RADICL CTF: Low-Cost Capture the Flag Platform for Industrial Control Systems Education

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***Abstract*—To address the nationwide workforce shortage of skilled and educated cyber-informed engineers, we must develop low-cost and highly effective resources for industrial control systems education and training. College curricula in technology management, cybersecurity, and computer science aim to build students' computational and adversarial thinking abilities but are often done only through theory and abstracted concepts [1]. To better a student's understanding of industrial control system applications, post-secondary institutions can use gamification to increase student interest through an interactive, user-friendly, hands-on experience. RADICL CTF can provide post-secondary institutions with new opportunities for low-cost, guided exercises for industrial control system (ICS) education to help students master adversarial thinking. Based on an extension to picoCTF, RADICL CTF is a platform for students to design, implement and evaluate exercises that test their understanding of core concepts in industrial control systems cybersecurity, answering the need for more interactive education methods. The main contributions of this paper are the improvement of the cyber-security curriculum through extending the picoCTF platform to promote the gamification of industrial control system concepts with consideration to the Purdue Reference Architecture.**

Keywords—Cybersecurity, Capture the Flag, Gamification, Cyber-Physical Systems, Industrial Control System, Education, RADICL, picoCTF

I. INTRODUCTION

Less than ten years ago, a well-defined computer science curriculum was largely absent from state-level standards for students in K-12 education, with most of their interaction happening in enrichment opportunities [2]. Our education system is adapting to a growing demand for cybersecurity professionals. Today's STEM education has more consideration for computer science, focusing on developing students' computational thinking [3]. Computational thinking encompasses problem-solving, and system design through logical steps and algorithms with consideration of human behavior [3]. In post-secondary institutions, computer science courses should now aim to mature students' computational thinking to consider the adversarial mindset [4]. Applying the adversarial mindset encourages the development of security concepts within the implementation of the computational process.

In August of 2022, the Pentagon tested the security of microgrids at DEFCON in Las Vegas before they were deployed to 134 bases across the United States. Their goal was to test the reliability and security of their design as a realistic evaluation of potential cyberattacks against our nation's public infrastructure. With over 1,700 in attendance at DEFCON, multiple vulnerabilities brought down the mock infrastructure. One of the attacks was a trivial integer overflow of the temperature sensor stopping the availability of wind, and solar power [5]. The inherent problems of putting engineering before security seen at DEFCON prove that we should introduce students of all disciplines to adversarial thinking. Adversarial thinking can strengthen our reliance on information and services - including industrial control systems.

There is a high demand to support the development of resources that improve adversarial thinking in education. Educational courses need hands-on activities to complement the analysis of theories and principles [4]. One of the ways educators are meeting the demand for hands-on activities is through gamification. Gamification implements learning concepts as game elements to increase social interaction, user-engagement and enhance positive learning patterns [6]. Gamification, which began as a method for understanding marketing and customer engagement, is being used across educational disciplines. A literature review of game-ifying learning concepts in 2014 proved the acceptance and use in the industry to produce positive results in retention [6].

A. Need for Game-based Cybersecurity Education

The cybersecurity curriculum is evolving with the constant state of risk, which causes a lack of technical training and materials [1]. Educational resources for teaching cybersecurity affect the next generation of cybersecurity professionals who will help research and develop countermeasures against attacks on ICS networks [7]. Current methods of teaching cybersecurity education focus on analyzing abstraction and principles about specific case studies to teach adversarial thinking [4]. The curriculum needs to improve adversarial thinking for students by applying these concepts to design, and implementation [4]. This paper presents RADICL CTF as a platform for students to design, implement, and evaluate small-scale physical systems to master adversarial thinking, build students' understanding of operations technology, and improve the national cybersecurity curriculum. We plan to expand gamification in computer science and cybersecurity specializations to further educational resources around industrial control systems, operations technology (OT), and critical infrastructure resilience. Education in these disciplines is still in its infant stages due to its complexity and lack of educational resources. With the importance of preparing the next cyber-resilient workforce, partnerships have been developing to provide post-secondary education students access to current trends, and modern problems in critical infrastructure security [8]. While these partnerships improve education, they are not widely available across educational institutions and target students with existing interests or experience. RADICL CTF aims to bridge the academic gap through the gamification of these specialized topics targeting a broader range of students with all experience levels.

B. *RADICL CTF Objectives*

The objectives of the RADICL CTF include the following:

1. Integrate a guided learning experience for interacting with CPS/ICS/IoT devices in mock operations networks;
2. Maintain a realistic network architecture modeled on the Purdue Reference Architecture; and
3. Increase the availability of resources by using educationally available or open-source software and inexpensive hardware.

II. BACKGROUND

A. *Reconfigurable Attack Defend Instructional Laboratory (RADICL)*

The Idaho Falls RADICL Lab aims to provide a resilient cyber range for students to practice using reconfigurable defense-in-depth networks to leverage multiple systems in a realistic learning environment. It has evolved since its adoption in 2004 to assist as an educational tool against the evolving cybersecurity curriculum [9] [10]. Funding from the state of Idaho and grants from NSF have helped develop an isolated and controlled network for students to engage in realistic attack and defense exercises. The lab also produces data sets for additional research and learning. Applying hands-on cyber-physical activities working with malware samples in real-time makes RADICL a unique environment to help fill knowledge gaps between enterprise and operations networks in current cybersecurity education.

