there still work to do in this domain. Luijif [25] describes the security of ICS as a societal challenge, and recommends: “Many of these challenges have to be overcome by both end-users, system integrators and ICS manufacturers at the long run: (...) proper education and workforce development”.

Despite the problem of education being widely acknowledged, according to a recent report published by SANS Institute [19]: “It is clear from our results that most of our respondents hold security certifications, but the largest number of these (52%) is not specific to control systems (...) IT security education is valuable, particularly with the converging technology trends, but it does not translate directly to ICS environments.”

In order to effectively improve the security of ICS it is thus crucial to educate researchers and practitioners such that they are able to understand the subtleties and domain-specific requirements and constraints of security and ICS. As recently pointed out by Luijif in [25]: “(...) ICS and (office) IT have historically been managed by separate organizational units. ICS people do not consider their ICS to be IT. ICS are just monitoring and control functions integrated into the process being operated. ICS people lack cyber security education. The IT department, on the other hand, is unfamiliar with the peculiarities and limitations of ICS technology. They do not regard the control of processes to have any relationship with IT. Only a few people have the knowledge and experience to bridge both domains and define an integrated security approach. Organizations that have brought the personnel from these two diverse domains together have successfully bridged the gap and improved the mutual understanding of both their IT and ICS domains. Their security posture has risen considerably.”

3.2 Problem Statement

With the challenges from Section [31] as a high-level goal in mind, in the following we discuss the problem statement and the proposed solutions.

Based on the literature and our experience, we think that traditional IT (security) professionals need more information about the following topics:

- Common device classes, network topologies, and protocols used in ICS.
- Design methodologies best-practices and operational objectives in ICS.
- Physical processes specifications.
- Control theory models.

Furthermore, training for ICS (security) professionals can be beneficial in the areas of:

- Common “modern” Internet communication technologies (Ethernet, IP, TCP, UDP, NAT).
- Common security challenges and standard solutions (MitM attacks, TLS, firmware and software update schedules).
- Standardization and specifications related to security products.

Problem statement How can we create an impactful educational experience that addresses the aforementioned gaps?

3.3 Proposed Solution Approaches

We now propose a number of approaches to alleviate the outlined problems. We then present a solution that covers several of the proposed approaches.

1. A set of common use cases for ICS. In particular, the use cases would include a fictional or real physical process and details on the communication network topology.
2. Interactive ICS testbeds, that allow users to familiarize themselves with the control devices and protocols used and interact with the underlying physical process.
3. Practical training on ICS and information security.
4. Testing of security solutions through external parties, and standard certifications.

3.4 The SWaT Security Showdown

In this work, we focus on the aspect of training and validation of applied security skills for industry professionals and researchers. Gamification in education has been advocated as a means to en-
rich the learning experience [22]. In particular, within IT security, the implementation of CTF-like competitions have been argued to be advantageous for education and training [40]. Inspired by the gamified nature of CTF, we propose the following approach.

Our goal is to create a realistic environment where participants are encouraged to think out of the box. In real-life ICS settings, several intrusion detection mechanisms are in place to safe-guard critical operations. A successful attacker would have to bypass such systems in order to pose a threat, and simulating such settings would stimulate a participant’s ingenuity to attempt creative attacks. On the other hand, if successful, such attacks will potentially unveil limitations of the defense mechanism. Therefore, we propose to divide participants in a training event into two categories: participants interested in developing defenses for ICS (defenders) and participants interested in testing the security of ICS (attackers).

In order to get the most out of an interaction with a real ICS testbed, it is important to learn fundamental concepts of ICS security. However, this learning phase should be as hands-on and gamified as possible. To this extent, we propose an on-line training phase, where attackers get familiar with ICS concepts and a particular critical infrastructure by means of a jeopardy-style CTF. Different from traditional CTFs, the challenges are tailored to highlight ICS concepts and use realistic simulations of ICS networks and remote interaction with ICS hardware. In this phase, attackers also should be aware of the internal workings of common defense mechanisms in place, and documentations there-of are shared with them.

After this preparation, in a live phase attackers phase interaction with a live system that is being monitored by defenders. In this setting, attackers should have concrete goals to achieve (or flags in CTF jargon), and their scoring should be influenced by the number of defenses triggered during their attack. In order to motivate attackers to perform more creative and difficult attacks, different attacker models can be suggested to them (i.e. insiders with administration capabilities, outsiders with network access) and the scoring can be adjusted according to the attacker model chosen.

Finally, participants will have access to statistics on their performance based on a unified scoring system taking into account both phases. Attackers will benefit from this experience since in order to solve the on-line and live challenges they will have to go through several of the topics discussed in the previous subsection. On the other hand, defenders will benefit by putting their solutions to the test against creative attackers.

We have implemented the proposed concepts at our institution in 2016, under the name SWaT Security Showdown. In the following two sections, we present the two main phases of that event, which represent the two target systems we introduced earlier: a) online challenges using questions and simulated systems, and b) live events using a real physical ICS. Due to organizational constraints, and in order to maximize the learning experience, we decided to limit the participants to SWaT Security Showdown to selected invited teams from academia and industry, both for attacker and defender roles, for a total of 12 invited teams (6 attackers, 6 defenders, of which 3 academic and 3 industrial teams respectively). Teams were not limited in size, but only a maximum of 4 members could participate physically in the live event whereas remaining team members could join remotely.

4. ONLINE PHASE OF S3

In this section we will present the SWaT Security Showdown online event, and the details about its setup, and presented challenges. We will describe more in detail three set of challenges from the MiniCPS, Trivia and Forensics categories. We conclude the section with a summary of the collected results.

