Abstract—Additive manufacturing cyber-physical system is vulnerable to both cyber and physical attacks. Statistical methods can estimate the probability of breaching security but hackathons have revealed that skilled humans can launch very innovative attacks not anticipated before. Here, we summarize lessons learned from the past two offerings of HACK3D hackathon.

I. INTRODUCTION

Digital manufacturing methods, such as additive manufacturing (AM), are fueling the next industrial revolution. It is estimated that over 600,000 desktop 3D printers were sold in 2019 and the cumulative annual growth rate of this sector is 25% over the past three years. AM is expected to revolutionize the $13 trillion large-scale manufacturing by bringing the manufacturer closer to the user, shortening the supply chain and enabling customization of products at low cost. AM has been adopted by medical [1], [2], automotive [3], aerospace [4], and consumer goods industries that require customized products in small production runs. The benefits of AM include the ability to manufacture parts with complex internal structures and geometries that cannot be made with traditional manufacturing methods.

AM security is gaining attention due to the involvement of trusted, partially trusted, and untrusted parties in the AM supply chain. This requires a taxonomy of analysis of threats and vulnerabilities and developing security methods specific to AM. For example, it is essential to assess the AM printers used to protect the intellectual property (IP) of the designers and to assure the quality of the raw materials.

AM attack vectors and impacts have been discussed from a cyber-physical perspective in [5]. For example, they demonstrate insertion of voids in the stereolithography (STL) files that go undetected by traditional finite element analysis (FEA) and mechanical testing. Similarly, a stealthy AM tool path modification attack can go undetected [6]. These attacks highlight the need for improved quality controls, cybersecurity education, and development of AM security assessment. A methodology for detecting attacks on an artifact’s intrinsic behavior is presented in [7]. This adapts structural health monitoring techniques by using antennas connected to piezoelectric transducers to obtain the impedance signature of parts. This approach is limited to attacks that alter this signature.

The AM process model has been studied and a new "federated" information systems architecture for AM has been developed in [8]. This architecture establishes specific requirements for end-to-end information sharing, quality control, and performance assurance. [9] investigate IP protection for outsourced AM, and study an alternative model that incorporates third party process tuning experts. The paper presents a risk assessment focused on IP protection and provides recommendation to minimize the risks of this model. Furthermore, [10] surveys the significance of AM for national security. The authors explain the benefits of AM for regenerative medicine, especially in battlefield injuries, and highlight threats from counterfeiting and IP theft.

Considering that critical applications in aerospace and medicine are enabled by AM parts, security methods need to be tested extensively to understand potential vulnerabilities. This study reports the outcomes of a crowd sourcing approach to understand the strengths and weaknesses of the security methods developed for AM.

Paper roadmap. The paper is organized as follows: in Section II we provide a brief overview of AM cyber-physical system (CPS) and a taxonomy of cyber threats. Section III presents HACK3D, a hackathon we organized to evaluate the strengths of certain security methods by crowdsourcing. Our concluding remarks are discussed in Section IV.

II. THE AM CYBER-PHYSICAL SYSTEM

A. The AM process chain

Figure 1 shows the AM process chain that includes computer-aided design (CAD), design refinement by simulation tools such as finite element analysis (FEA), manufacturing of the part on a 3D printer followed by testing and assembly. The product design process remains the same even in traditional manufacturing such as machining or milling. Due to innovation in automation, an increasing number of manufacturing methods are coming online. All steps involved in AM are dependent on computers and cloud for collaboration, machine control, and data acquisition and analysis. Hence, all these steps are targets for cyber attacks.

B. Taxonomy of cyber threats faced by AM

The attacks involved in the AM supply chain are classified in four categories as illustrated in Figure 2 [12]. Some of the attacks such as counterfeit production and reverse engineering require extensive computer and software support for 3D scanning, CAD modelling and other steps, but they do not involve...
interacting with the AM supply chain except for procuring the part. Other threats such as direct sabotage by hacking 3D printers require cybersecurity strategies such as network access monitoring and control, firewall, and communication channel encryption. As shown in Figure 3, the cybersecurity threats present in the AM supply chain can be classified across five orthogonal dimensions (what, when, how, why and effect) and can cover various threat categories listed in Figure 2. Many of the defects introduced in the AM may not be detected by the commonly used characterization methods. Several security methods are available that can be applied to AM supply chain but strength of these methods for AM supply chain needs to be analyzed. Table 1 presents analysis of some of the common threats as well as their level of impact on a typical AM supply chain. Not all attacks can cause the same degree of harm; for example, an attack during the CAD phase may have low success probability since measurements taken in several subsequent steps can show the deviations. However, an attack during the slicing step where only one operator is typically involved may go undetected depending on the testing method.