1) The Goals of Hands-on Cybersecurity: For students to master adversarial thinking through hands-on activities and for the mission of RADICL to be effective, students must engage in the five freedoms of play. The US Naval Postgraduate School, in collaboration with the University of Washington, published an article titled *Security through Play*. This article showcases two tabletop exercises developed around learning concepts in cybersecurity. Their work is a successful example of the gamification of security concepts considering five elements essential to children's playground games [11]. Similarly, RADICL's hands-on exercises work to meet the following four freedoms.

- **Freedom to Experiment** - the freedom for students to experiment with defenses against adversaries.
- **Freedom to Fail** - the freedom to observe adversarial attacks.
- **Freedom to be an Adversary** - the freedom to assume the adversary's mindset and explore motivations.
- **Freedom for Reinforcement Learning** - the freedom to improve strategy and learn lessons about the game through playing the game.

These freedoms allow students to consider multiple perspectives to master the adversarial mindset. Students meet the above freedoms within this project by building challenges, observing packet captures, or completing challenges. Multiple platforms engage students to learn cybersecurity concepts through gamification with similar freedoms. Capture the flag (CTF) is a more serious gaming experience inspired by military training with realistic game mechanics. In cybersecurity, gamification and CTFs help introduce students to a breadth of specialization topics.

B. *Open Source CTF Platforms*

CTF platforms are one of the many competitive educational tools that can guide students to understand learning concepts through gamification. Using a CTF platform, we provide a learning experience for students to engage in multiple challenges that evaluate realistic vulnerabilities found in industry.

When evaluating CTF engines for the RADICL lab, we considered the underlying services, community support, and flexibility in challenge deployment. Our lab needs a full-stack CTF engine with a user-web interface, admin control interface, database, and documentation for challenge creation and deployment. The CTF engine should also interact with docker containers for ephemeral, controlled environmental connections. To aid in our decisions, research in 2020 analyzed twenty-five well-known cyber ranges, including the NATO Cyber Range, Virginia Tech, and Georgia Cyber Range. They then interviewed ten diverse ranges to inform the University of West Attica about the essential components to run and manage a secure range [12]. Educational cyber ranges provide a wide variety of gamification around web security, forensics, and malware analysis challenges. Their research revealed that most cyber ranges have open-stack solutions with remote or on-premise access options. Ansible is widely used to configure infrastructure, and the environment's gamification scoring often involves YAML or JSON-formatted documents.

Another consideration for the CTF platform is to educate students in multiple stages. Students can learn through a jeopardy-style CTF and then participate in a red-blue exercise with the physical platforms. The CTF engine should be able to manage a jeopardy-style competition, but the cyber range should utilize additional tools to evaluate the availability of ICS services. This method of ICS gamification has been seen in 2017. The SwaT Security Showdown (s3) competition was created as an international two-stage CTF to address the problems of education around ICS systems through a CTF platform [13]. Researchers in Singapore conducted the CTF in two phases around a water treatment testbed. In their red-blue exercise, they virtualized the PLC and considered the architecture similar to an ICS honeypot - a valuable solution to implementing diverse challenges within our cyber range. Using the research presented, the following are a few notable CTF platforms that we took into consideration when deciding on our CTF engine.

- **KCTF** - A versatile, Kubernetes-based CTF infrastructure created by Google [14]. With security in mind for hosting vulnerable applications, kCTF offers local and remote deployments through gcloud [14].
- **CTFd** - A CTF framework that uses python flask to host challenges in a Docker image [15]. CTFd offers easy management for administrators and simple use for its users; however, there are additional costs to hosting different style challenge questions.
- **picoCTF** - A full-stack jeopardy-style CTF with a supportive community. The available code for picoCTF is based on their 2019 competition and uses multiple systems to host different types of challenges [16].
- **Facebook CTF** - A full-stack jeopardy or king of the hill style CTF that uses Vagrant or Docker to host challenges. The platform uses an interactive world map where each country can represent separate challenges. The project was last active in 2018 [17].

With multiple frameworks for an open-source CTF engine available, our team decided on working with the picoCTF framework as it provides the most diversity in challenge provisioning with options for local and remote deployments. It is particularly adept at managing multiple Docker containers, and multiple simultaneous users can spawn simultaneous and different challenge types. By leveraging the existing code base for Docker challenge deployments, we can extend the platform to interact with a networked hardware environment, including mock industrial control systems.

C. picoCFF

Researchers at Carnegie Mellon University first published a paper about their 2013 picoCTF competition's success after recognizing the shortage of computer security experts [18]. Their initial competition introduced a game-based competition with over 2,000 high-school teams. They released their source code for the competition online, which quickly became adapted as a part of the curriculum in 40 high schools. The code base continued to be supported and saw significant improvements after the 2019 picoCTF competition. Within the last three years, dependencies within the infrastructure lost support, and interest in students maintaining the code base diminished; the code base became archived on GitHub at the end of 2022.

D. Purdue Enterprise Reference Architecture

The Purdue Reference Architecture has been long-established in modern ICS networks as six levels separating physical assets and services. Level zero is the lowest level of the model. It includes physical processes, sensors, and actuators, while level four and five are the highest and represent the information technology/enterprise side of the organization for ICS networks [19]. Fig 1 shows the official separation of the Purdue Enterprise Reference Architecture.