4.1 Online phase Setup and Challenges

The SWaT Security Showdown online phase involving six teams of attackers, three from industry, and three from academia. We presented a total of twenty challenges in preparation for this phase, and we offered to each team a limited time to access to Secure Water Treatment, and the required documentation to get familiar with the SWaT and Ethernet/IP. We organized two sessions, each one 48 hours long, where three teams at a time attempted to solve the challenges for a total amount of 510 points.

The S3 online phase was structured as a jeopardy-style CTF, and did not require physical access to the SWaT. The main goal of this phase was to provide an adequate training to the attacker teams (third goal from Section 3.3). Please refer to Section 5 for more information about Capture-The-Flag events.

Table 1 summarizes the proposed tasks. We presented twenty tasks divided into five categories: MiniCPS, Trivia, Forensics, PLC, and Misc, for a total of 510 points. Each category exercised several ICS security domains, such as Denial-of-Service, and Main-in-the-Middle attacks. It is important to notice that categories such as MiniCPS, Trivia, and PLC are novel in the domain of traditional jeopardy-style CTFs. Following CTF design best-practices we presented the challenges of each category in increasing order of difficulty e.g.: solving challenge x helped to solve challenge x + 1, and when necessary, we gave hints e.g.: you could use tool/x to accomplish a certain task. In general, we used the online event as a training session to prepare the attacker teams for the S3 live event that is described in Section 5.

| Category  | Tasks | Points | Security Domains                          |
|-----------|-------|--------|-------------------------------------------|
| MiniCPS   | 5     | 210    | network mapping, DoS, reconnaissance, MitM |
|           |       |        | attacks in ENIP, tampering, tank overflow  |
| Trivia    | 6     | 45     | SWaT’s physical process, devices and attacks |
| Forensics | 4     | 105    | packet inspection, processing and cryptography |
| PLC       | 3     | 60     | ladder logic, code audit and development  |
| Misc      | 2     | 90     | web authentication, steganography          |

We built a Webapp to run the S3 scoring system using the flask Python framework [32] (Figure 2). The web pages were served over HTTPS, using Let’s Encrypt [20], and a basic brute-force attempts detection mechanism based on user input logging was put in place on the backend side. A dedicated web page was showing a live chart with the scores from all the teams. We offered live help with two different channels: an IRC channel on freenode.org, and via email. The following is an example of user interface interaction with our Webapp: member of team A logs in to S3’s Webapp (using the provided credentials), she navigates to challenge X’s Web page, then enters the flag on an HTML form. If the flag is correct, she receives N reward points,
4.2 MiniCPS Category

The online phase presented five challenges in the MiniCPS category. MiniCPS was used to "realistically" reproduce (simulate) part of the Secure Water Treatment, including the hydraulic physical process, the devices and the network. Each simulated instance accessed by the attackers' teams was running on Amazon Web Services Elastic Compute Cloud (AWS EC2), using an m3-type virtual machine (one instance per team).

Figure 3 shows the simulation setup of a single instance, that was replicated for all the six teams. Each attacking team was provided with the credential to access an SSH server running on a simulated chrooted gateway device. The attacker had access to the emulated virtual control network that used the same topology, addresses (IP, MAC, net masks), and industrial protocol (Ethernet/IP), of the SWaT.

The attacker could interact with other simulated SWaT’s devices in the star topology (four PLCs and an HMI), and alter the state of the simulated water treatment process affecting the two simulated water tanks (the Raw water tank and the Ultra-filtration tank). For example, an attacker might send a packet containing a false water level sensor reading of the Ultra-filtration tank to the HMI, or a packet that tells to PLC2 to switch off the motorized valve, that controls how much water goes into the Raw water tank. As a side note, Figure 3's setup is part of an internal project involving the development of novel honeypots for ICS [7].

The following five paragraphs summarize each of the MiniCPS challenges, with the attacker’s goals and a reference solution:

Network warm up. The goal of the first challenge is to perform a passive ARP-poisoning MitM attack between PLC2 and PLC3. The attacker has to perform a network scanning to discover the hosts addresses and then use ettercap to read the flag on the wire.

Ethernet/IP warm up. The goal of the second challenge is to read the flag stored in PLC2’s Ethernet/IP server, and addressable with the name README:2. The attacker has to understand which PLC owns the README:2 tag, and how to use cppppo, the suggested Ethernet/IP’s Python library [23].

Overflow the Raw water tank. The goal of the third challenge is to overflow the simulated Raw water tank. The attacker has to understand the simulated dynamic of a water tank e.g., who drives inflow and outflow, and tamper with the correct actuators to increase the water level above a fixed threshold. Some hints were given to explain the binary encoding e.g., use m/n to switch ON/OFF a water pump and OPEN/CLOSE a motorized valve.

Denial of Service HMI. The goal of the fourth challenge is to disrupt the communication (Denial-of-Service) between the HMI and PLC3, and then change a keep-alive tag value to 3 on PLC3 Ethernet/IP’s server. In normal working condition the keep-alive tag is periodically set by the HMI to 2. Given the knowledge acquired from the previous three challenges, the attacker has to perform an active MitM attack that drops all the packets between the HMI and PLC3. Notice that, it is not sufficient to just write the required keep-alive tag value on PLC3 Ethernet/IP’s server.

Overflow the Ultra-filtration tank. The goal of the fifth challenge is to overflow the Ultrafiltration water tank. The attacker has to reuse a combination of the previously used techniques to set up an active MitM attack using custom filtering rules e.g., use ettercap and etterfilter.

4.3 Trivia Category

The online phase presented six challenges in the Trivia category. The Trivia challenges were intended for the attackers to understand the plant structure, behavior, and the defense mechanisms. The knowledge gained from these challenges is expected to be of use to the attackers in other phases of the event. In the remainder of this section, we briefly describe the six challenges, their goals, and the steps needed to capture the flags.

The trivia challenges can be divided into two types, the first type involved the knowledge on SWaT, and the second type involved research papers on SWaT.