Threat analysis needs to be conducted for specific products to determine the appropriate security strategies.

III. HACK3D TO ASSESS STRENGTH OF AM SECURITY

A popular approach to assess the strength of security strategies is to conduct a red-team-blue team challenge involving participants from diverse backgrounds. Owing to the cyber-physical nature of the AM process, the diversity of backgrounds include materials science, mechanical engineering, industrial engineering, and computer science. This study designed challenges and invited red teams (especially students of diverse education levels and backgrounds) to participate in the HACK3D challenge. In the preliminary rounds of HACK3D the red-team participants worked locally using locally available resources. The final round was held onsite at NYU Center for Cybersecurity as part of the annual CSAW event in early November [13]. The onsite participants had a fixed amount of time to solve the HACK3D AM security challenges. While challenges 1 and 3 described below were used in the preliminary rounds, challenges 2 and 4 were given in the onsite final rounds. A large number of red teams participated in the preliminary rounds. However, we limit our study to the approaches taken by the finalists who competed onsite in solving the HACK3D challenges

A. HACK3D Challenge 1

Challenge. The participants received a set of XYZ coordinates in the 3D space describing the shape of a part (see Figure 4(a)). The red-team participants use this information to recreate a 3D

1 Interviews with participants helped form a full picture of the approaches.

2 For example, to steal designs from limited information.
Fig. 3. A taxonomy of security threats faced by AM.

model of the object. The XYZ coordinates can be visualized as a point cloud shown in Figure 4(b).

**Reported Attacks:** The attackers needed to recreate a 3D model based on the coordinates. One team used Microsoft Excel to convert the coordinates to a point cloud format and imported it into SolidWorks. They created a mesh using GeoMagic Add-in and obtained reference curves from the meshes. By combining the reference curves and the point cloud outline, the red team recreated the 3D model.

Another red team leveraged FeatureScript tool in OnShape [14]. FeatureScript allows users to generate 3D models using JavaScript or C. The team developed scripts to automatically extract information from the coordinates, draw poly-lines, and delete unnecessary faces layer by layer. They used this way to recreate 234 layers and assembled them to recreate the model of the final design. Finally, a HACK3D red team of mechanical engineers used the Scanto3D tool in SolidWorks to reconstruct the 3D model of the design. This shows that a commercial software can not only aid design, but also provide a fast track for attackers to launch attacks.

**B. HACK3D Challenge 2**

**Challenge.** The participants received the STL files of two designs (Figure 5(a)) and were required to identify correct slicing and printing orientations that would remove all surface and internal defects from the files. These two models were designed to have security features such that if they are not printed in a certain orientation, the prints will have either internal or surface defects.

**Attacks.** Most teams made efforts to slice the models in different orientations to check whether defects or nicks survive. Some participants created a table to enumerate all possible rotations. There are three axes (X, Y, Z) and each of them can rotate by 360 degrees, so in total it creates $360^3 \approx 4.7 \times 10^7$ possible combinations (considering 1 degree rotation step). Although the basic principles is to try all possible combinations using brute force, different teams came up with smart strategies to quickly narrow down the search space, so that they can approach the correct solution within the tight time constraint of 7 hours.

First, the challenge participants characterized design A as a complex, open prism with several holes. The main flaws were introduced due to the presence of segmentation in each layer (Figure 5(b)), which decreases structural integrity of the print. Therefore, the main goal is to find an orientation for design A such that each layer shows a continuous toolpath. Second, the surface area of the bottom layer is also taken into consideration when the challenge participants were seeking the correct orientation. The bottom layer needs larger area and mass, so that it can lead to a higher quality of printing as a larger bottom layer provides a much greater adhesion to the base plate. After a few trials of different orientations, some of the participants successfully found the correct orientation for printing. The correct orientation is shown in Figure 5(d).