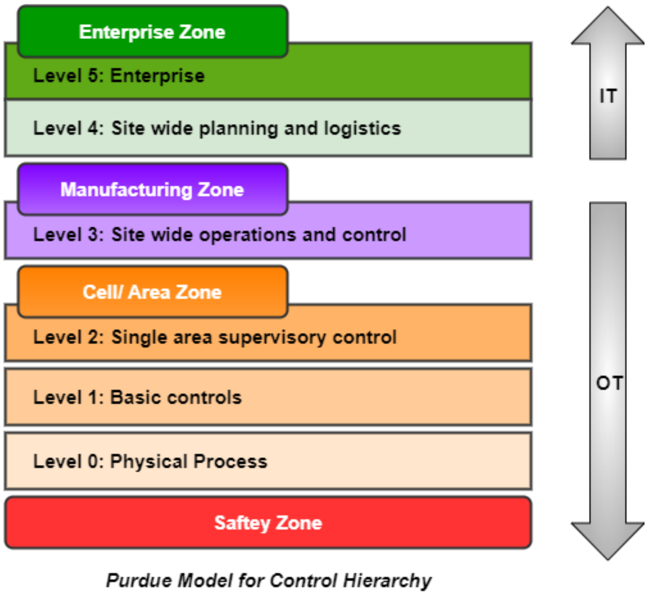

Enterprise Zone
Level 5: Enterprise
Level 4: Site wide planning and logistics
Manufacturing Zone
Level 3: Site wide operations and control
Cell/ Area Zone
Level 2: Single area supervisory control
Level 1: Basic controls
Level 0: Physical Process
Saftey Zone
IT
OT
Purdue Model for Control Hierarchy

Fig. 1. Purdue Enterprise Reference Architecture

Understanding the different levels of the Purdue Enterprise Architecture helps build a reference for deploying mitigations against adversary techniques. To cause physical damage using an actuator, an adversary must move through the levels of the Purdue Reference Architecture to conceal and carry out their attack. This reference architecture provides a blueprint for systems engineers to build a more defensible system, wherein the components of the system's various detective and preventive controls are segmented and controlled. At a most basic level, the architecture describes how to segment a network and critical business and operations functions based on logical and functional groupings.

III. RADICL CTF ARCHITECTURE

While RADICL CTF is unique in its goals and methodology, some existing successful CTFs and workshops interact with physical devices or virtualize the interaction. CTFs like Microcorruption teach adversarial thinking around virtualized systems. RADICL CTF is different from Microcorruption, Hack the Box, and other web-based red-team exercises as RADICL CTF creates and destroys virtual connections to physical systems allowing for a more comprehensive opportunity for visual gratification.

A. Cyber-physical Platform

Our cyber-physical platform design is a new and unique take on a mock ICS network. The platform contains 2 RaspberryPis, an arduino, a PLC, and a physical process. We plan for the physical process to represent a process used within critical infrastructure with the visible use of a relay, led, or actuator. The platforms will contain challenges representing each level of the Purdue Reference Model. Two din rails separate the infrastructure to communicate and check the status of the network and the OT network; the top din rail is for a gateway RaspberryPi with connects a platform to the cloud infrastructure. All student communication travels through a physical switch to the gateway pi. The gateway pi is also responsible for observing the environment and communicating to a status light controlled by a relay to inform the instructor. When the tower light is green, it indicates that the challenge is ready for a student to interact with the platform. A student successfully interacts with the platform when the tower light turns yellow. And when the tower light turns red, a student successfully interacts with the physical process. The bottom dim rail is for RaspberryPi containing the docker challenge for all levels of the Purdue Reference Model. Students will complete new challenges and interact with physical processes as they connect further with the environment. Fig. 2 shows an example platform with a coffee pot as the physical device.

B. Cloud Infrastructure

Our research aims to extend the picoCTF method for local deployment to include configuration and communication with a physical ICS network. We first configured oVirt as a virtualization solution on a Rocky 8 operating system to provide the cloud infrastructure. We then created two Ubuntu 20 virtual machines and used Ansible playbooks from the picoCTF GitHub repository. We had to modify the repository to work with Ubuntu 20 servers and many of the python dependencies in the Ansible playbook. When the Ansible playbook finished, we were able to use successfully use SSH for management and Nginx, python-flask, and MongoDB for web hosting and challenge deployment. The picoCTF community created the architecture in Fig. 3, which shows the communication between two deployed virtual machines. [16].

For containerized challenges to work on picoCTF, the shell manager command with support of the hacksport library and the flask web API with support of the service gunicorn must be operational. The following diagram is on the picoCTF's GitHub repository for On-Demand Challenges. Fig. 4 shows the relationship between the client, shell, web, and docker using shell manager and the API.