Knowledge on SWaT. Three challenges fall under this category. The goals of these challenges are to focus on the physical process of SWaT [38], the control strategy of SWaT, and the set points of the sensors and actuators. Following are the details regarding the challenges.

Trivia 1 The goal of the first challenge is to identify the analyzer that is used by the PLCs to control a specific dosing pump. In order
to identify the device, the participant has to understand the control strategy of the particular dosing pump. As the PLC uses a number of different inputs to control the dosing pump, the participant has to trace the signals and identify the particular analyzer.

**Trivia 2** The goal of the second challenge is to find out the set point that triggers the start of the backwash process. During the filtration process, small particles clot the Ultrafiltration membrane. To remove them and clean the Ultrafiltration membrane, a backwash process is started after reaching a specific threshold. In order to answer this challenge, the participant needs to revise and understand the backwash process.

**Trivia 3** The goal of the third challenge is to identify the set point of the hardness analyzer used by a PLC to shut down the RO filtration. The hardness analyzer measures the water hardness in SWaT. The set point is a desired value of a particular sensor which is used by the PLC to control the plant. In the current scenario, when hardware analyzer exceeds desired value, PLC shuts down the RO filtration. In order to answer this challenge, attacker should understand the set points and control strategy of the RO process.

**Research papers on SWaT.** The remaining three challenges fall under this category. The goals of these challenges are to raise awareness about ICS attacks techniques and their classification in the context of SWaT. We selected the following three papers: [1], [2], [21] as reference attack vectors targeting ICS. Following are the details of these challenges.

**Trivia 4** The goal of this challenge is to familiarise the attacker with possible attacks on SWaT and potential impact of those attacks on SWaT. We provided a research paper [2] that presents an experimental investigation of cyber attacks on an ICS. In order to answer the challenge, the participant needed to read the paper and understand it.

**Trivia 5** The goal of this challenge is to familiarise the participant with a security analysis of a CPS. We provided another research paper [21] that presented a security analysis of a CPS using a formal model. In order to answer the challenge, the attacker should read the paper and understand it.

**Trivia 6** The goal of this challenge is to familiarise the attacker with multi-point attacks on ICS. We provided a third research paper [1] that discussed multi-point attacks. A multi-point attack leverages more than one entry point, e.g., two or more communications links, to disturb the state of an ICS. In order to answer the challenge, the participant needed to read the paper and understand it.

### 4.4 Forensics Category

The forensics challenges focused on network capture files, in particular `pcap` files, that are easy to process using programs such as `wireshark` and `tcpdump`. The participant had to learn how to process and extract information from a file containing pre-recorded network traffic from an ICS. The target industrial protocol was Ethernet/IP. We now provide details on three of the four challenges.

**Identify the ICS hosts.** The goal of the first challenge is to perform an analysis of the ICS hosts inside a captured ICS network traffic. To achieve that goal, the attacker should search for the hosts inside the captured traffic, classify them based on their IP addresses, identify whether a host is inside the ICS network or not and enumerate them.

**Finding the poisoning host.** The goal of this challenge is to search for a host that has performed an ARP poisoning Main-in-the-Middle attack, inside a captured network traffic. Then, the attacker will identify the start point and end point of captured ARP poisoning attack inside the captured network traffic. As an example, the flag of this problem will be the start and end TCP sequence number in the form of `aascflag(A-B)`, where the A is the starting TCP sequence number and B is the ending TCP sequence number.

**Understanding the CIP protocol structure.** The goal of this challenge is to find a particular pattern inside the payload of CIP messages. In particular, the attacker has to recognize that a CIP payload contains encrypted data and then he has to decrypt it. So, the attacker can decrypt the ciphertext by performing a XOR it with a key included in the payload or performing a brute-force.

### 4.5 Results from the Online phase

Table 2 presents the scores of each team, the number of captured flags, and an estimation of the time spent playing, computed as the difference between the last and the first flag submitted by a team. As we can observe from the table, two teams were able to fully complete all tasks, with Team 6 being by far the most efficient. On average teams spent 25.67 hours to solve the challenges (53% of the maximum of 48 straight hours), with a standard deviation of 13.06 hours. The teams scored an average of 268.83 points (52.7% of the maximum of 510). We believe that both the time invested and the percentage of challenges solved shows a notable investment in the game, and provides evidence on the engagement generated by the gamification strategy. In addition, we note a correlation between the number of hours invested, and the points achieved. In fact, when the outlier (Team 6) is removed, there is a 0.97 Pearson correlation coefficient (PCC) between time spent and points achieved.

| Team   | MCPS Flags | T Flags | F Flags | P Flags | M Flags | Σ Flags | Score | Time |
|--------|------------|---------|---------|---------|---------|---------|-------|------|
| Team 1 | 2          | 6       | 4       | 0       | 1       | 13      | 250   | 30h  |
| Team 2 | 5          | 6       | 4       | 3       | 2       | 20      | 510   | 44h  |
| Team 3 | 0          | 4       | 2       | 0       | 1       | 7       | 86    | 27h  |
| Team 4 | 4          | 4       | 2       | 0       | 0       | 10      | 161   | 28h  |
| Team 5 | 0          | 4       | 2       | 0       | 1       | 7       | 66    | 21h  |
| Team 6 | 5          | 6       | 4       | 3       | 2       | 20      | 510   | 4h   |

To conclude the online event, we believe that the gamification factor played an important role. Gamification helped us to combine different categories in an unified ICS security theme, to motivate the attacker teams to do their best to get the maximum points, and to implicitly train them for the upcoming live phase.

### 5. LIVE PHASE OF S3

As discussed in Section 3.4, the goal of the online phase was to prepare teams for the live phase of S3. In this section we will present the SWaT Security Showdown live event, and the details about its setup, and scoring system. Afterwards, we will describe two of the academic detection mechanisms, ARGUS and HAMIDS, that were used during the event. We conclude the section providing a summary of the collected results.