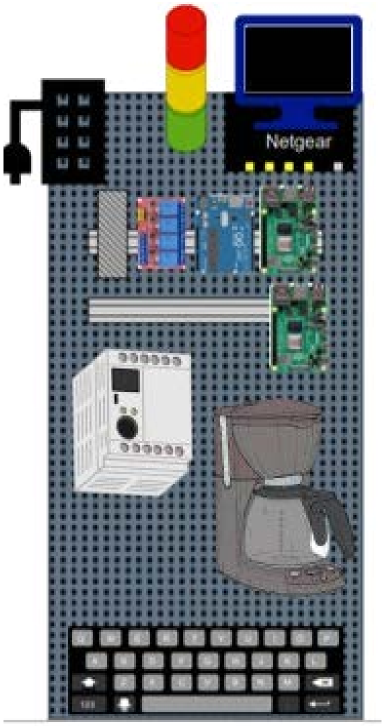
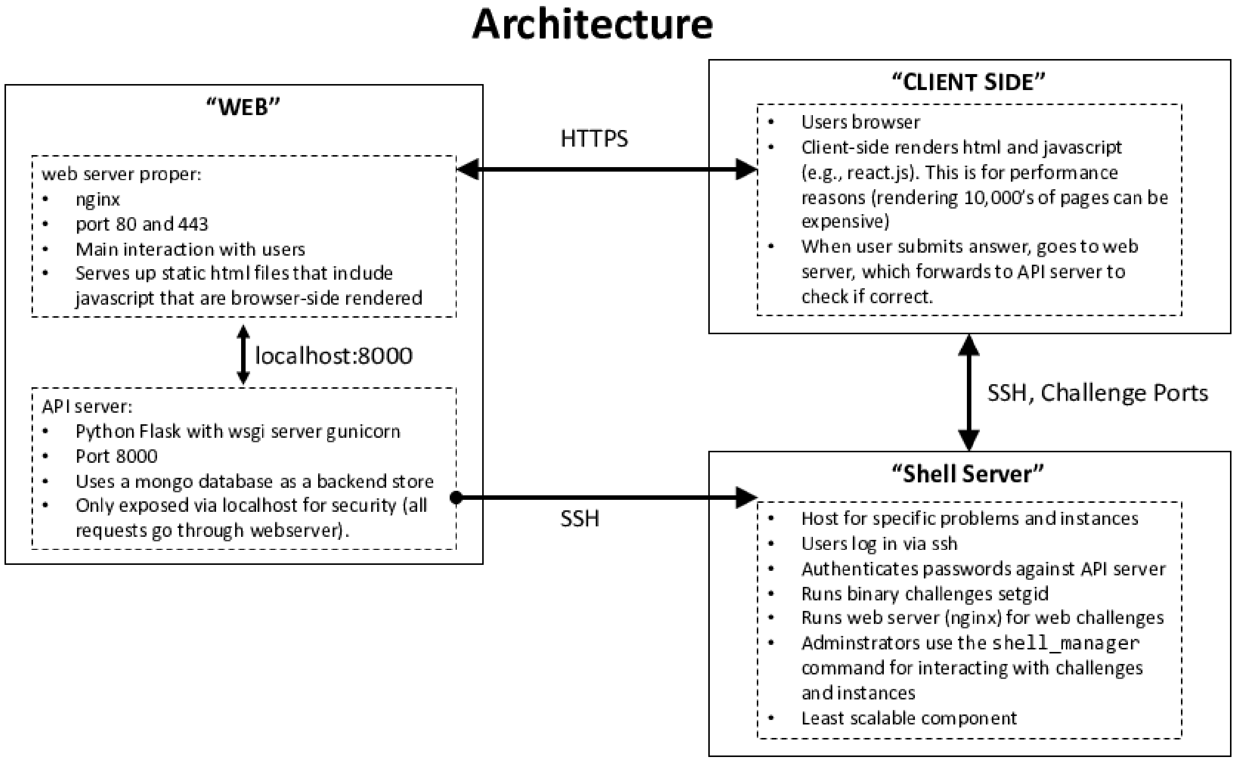


Fig. 2. ICS Target Learning Platform



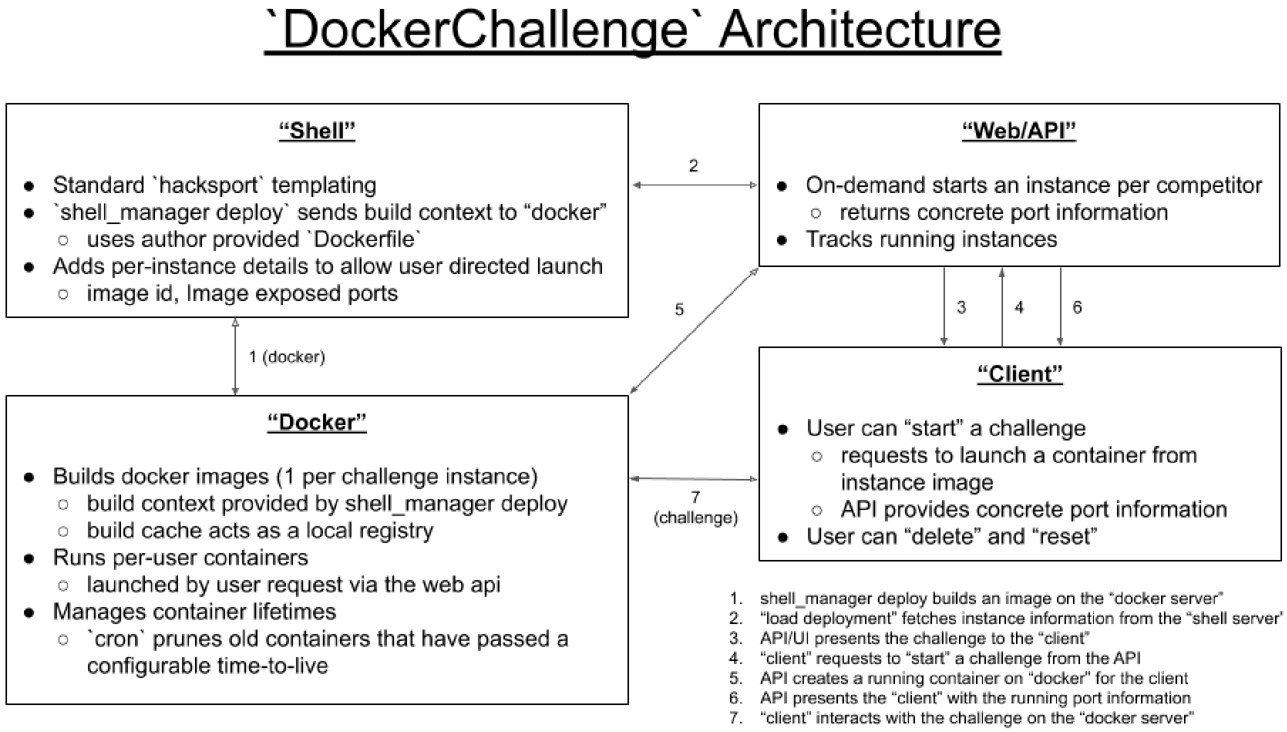
web server proper:
- nginx
- port 80 and 443
- Main interaction with users
- Serves up static html files that include javascript that are browser-side rendered