#### 5.1 Live phase Setup

The live phase of S3 was held at SUTD over the course of 2 days in July 2016. All six attacker teams that participated in the online phase were invited. Each team was assigned a three hour timeslot, in which it would have free access to SWaT to test and deploy a range of attacks, taking advantage of the knowledge gained during the...
the online phase presented in Section 5.1. In addition, teams were able to visit the SWaT testbed for one working day, to perform passive inspection before the event to prepare themselves.

The main goal of the live phase was two-fold: firstly, the teams would be able to learn more about an actual ICS and its security (second and third goals from Section 5.3). Secondly, we would be able to test a number of (internally developed) detection systems that were deployed in SWaT to evaluate and compare their performances (fourth goal from Section 5.3).

5.2 Scoring and Attacker Profiles

We designed the scoring system for the live phase with the following goals:
- Incentivise more technically challenging attacks.
- De-incentivise re-use of same attack techniques.
- Provide challenges with different difficulty levels.
- Relate the attack techniques to realistic attacker models.
- Minimize damages to the participants and the actual system.

We now briefly summarize the scoring system we devised. In general, points were only awarded if the attack result could be undone by the attacker (to minimize the risks of permanent damages).

Equation 1 defines how to score an attack attempt:

\[ s = g \cdot c \cdot d \cdot p \]  

(1)

With \( s \) being the final score, \( g \) a value representing the base value of the goal, \( c \) a control modifier to value the level of control the attacker has, \( d \) a detection modifier, and \( p \) the attacker profile modifier. Most modifiers were in the range [1, 2], while the base value for the targets was in the range [100, 200].

We now describe in detail the four modifiers from Equation 1.

Goals could be chosen from two sets: physical process goals and sensor data goals.

Physical Process Goals \( g \). Control over actuators, and physical process (water treatment):
- 100 points: Motorised Valves (open/close/intermediate).
- 130 points: Water Pumps (on/off).
- 145 points: Pressure.
- 160 points: Tank fill level (true water amount, not sensor reading).
- 180 points: Chemical dosing.

Sensor Data Goals \( g \). Control over sensor readings at different components:
- 100 points: Historian values.
- 130 points: HMI/SCADA values.
- 160 points: PLC values.
- 200 points: Remote I/O values.

Control modifiers \( c \). The control modifier determined how precise control the attacker had. As guideline the modifier was 0.2 if the attacker could randomly (value and time) influence the process, up to 1.0 if the attacker could precisely influence the process or sensor value to a target value chosen by the judges.

Detection modifiers \( d \). Not triggering a detection mechanism while the attack is executed would increase the detection modifier, using the following formula: \( 2 - x/6 \), with \( x \) the number of triggered detection mechanisms.

Attacker profile modifiers \( p \). For each attack attempt, the attacking team had to inform the judges about the chosen attacker model before the attack is started. The overall idea is that a weaker attacker profile would yield a higher multiplier. The attacker profiles were based on [31] and the higher is the modifier the weaker is the attacker model. The SWaT Security Showdown live event used three attacker profiles: the cybercriminal, the insider, and the strong attacker.

The cybercriminal model had a factor of 2. The cybercriminal was assumed to have remote control over a machine in the ICS network, and was able to use own or standard tools such as nmap, and ettercap. The cybercriminal did not have access to ICS specific tools, such as Studio 5000 (IDE to configure SWaT’s PLCs), or access to administrator accounts.

The insider attacker had a factor of 1.5. It represented a disgruntled employee with physical access and good knowledge of the system, but no prior attack experience, and only limited computer science skills. In particular, the attacker was not allowed to use tools such as nmap or ettercap, but had access to engineering tools (such as Studio 5000), and administrator accounts.

The strong attacker effectively combined both other attackers, resulting in the strongest available attacker model, and yielded a factor of 1.

Attackers could earn points for one or more attacks. If more than one attack was successfully performed, the highest scores from each goal was aggregated as final score. For example, if an attack on pumps was successful both using the strong attacker model, for a total score \( s \) of 130 points, and the cybercriminal attack model, for a total score \( s \) of 200 points, then only 200 points would be counted for that attack goal (attack a pump).

5.3 Detection mechanisms

As discussed in Section 5.1 as part of the design of our approach we included academic and commercial detection mechanisms as means to incentivate the creativity of attackers: the less detection mechanisms triggered the more points obtained, as discussed in the previous subsection. Also, the experience was designed to serve as feedback to the designers of detection mechanisms when confronted with various human attackers and a wider range of attack possibilities. In the following we emphasise two academic detection mechanisms implemented at SUTD.

5.3.1 Distributed detection system

The distributed attack detection method presented in [4,6] was implemented in Water Treatment Testbed as one of the defense methods used in the S3 event. The method is based on physical invariants derived from the CPS design. A “Process invariant,” or simply invariant, is a mathematical relationship among “physical” and/or “chemical” properties of the process controlled by the PLCs in a CPS. Together at a given time instant, a suitable set of such properties constitute the observable state of SWaT. For example, in a water treatment plant, such a relationship includes the correlation between the level of water in a tank and the flow rate of incoming and outgoing water across this tank. The properties are measured using sensors during the operation of the CPS and captured by the PLCs at predetermined time instants. Two types of invariants were considered: state dependent (SD) and state agnostic (SA). While both types use states to define relationships that must hold, the SA invariants are independent of any state based guard while SD invariants are. An SD invariant is true when the CPS is in a given state; an SA invariant is always true.

The invariants serve as checkers of the system state. These are coded and the code placed inside each PLC used in attack detection. Note that the checker code is added to the control code that already exists in each PLC. The PLC executes the code in a cyclic manner. In each cycle, data from the sensors is obtained, control actions computed and applied when necessary, and the invariants checked against the state variables or otherwise. Distributing the
attack detection code among various controllers adds to the scalability of the proposed method. During S3, the implementation was located inside the Programmable Logic Controllers (PLCs) [4].

5.3.2 The HAMIDS framework
The HAMIDS (Hierarchical Monitoring Intrusion Detection System) framework [5] was designed to detect network-based attacks on Industrial Control Systems. The framework leverages a set of distributed Intrusion Detection System (IDS) nodes, located at different layers (segments) of an ICS network. The role of those nodes is to extract detailed information about a network segment, combine the information in a central location, and post-process it for real-time security analysis and attack detection. Each node uses the Bro Intrusion Detection System (IDS) [29].

Figure 4 shows our deployment of the HAMIDS framework instance deployed in the SWaT. As we could see from Figure 4 each L0 (Layer 0) DLR segment has an additional Bro IDS node that is collecting data flowing from a PLC to the RIO device. An additional Bro IDS node is connected to a mirroring port of the L1 (Layer 1) industrial switch, and is collecting the traffic in the L1 star topology. Every Bro IDS node is sending data to the central HAMIDS host, by means of a secure channel (using SSH). Elasticsearch [16], a distributed, RESTful storage and search engine, is used to provide a scalable and reliable information recording and processing.

The HAMIDS detection mechanism is entirely isolated from the ICS network, and thus as part of the live event, the attackers were not able to have direct access to the detection system. So the attackers will have hard times trying to stop the detection mechanisms of the HAMIDS framework. On the other side, there are two ways to access data from a defender perspective: a Web interface and a SQL API.

The web interface is a user-friendly interface that can be used by less technical ICS operators and it is capable of listing all alarms generated by the central node, and eventually help in detecting an ongoing attack. The expert user can directly use the SQL API to query the central node, and obtain more detailed data about the observed packets.

For the event, the framework was configured to present high-level information about the status of the detection system, suitable for non-expert defenders. Using the web user interface, the defender could read the generated alarms related to triggered alarms due to observed network traffic in the industrial control system. In addition, expert defenders could read the detailed information about the ICS process by using manual SQL queries to retrieve data for further analysis.

5.4 Results from the Live phase
Table 3 shows the final scores, the number of performed attacks and the cumulative detection rate \( d_{rate} \) of the live phase. The cumulative detection rate was computed as the average number of detection mechanisms triggered (considering only the two academic detection mechanisms discussed before) in all successful attacks by a given team.

In order to show more in depth insights of the live phase, we now provide details on several attacks that were conducted by the participants during the SWaT Security Showdown live event (see Table 3). We classify those attacks in two types, the “cyber” attacks were conducted over the network using either the cybercriminal, or the strong attacker model, while the “physical” attacks were conducted having direct access to the SWaT using either the insider, or the strong attacker model. We now describe each of those attacks.

**DoS by SYN flooding.** The first attack was a cyber-attack, and the attacker used the insider attacker model. The attacker had access to the administrator account and associated tools. The attacker performed a SYN flooding attack on PLC1’s Ethernet/IP server. SYN flooding is a Denial-of-Service (DoS) attack, where the attacker (the client) continuously tries to establish a TCP connection, sending a SYN request to the Ethernet/IP server, the Ethernet/IP server then responds with an ACK packet, however the attacker never completes the TCP three-way-handshake and continues to send only SYN packets. As a result of this DoS attack, the HMI’s is unable to obtain current state values to display, and would display 0 or * characters instead. Such effects would impede the supervision of ICS in real applications. However, the attack did not interrupt or harm the physical process itself. The HAMIDS detectors was able to detect the attack by observing the high number of SYN requests without follow-up. The ARGUS detector was not able to detect the attack.

| Team | Score | Successful Attacks | \( d_{rate} \) |
|------|-------|-------------------|----------|
| Team 1 | 666 | 4 | 1 |
| Team 2 | 458 | 2 | 1 |
| Team 3 | 642 | 3 | 1 |
| Team 4 | 104 | 1 | 1 |
| Team 5 | 688 | 5 | 5 |
| Team 6 | 477 | 3 | 4 |

**Table 4:** Live Attacks and Detections summary: ○ = undetected, ● = detected.

| Attack | Type | Score | ARGUS | HAMIDS |
|--------|------|-------|-------|--------|
| SYN flooding (DoS) PLC | Cyber | 396 | ○ | ● |
| DoS Layer 1 network | Cyber | 104 | ○ | ● |
| Tank level sensor tampering | Physical | 324 | ● | ● |
| Chemical dosing pump manipulation | Physical | 360 | ● | ○ |
attack, as the physical process was not impacted.

DoS. The second attack was a cyber-attack, the attacker used the cybercriminal attacker model. The attacker had access to the network and attack tools. The attacker performed an ARP poisoning Man-in-the-Middle attack, that redirected all traffic addressed to the HMI. The redirected traffic was then dropped and prevented from being received. The attack drove the HMI to an unusable state, and it took a while to restore the system state after the attack. We did not allow the attack to run long enough to affect the physical process. HAMIDS detected the attack due to the changes in network traffic (i.e. malicious ARP traffic, changed mapping between IP and MAC addresses in IP traffic). In contrast, ARGUS did not detect the attack, as the physical process continued to operate without impact.

**Tank level sensor tampering.** The third highlighted attack involved an on-site interaction with the system, the attacker used the strong attacker model. The attacker focused on one of the L0 segments, and he demonstrated control over the packets sent in the Ethernet ring. Indeed, the attacker was able to alter the L0 traffic in real time, and manipulate the communication between the PLC and the RIO. ARGUS was able to detect the attack due to the sudden changes in reported sensor values (bad data detector). In addition, the HAMIDS framework detect the attack by observing the change in data reported from the PLC to the SCADA (and potentially, in L0 as well).