API server:
- Python Flask with wsgi server gunicorn
- Port 8000
- Uses a mongo database as a backend store
- Only exposed via localhost for security (all requests go through webserver).

- Users browser
- Client-side renders html and javascript (e.g., react.js). This is for performance reasons (rendering 10,000's of pages can be expensive)
- When user submits answer, goes to web server, which forwards to API server to check if correct.

- Host for specific problems and instances
- Users log in via ssh
- Authenticates passwords against API server
- Runs binary challenges setgid
- Runs web server (nginx) for web challenges
- Adminstrators use the `shell_manager` command for interacting with challenges and instances
- Least scalable component

Fig. 3. picoCTF Platform [16]



- Standard `hacksport` templating
- `shell_manager deploy` sends build context to "docker"
  - uses author provided `Dockerfile`
- Adds per-instance details to allow user directed launch
  - image id, Image exposed ports

- On-demand starts an instance per competitor
  - returns concrete port information
- Tracks running instances

- Builds docker images (1 per challenge instance)
  - build context provided by shell_manager deploy
  - build cache acts as a local registry
- Runs per-user containers
  - launched by user request via the web api
- Manages container lifetimes
  - `cron` prunes old containers that have passed a configurable time-to-live

- User can "start" a challenge
  - requests to launch a container from instance image
  - API provides concrete port information
- User can "delete" and "reset"

1. shell_manager deploy builds an image on the "docker server"
2. "load deployment" fetches instance information from the "shell server"
3. API/UI presents the challenge to the "client"
4. "client" requests to "start" a challenge from the API
5. API creates a running container on "docker" for the client
6. API presents the "client" with the running port information
7. "client" interacts with the challenge on the "docker server"

Fig. 4. picoCTF Platform [16]

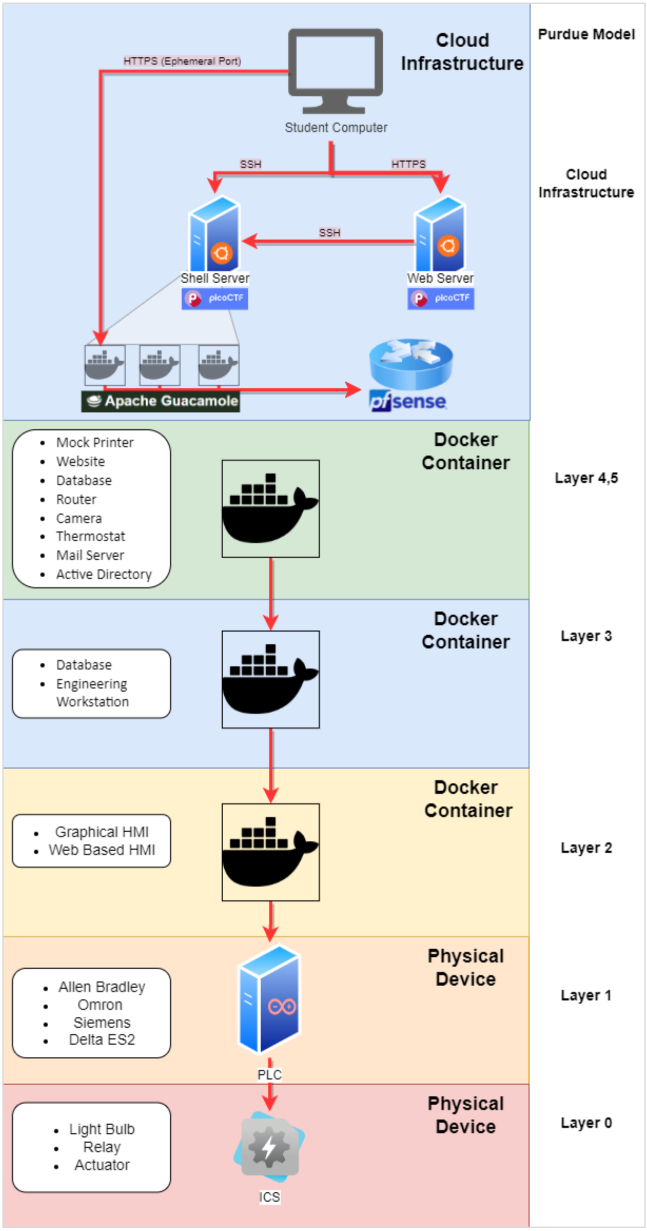


Fig. 5. RADICL CTF Architecture

As shown in Fig. 5, our extension of the picoCTF platform adds additional functionality to the API and on-demand docker challenges. When a student accesses the web interface, the student can start a challenge and instantiate a containerized jump box web accessible from an ephemeral port on the pico web server. The docker jump box uses Apache guacamole, allowing VNC and SSH over HTTP to complete containerized challenges and interact with a physical platform. After the student connects to the ephemeral port on a web browser, the student can access a desktop with all the necessary tools and isolated network connectivity to a learning platform. After reviewing the challenge description on the pico web server, the student will connect to different docker containers residing on the RaspberryPi on the second din rail until they can interact with the physical process.