**Chemical dosing pump manipulation.** The fourth attack was a physical-attack, and the attacker used the insider attacker model. The attacker was able to alter the chemical dosing in the second stage (Pre-treatment) of the SWaT by interacting directly with the HMI interface, and overriding the commands sent by the PLC (that was set in manual mode). The attack would have resulted in an eventual degradation of the quality of the water, however we stopped the attack before that case occurred. ARGUS was able to detect the attack because the updated setpoints diverged from their hardcoded counterpart in the detection mechanism. The HAMIDS detection was unable to detect this scenario as the network traffic did not show unusual patterns or changes (as typical for attacks using the insider model).

## 6. DISCUSSION OF S3

In the following section we present an analysis of a survey that we ran after the SWaT Security Showdown, and some lessons learned during the online and live phases of S3.

### 6.1 Post-S3 Survey Analysis

After the end of the SWaT Security Showdown event, we distributed an anonymous survey, both to the attacker and defender teams. The survey asked targeted questions about the online and the live phases, and for each question the team has to select a score from 1 to 5; e.g., 1 corresponded to full disagreement with the proposed question, and 5 to full agreement. We present some insights from the survey process, that overall resulted in a positive feedback from the participants and in an interest to participate again in an security competition targeting ICS, such as S3.

Table 5 shows the statistics of the answers received from the attacker teams. As it can be seen from the table, the overall satisfaction level is high, however there are two low scores, one regarding the difficulty level of the online event, and the other regarding the information shared beforehand. Most of the teams commented that the time given to prepare the attacks in the live phase was not enough. Indeed, more time to interact with the system is ideal and we will considering organizing future events. However on the one hand, we think that strict time constraints increase the level of realism of the competition, e.g., an attacker who penetrated a guarded ICS does not have unlimited time to perform his attack. On the other hand there are some inherent time and organizational constraints: it is impossible to parallelize such a competition, to avoid teams interfering with each other, and holding such an event with even a restricted number of teams for several days is resource-consuming (lab engineer and judges must be constantly present).

In particular, we present two constructive feedbacks, one from an attacker team, and one from a defender team, that we will take into account in the next SWaT Security Showdown iteration:

- **Attacker team:** “There were some differences between the online and offline event, we made assumptions based on what we did online that ended up being wrong for the offline challenges. Overall it was a good lessons learnt for next time!”
- **Defender team:** “I think that the attackers shouldn’t have access to the HMI even with the insider profile. An insider should know the process and tags names and even have access to the HMI machine, but to perform an attack from the HMI itself is not only a boring attack that in the same manner the operator can do almost everything he wants, (…) I think that the usage of the HMI should be only if the hackers manage to hack the HMI software and not from the user interface.”

Regarding the attacker comment, this is motivated by the fact that in the simulations used in the live phase there were unavoidable simplifications of the real system, which might have been misleading to some participants. In future events we will better highlight this differences to better prepare teams. The defender comment is interesting: indeed some defense products are aimed to protect against malicious external attackers, while trusting plant operators with administrator privileges. However this highlights the shortcomings of such mechanisms against malicious and powerful insiders.

### 6.2 Online phase: Lessons learned

We have learned a number of useful lessons from the MiniCPS related challenges, and we will present three of them. Firstly, it
is hard to reproduce (simulate) the Secure Water Treatment: we were able to provide partial support of the Ethernet/IP protocol, and replicate only the hydraulic part of the SWaT. Secondly, crash recovery and management is hard: during the competition we suffered some downtime caused by attackers trying to use (legitimate) brute-force attack techniques, and because of that some of them wasted their time waiting for us to restore the system. Indeed, it is very important to develop a simulation environment that is able to gracefully shutdown, and restart automatically in most of the cases. Finally, side channel attacks mitigation is hard. By side channel attack, we mean any attack that uses a different channel from the ones intended by the competition. Remember that, an attacker had to find one hole in our simulation environment however we had to try to cover all of them. Indeed it is important to not overlook the basic configuration of your system, even the parts not directly related to the security competition. For example, remove unnecessary software, and update all your software to the most recent (secure) version.

We have learned mainly two useful lessons from the Trivia related challenges. Firstly, it was helpful to present to the attacker general questions related to the SWaT’s physical process, however presenting more advanced ones would have helped the attacker in the live phase to prepare more effective attacks. The same was true for the presented attack techniques. Given that the majority of the participants was not from the ICS security domain, we decided to present only basic attack techniques (already tested on the SWaT), however after the event we realized that we could have presented more elaborated ones.

6.3 Live phase: Lessons learned

A key aspect of the live event is the interaction of the participants with real devices, and with other people in a realistic environment. Even though an online event is low-cost, scales better with the number of participants, and presents less risks in terms of safety, we learned that a live event is an essential part of a security competition, and it was crucial to include it in S3, even if it required more effort and risk management.

Furthermore, we understood how important was to distribute documentation about the SWaT, and give access to it before SWaT Security Showdown. During the live event it was easy to spot the teams who did not read the provided documentation, and those teams got a lower score because they wasted a lot of time to acquire the basic information about the testbed, such as: number of devices, network topologies, and PLC programming.

The major lesson that ICS professionals should learn from the live phase is that ICS security consists of two intertwined parts: network and physical security. It is important to repeat that the attacker surface of an ICS is broad, because it results in both cyber and physical attack. Indeed, ICS security professionals should consider both the cyber and the physical risk at the same time when dealing with ICS security.