Each level of the Purdue Reference Model will have virtual challenges that reside on separate docker-generated networks. The goal is for students to recognize the importance of network segmentation, recognize misconfigurations, and understand where devices and services should reside. When a student starts a challenge from the pico web server, A static configuration image creates new Docker containers for each level of the reference model. The following are example containers our team would like to see implemented for each level of the Purdue Reference Model.

C. *Enterprise Containers*

Enterprise Docker containers represent devices at levels four and five, such as enterprise or ICS services, that companies may typically expose to the Internet. These services may include web servers, VPN servers, IoT devices, cameras, and database management interfaces.

D. *Operations and Control Services*

Level three of the Purdue model contains engineering workstations, historians, manufacturing execution systems (MES), Manufacturing Operations Management (MOM) systems, and databases. These services would exist in a realistic environment to manage plant production and aggregate data to devices at level four. Students can access the physical system on level three using existing services from the enterprise container. After completing the challenge, the student can access a network containing level-two devices.

E. *Control Systems*

Level two of the Purdue model consists of supervisory control and data acquisition systems (SCADA), programmable logic controllers (PLCs), remote transmission units (RTUs), and human-machine interfaces (HMIs). These devices would exist on the plant floor to control and operate physical processes and systems seen at level one. In our target platforms, these devices represent a combination of real PLCs.

F. *Physical Processes*

Purdue levels one and zero are physical systems with sensors, actuators, and running processes. Students will be able to see the physical effects of these systems from their manipulation of control systems at level two. Future work for the facility is to include a separate network of IP-based cameras that will allow remote students to interact with the physical systems.

IV. CHALLENGE DESIGN

When considering the design of future challenges, we plan on considering the effectiveness in conveying learning concepts through challenge design; however, the 2014 USENIX conference published a paper on the learning obstacles in CTFs. Their findings showed some of the downfalls in education through gamification is the difficulty of playing [20]. For future challenges, we will consider the learning objective relative to the challenge's difficulty.

We created our first challenge to test our ideas as a proof of concept and to recognize further difficulties that may prevent progress. To exercise our architecture, We connected the pico shell and web servers on the oVirt cloud infrastructure to a cyber-physical platform. We added an on-demand challenge to the CTF engine for the student. The challenge asks for students to start brewing coffee for the DVCP company. ① The student starts the challenge by clicking a button to instantiate a docker jump box on the pico shell server connected to an ephemeral port. ② The student can then access the web desktop and connect to the cyber-physical platform. ③ To communicate to the platform associated with the challenge, a pfSense router facilitates the communication to the correct cyber-physical platform.

④ The pfSense router then communicates to the gateway pi, which forwards the connection to a Docker container. ⑤ The first challenge presents a website that would exist at level four or five of the Purdue Reference Architecture. The initial webpage is simple, with only a login interface. Exercising a known vulnerability, students solve the challenge by inputting default credentials. Once logged in, the student can access the website's interior pages. A tab in the sidebar reads "Ping the OT environment". The second challenge is for the student to perform a cross-site scripting attack. In the input field, the student can traverse the directories of the Docker container to discover an engineering account with a text document containing the engineering workstation's IP address. ⑥ The student can then access the engineering workstation using SSH and complete a simple forensics-based challenge. Once the student solves the forensics challenge, they can use RealVNC viewer on the jump box to connect to a python Tkinter HMI container at level two of the Purdue model. ⑦ After the student connects to the container running the HMI; they can interact with a Click PLC. By interacting with the PLC, the student can turn on the coffee pot and see the flag written on the platform display.

While our proof of concept does not have a challenge for level one of the Purdue model, we could further expand the challenge to include more Docker containers to create a realistic environment. Because of OS limitations, there are plans to expand the cyber-physical platforms to include challenges on Microsoft Windows to interact with PLCs dependent on the operating system, such as the Click PLC.

V. PROBLEMS DURING DEVELOPMENT

When developing RADICL CTF, we expect difficulties with multiple students trying to access a single platform, resetting the physical environment, and separating student communication from management. The following is a breakdown of our team's concerns and solutions to the problems faced during the deployment and evolution of RADICL CTF.

A. P1: Resetting the Physical Environment

One of the difficulties for students to practice on cyber-physical platforms is the ability to reset the mock OT network. The pico web server has buttons for students to start, stop and reset challenges that exist as an API that we can modify. Another method for operators and teachers to reset the environment is to implement an administration page that allows for the same reset functionality for any active platform. Additionally, after a student completes a training exercise on the physical network, destroying the student's jump box container should successfully trigger a reset of the cyber-physical platform. Our solution utilizes existing remote code execution available through picoCTF, Docker, and Ansible to orchestrate the commands and reduce the management overhead of RADICL CTF.

Likewise, we continue to explore robust and resilient methods of resetting physical processes and devices as the student sessions during challenges are abandoned or dropped after being partially completed.

B. P2: Separating Management and Student Communication

The physical network design involves devices at each level of the Purdue model. While the devices exist to promote a learning experience about industrial control system networks, the small-scale network does not allow the devices to be dual-homed; therefore, student network communication is not representative of a real-world ICS attack.

Separating the management and student communication is essential for students to review PCAP files from an exercise and observe an adversarial attack. The hardware on each cyber-physical platform is limited in the number of physical connections, and management interactions are critical to reset a platform from an unplanned state. To solve this problem, all communication from the students will travel as described in Fig. 6 and Fig. 7; however, communication between the management network, pfSense, and each platform is VLAN tagged on the same interface - effectively separating communication between students and operators on the platforms.

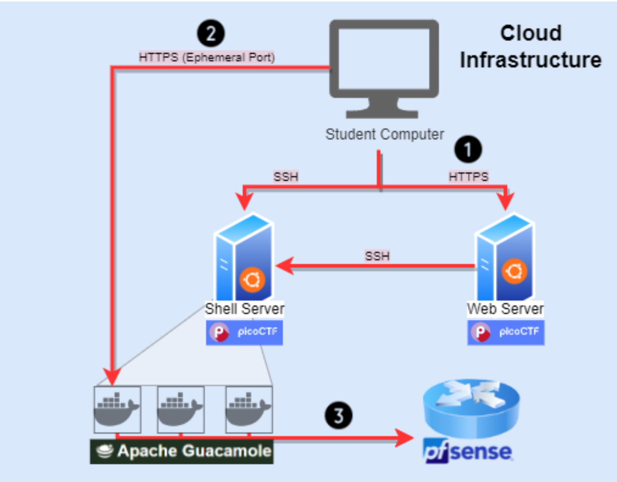


Fig. 6. Initial Steps to Interact with a Platform

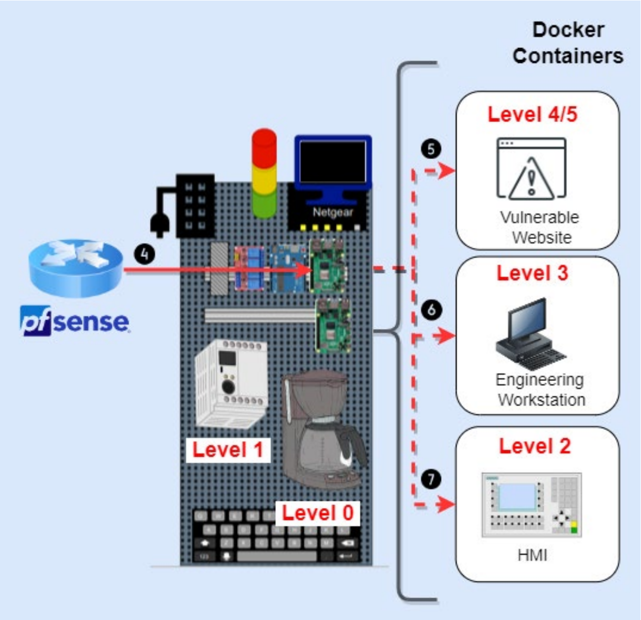


Fig. 7. Interacting with the Physical Process

C. P3: Multi-use Lockout

When a student creates a solution to pivot from an enterprise container to the physical network, RADICL CTF should be able to identify if a current student is already communicating with the physical device to prevent two students from working on the same exercise. If two students connect to the same device, the actions of one student could affect the solution of another and the overall learning experience. Therefore, we implement a load balancer that forwards communication from a Docker jump box to a cyber-physical platform. Load balancing is a system that distributes network or application traffic across a group of servers.

We initially believed that implementing an Nginx load balancer would be the best solution to forward student connections; however, with our current implementation, we can perform load balancing on the pfSense router. For these challenges, a new ipvlan docker network should be created on the pico shell server for communication to the router. Currently, all communication from the Docker container jump boxes is on the default docker bridge network; therefore, all communication from the jump box appears as the pico shell server. Future work should expand the segmentation of challenge availability by creating a new ipvlan network for each challenge, thus only allowing the desired communication.

VI. RESULTS

A. Cyber-physical Platforms

At the end of the project, we successfully created two cyber-physical platforms that integrate with RADICL CTF. Students can practice basic web exploitation and standard access methods to disrupt the Coffee Pot Company or Light Company. Fig. 8 and Fig. 9 show the assembled platforms in a functional state.