Finally, it is important to notice that designing a CTF is a hard and time-consuming task. Two key design aspects are the selection of vulnerabilities and the scoring system. Let’s use a jeopardy-style CTF as an example. If the challenges are too hard then the newcomers may lose interest after playing for a while, however, if the challenges are too easy the participants will not enjoy the competition. Indeed is crucial to design the challenges according to the audience expertise, and to present novel threats rather than reusing material from other passed events. The scoring system has to “incentivize” good behaviors and “punish” bad behaviors, according to the CTF rules. However, it is impossible to predict, and stop attackers from finding the novel technique to break the rules, and in some CTF (like DEFCON) there are no rules at all! In general, a good scoring system has to be fair, automated and easy to understand, e.g., participants will have to focus on the CTF challenges, rather than try to find a way to exploit an overcomplicated scoring system.

7. RELATED WORK

In the following we review some related efforts in gamification for security education.

There exists several popular CTF competitions, of which one of the most established ones is DEFCON [12]. This is an annual hacking conference organized by information security enthusiasts. The DEFCON CTF is part of the main event, and it is one of the most well known, and competitive CTF events worldwide. DEFCON CTF has a jeopardy-style qualification phase, and an attack-defense final phase, indeed its structure is similar to the one of SWaT Security Showdown, however ICS security is not the main focus of DEFCON’s CTF. Several other similar CTF competitions are listed in [13].

In [40] Vigna propose to use gamified live exercises similar to CTFs to teach network security. The motivations and philosophy of this work are similar to ours, however the focus is on traditional IT and network security (such as gaining root privileges in a web-server and steal data from an SQL database).

Inspired by [40], in [11] authors of the iCTF event (organized by an academic institution) presented two novel, live, and large-scale security competitions. The first is called “treasure hunt” and it exercises network mapping and multi-step network attacks. The second is a “Botnet-inspired” competition and it involves client-side web security, in particular Web browsers exploitation. Unlike the presented paper, both competitions focus on traditional client-server ICT network architectures and attack-only scenario.

The MIT/LL CTF [42] was an attack-defense CTF with a focus on web application security. The main goal of the event was to attract more people towards practical computer security, lowering the barriers of a typical CTF that requires an extensive background. The CTF takes inspiration from Webseclab [9], a web security teaching Virtual Machine that is packed with an interactive teaching web application, a sandboxed student development environment, and a set of useful programs. Both are interesting projects but they are not covering the ICS security domain, even though they share some of the presented goals.

BIBIFI [13] is a cyber-security competition held mainly in academic environments that adds secure development (Build-it) as a major component, together with the attack (Break-it) and the patch (Fix-it) components. This effort was targeted at improving secure software construction education, and thus the exercises proposed in this competition do not cover the ICS security domain.

In [27] Mink presents an empirical study that evaluates how exercises based on gamification and offensive security approaches increase both, the motivation and the final knowledge of the participants. Our work tries to extend this message to ICS security, while the paper focuses on traditional Information security.

In sum, to the best of our knowledge, we are the first to organize an academic CTF style event on a realistic ICS testbed aimed at improving ICS security training in academic and industrial environments.

8. CONCLUSIONS

In this work, we discussed problems faced by security experts and ICS engineers. In particular, security experts require easy platforms to learn about ICS in general, and practise applied attacks
and defenses. In addition, ICS engineers often require additional training in offensive and defensive security techniques. We proposed to use gamified events such as online and live challenges to mitigate those problems. We presented the design and implementation of two events (online and live) that were conducted together by us in 2016, leveraging a realistic ICS plant. To our best knowledge, this event was the first attempt to gamify security education, using both live and virtual ICS testbeds. Overall, the six participating teams submitted 77 correct flags in the online phase of the S3 event. In the live phase, the participating teams performed 18 successful attacks, of which most were detected by at least one of our detection mechanisms. We provide a summary of challenges for both events, and the achieved solutions by the participants, describe some of the design choices made, e.g., relating to attacker profiles, goals and scoring for the live event. The presented work should provide a foundation to enable others to run similar events in the future.

Acknowledgements
We thank Kaung Myat Aung and all the staff from iTrust for their support and contributions for event organization and management. We thank all the attacker and defender teams for their participation and valuable feedback.