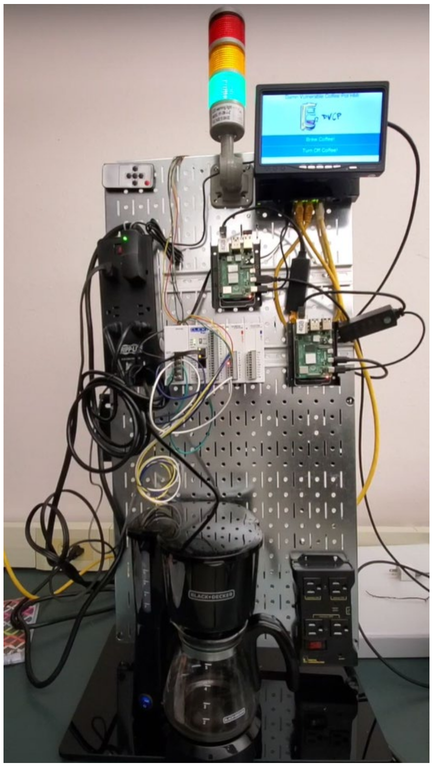


Fig. 8. The Coffee Pot Company

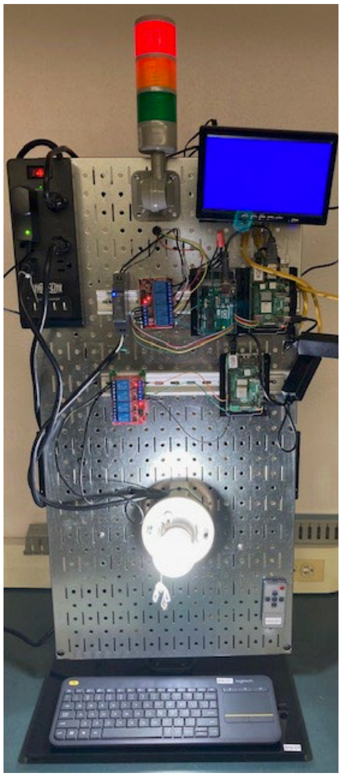


Fig. 9. The Complicated LightBulb Corporation

The coffee pot cyber-physical platform has the same elements described in Section 3A. In contrast, the light bulb cyber-physical platform makes use of an Arduino to communicate to the status light tower and relays to control 20 volts to the light bulb and the status light tower. We considered several design choices in developing cyber-physical platforms, which one can read more about in the research paper *Cyber-physical Shooting Gallery: Gamification to Address the IT-OT Gap in Cybersecurity Education.*

B. *Our Improvements to picoCTF*

While using the platform, our team updated 20+ dependencies defined in Ansible playbooks for services that relied on python2, python3, and cryptography. We also updated the support for the infrastructure to work on Ubuntu 20 systems. After utilizing the picoCTF framework for local competitions unrelated to this research, we extended the capabilities of picoCTF to allow multiple correct answers for a more user-friendly experience. Our work on improving the user experience and extending the functionality led us to remove features such as the picoCTF anti-cheating mechanism. Because of our contributions, RADICL CTF is a branch of the primary picoCTF code base and has been made available on GitHub.

https://github.com/taeganw/RadiclCTF

C. *Our Solution to Problems*

One of the critical functions of the user experience is the ability to reset the environment after an exercise for another student to use. To reset a cyber-physical platform, our team modified the web API to recognize a student's interaction with the pico web server. When a student creates or destroys a jump box, the pico web server first queries the Mongo database for the active challenge. It then communicates to the pico shell server over SSH. The pico shell server then executes an Ansible playbook that communicates to the RaspberryPi on the platform to restart the docker containers and the RaspberryPi on the top din rail to reset the tower light and platform status checks. Additionally, after a student completes a training exercise on the physical network, the CTF engine destroys the student's jump box container and resets the physical environment. While we successfully reset the environment without intervention between the student and the cyber-physical platform, future work should expand the administration interface to allow an administrator to start, stop, and reset any active platform.

We have yet to reach a point to work on problems two or three. Still, monitoring communication between a student and the platform is possible by capturing communication on the pfSense router and recognizing the automatic commands that start, stop, and reset the cyber-physical platforms. By mirroring the communication to a new interface on the pfSense router and using python, we can create pcap files for each interaction with the physical platforms; further work will need to plan for decrypting the communication by knowing the encryption key. Problem three is another modification to the pfSense router that would load balance communication to individual platforms.

VII. FUTURE WORK

Through the ongoing implementation of RADICL CTF and with the interaction and gathered feedback of local high school students and collegiate cyber-defense students, we expect to expand the number of challenges available and improve the game platform. Beyond addressing the problems anticipated and discussed in the previous section, we plan to work with local industry partners in designing and deploying a more comprehensive selection of realistic cyber-physical systems platforms that represent systems in each of the 16 DHS Critical Infrastructure Sectors. Current platforms include logical/physical access control measures representing Government Facilities and multiple Energy and Manufacturing sector systems.

Additionally, as we improve and expand the capabilities of the RADICL CTF platform, the code developed to support our interactions with cyber-physical systems platforms and enhancements to the picoCTF engine will be made available on GitHub.

VIII. CONCLUSION

To prepare the next generation of cybersecurity professionals for building and defending resilient critical infrastructure, students need to build adversarial thinking skills [4]. Adversarial thinking considers how computational thinking applies considering modern protocols and security principles and in the presence of an intelligent adversary. Students can better prepare for future careers in critical infrastructure by improving adversarial thinking through access to more hands-on exercises focused on industrial control systems. RADICL CTF is a hands-on guided learning experience that promotes all levels of challenges to students. RADICL CTF aims to promote critical and adversarial thinking through the gamification of operations networks to build an understanding of industrial control systems. Using the picoCTF 2019 framework, Docker, pfSense, and several cyber-physical system platform designs, students can traverse the Purdue Enterprise Architecture and complete challenges to take control of physical processes. To better understand adversarial thinking, students must apply abstract ideas to the design and implementation [4]. With the reconfigurable design of the cyber-physical system platform, students can implement defensible industrial control system networks with different software at all levels of an OT network. The platform switch also segments management and student traffic, allowing for realistic packet captures of an artificial attack on ICS to be further used within academia. The RADICL CTF platform, paired with the selection of small-scale cyber-physical systems, allows students to gain hands-on experience with operations technology networks and expands and improves the cybersecurity curriculum.

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