9. REFERENCES
[1] S. Adepu and Aditya Mathur. Detecting multi-point attacks in a water treatment system using intermittent control actions. In Proc. of the Singapore Cyber-Security Conference (SG-CRC), volume 14, pages 59–74, January 2016.
[2] Sridhar Adepu and Aditya Mathur. An investigation into the response of a water treatment system to cyber attacks. In Proc. of Symposium on High Assurance Systems Engineering (HASE), pages 141–148. IEEE, 2016.
[3] Anonymous. Anonymized for review. In Proc. of Anonymous, January 2015.
[4] Anonymous. Defense framework. Anonymous, 2016.
[5] Anonymous. Detector x: Blinded for review. In Proc. of Blinded, January 2016.
[6] Anonymous. Distributed attack detection system. In Proc. of Anonymous, May 2016.
[7] Daniele Antonioli, Anand Agrawal, and Nils Ole Tippenhauer. Towards high-interaction virtual ICS honeypots-in-a-box. In Proc. of the Workshop on Cyber-Physical Systems-Security and/or Privacy (CPS-SPC). ACM, 2016.
[8] Daniele Antonioli and Nils Ole Tippenhauer. MiniCPS: A toolkit for security research on CPS networks. In Proc. of the Workshop on Cyber-Physical Systems-Security and/or Privacy (CPS-SPC), pages 91–100. ACM, 2015.
[9] Elie Bursztein, Baptiste Gourdin, Celine Fabry, Jason Bau, Gustav Rydstedt, Hristo Bojinov, Dan Boneh, and John C. Mitchell. Webscanel Security Education Workbench. In Proc. of Conference on Cyber Security Experimentation and Test (CSET), 2010.
[10] A. A. Cárdenas, S. Amin, Z.-S. Lin, Y.-L. Huang, C.-Y. Huang, and S. Sastry. Attacks against process control systems: Risk assessment, detection, and response. In Proc. of the ACM Conference on Computer and Communications Security (CCS), 2011.
[11] Nicholas Childers, Bryce Boe, Lorenzo Cavallaro, Ludovico Cavedon, Marco Cova, Manuel Egele, and Giovanni Vigna. Organizing large scale hacking competitions. In Proceedings of conference on Detection of Intrusions and Malware, and Vulnerability Assessment (DIMVA), 2010.
[12] Crispin Cowan. Defcon Capture the Flag: Defending vulnerable code from intense attack. In Proc. of - DARPA Information Survivability Conference and Exposition (DISCEX), volume 2, pages 71–72, 2003.
[13] CTFtime [https://defcon.org/]. Accessed: 2016-10-19.
[14] DEF CON hacking conference. [https://defcon.org/]. Accessed: 2016-10-19.
[15] Chris Eagle and John L. Clark. Capture-the-flag: Learning computer security under fire. Technical report, DTIC Document, 2004.
[16] Elasticsearch: Open Source, Distributed. RESTful Search Engine, [https://github.com/elastic/elasticsearch]. Accessed: 2016-10-19.
[17] Nicolas Falliere, L.O. Murchu, and Eric Chien. W32. stuxnet dossier (Symantec Security Response), 2011.
[18] Brendan Galloway and Gerhard P Hancke. Introduction to industrial control networks. IEEE Communications surveys & tutorials, 15(2):860–880, 2013.
[19] SANS institute. The State of Security in Control Systems Today, 2015. [https://www.sans.org/reading-room/whitepapers/analyst/state-security-control-systems-today-36042].
[20] Internet Security Research Group (ISRG). Let’s Encrypt. [https://letsencrypt.org/].
[21] Eunsuk Kang, Sridhar Adepu, Daniel Jackson, and Aditya P Mathur. Model-based security analysis of a water treatment system. In Proc. of Workshop on Software Engineering for Smart Cyber-Physical Systems (SE4CPS), 2016.
[22] Karl M Kapp. The gamification of learning and instruction: game-based methods and strategies for training and education. John Wiley & Sons, 2012.
[23] Perry Kundert. Communications protocol python parser and originator, [https://github.com/pjkundert/cpppo]. [Online; accessed 31-July-2016].
[24] Yao Liu, Peng Ning, and Michael K Reiter. False data injection attacks against state estimation in electric power grids. ACM Transactions on Information and System Security (TISSEC), 14(1):13, 2011.
[25] Eric Luijif. Cyber (in-) security of industrial control systems: A societal challenge. In International Conference on Computer Safety, Reliability, and Security (SafeComp), Springer, 2015.
[26] Eric Luijif and Bert Jan te Paske. Cyber Security of Industrial Control Systems. TNO technical report, 2015. [https://www.tno.nl/ics-security/]
[27] Martin Mink and Rainer Greiffeneder. Evaluation of the offensive approach in information security education. In Proc. of IFIP International Information Security Conference (IFIP SEC), pages 203–214, 2010.
[28] ODVA. Ethernet/IP technology overview, [https://www.odva. org/Home/ODVATECHNOLOGIES/EtherNetIP.aspx]. Accessed: 2016-08-01.
[29] Vern Paxson. Bro: a system for detecting network intruders in real-time. Computer Networks, pages 2435–2463, 1999.
[30] J Radcliffe. Capture the flag for education and mentoring: A case study on the use of competitive games in computer security training. [http://www.sans.org/reading-room/whitepapers/casestudies/capture-flag-education-mentoring-33018]. 2007.
[31] Marco Rocchetto and Nils Ole Tippenhauer. On attacker models and profiles for cyber-physical systems. In Proc. of the European Symposium on Research in Computer Security (ESORICS), September 2016.

[32] Armin Ronacher. Flask: web development, one drop at a time. http://flask.pocoo.org/.

[33] Andrew Ruef, Michael Hicks, James Parker, Dave Levin, Michelle L. Mazurek, and Piotr Mardziel. Build It, Break It, Fix It: Contesting Secure Development. In Proc. of the ACM Conference on Computer and Communications Security (CCS), 2016.

[34] Ahmad-Reza Sadeghi, Christian Wachsmann, and Michael Waidner. Security and privacy challenges in industrial internet of things. In Proc. of the Annual Design Automation Conference (DAC), pages 54:1–54:6, New York, NY, USA, 2015. ACM.

[35] Floris A Schoenmakers. Contradicting paradigms of control systems security: how fundamental differences cause conflicts, 2013.

[36] Aamir Shahzad, Malrey Lee, Young-Keun Keun Lee, Suntae Kim, Naixue Xiong, Jae-Young Young Choi, and Younghwa Cho. Real time MODBUS transmissions and cryptography security designs and enhancements of protocol sensitive information. Symmetry, 7(3):1176–1210, jul 2015.

[37] Jill Slay and Michael Miller. Lessons learned from the maroochy water breach. Springer, 2007.

[38] Anonymized reference to testbed, 2015.

[39] David Urbina, Jairo Giraldo, Nils Ole Tippenhauer, and Alvaro Cárdenas. Attacking fieldbus communications in ICS: Applications to the SWaT testbed. In Proc. of Singapore Cyber Security Conference (SG-CRC), January 2016.

[40] Giovanni Vigna. Teaching network security through live exercises. In Security education and critical infrastructures, pages 3–18. Springer, 2003.

[41] S. Weerakkody, Yilin Mo, and B. Sinopoli. Detecting integrity attacks on control systems using robust physical watermarking. In Proc. of Conference on Decision and Control (CDC), pages 3757–3764. IEEE, Dec 2014.

[42] Joseph Werther, Michael Zhivich, Tim Leek, and Nickolai Zeldovich. Experiences in cyber security education: The MIT Lincoln Laboratory capture-the-flag exercise. In Proc. of the Conference on Cyber Security Experimentation and Test (CSET), pages 12–12. USENIX Association, 2011.