Design B is a solid box with defined dimensions. However, inside the box, the rectangular prisms were embedded with spade shaped flaws, giving the surface several nicks (Figure 5(c)). It is anticipated that the undesirable nicks would decrease the overall integrity of the print. The participants discovered that the nicks remain if they do not turn the printing
### Table I

**Assessment of AM Risks.** High, medium, and low risk are represented as red, yellow, and green cells.

| Threat Scenario                                  | Vulnerability Description                                    | Impact | Likelihood | Estimated Risk |
|--------------------------------------------------|-------------------------------------------------------------|--------|------------|----------------|
| IP theft from design and specification files     | Weak access controls and improper authentication and authorization | Red    | Green      | Yellow         |
| Reverse engineering/reconstruction               | Lack of digital rights management                           | Green  | Green      | Green          |
| Ransomware attack                                | No backups, weak controls to critical content                | Yellow | Green      | Yellow         |
| Corruption of design files or material databases | No backups, weak controls to critical content                | Green  | Green      | Green          |
| Malicious modification of dimensions or shape of object | Inadequate tests, weak integrity controls, lack of proper validation | Red    | Green      | Yellow         |
| Malicious reduction in the structural integrity of the 3D artifact, introduction of defects | Insufficient structural integrity tests, file integrity controls, and post-production testing | Red    | Green      | Yellow         |
| Irreversible damage to hardware and mechanical elements of the 3D printer | Lack of hardware fail-safes, inadequate input validation | Green  | Green      | Green          |
| Installation of firmware Trojan on 3D printer    | Weak authentication, authorization and privilege management, insecure update process | Red    | Green      | Yellow         |
| Corruption of calibration of the 3D printer      | Insufficient file integrity controls, weak file access validation | Yellow | Green      | Yellow         |
| Memory safety violation on 3D printer firmware using malicious/out of spec file inputs | Inadequate input sanitizing, weak control flow integrity checks | Green  | Green      | Green          |
| Evading post-production structural integrity tests | Limited granularity in test methods, limited resolution of tests, inadequate sample size | Red    | Yellow     | Green          |

**Challenge.** The challenge red-teams mimic attackers who steal a partially damaged G-code file, which only models the bottom part of a chess piece, as opposed to a complete chess piece. Figure 6(a) shows the damaged G-code as viewed in a G-code viewer. The participants need to solve two problems: (1) identify the correct piece among three candidates pieces (Pawn, Bishop, and Queen) that the partial design represents and (2) complete the piece. The challenge organizers provided an orthographic image of all candidates in Figure 6(b) and a text file with the true z-heights of each piece. While it was possible, but difficult, to do measurements of curvatures and guess the most likely piece, the organizers embedded a non-trivial shortcut in the damaged G-code for solving the challenge like a puzzle. They placed the design file of the top half of the chess piece into a separate text file stored on the cloud, giving view-only access to those with a link. This link was embedded as a 3D QR code in the design of the chess base given to the participants [15]. Unsurprisingly, some participants approached the challenge without referencing to orientation, regardless of the choice of the bottom layer. By fine tuning the rotation angle, they eventually found the correct orientations for printing Design B without internal defects. The current orientation is shown in Figure 5(e). Although it seemed possible to create an algorithm that can rotate the parts automatically on all axes and find the orientation that would not have any holes in it, the presence of some of the design features in the geometry made the task more complicated. Also, the possibility that the best orientation can be obtained at rotation by a fraction of a degree, the actual cases that an algorithm would run is several orders of magnitude larger than $10^7$. This particular case highlighted the benefit of conducting the hackathon for testing the strength of the security features because participants could rotate the designs on a few axes and visually eliminate a large number of possibilities very quickly and focused on only a few plausible solutions.

C. **HACK3D Challenge 3**

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Fig. 5. The participants received STL files of two designs (A and B in (a)) to find the correct orientation to slice and print that would remove surface or internal defects. If printing without rotation, design A will be separated in multiple segments like (b) and design B will have internal slots as shown in (c). The correct orientations and supporting materials are shown in (d) and (e) for design A and B, respectively, to obtain high quality parts without defects.

Fig. 6. HACK3D Challenge 3: Given (a) partial (maybe damaged) G-code file, the attacker has to reconstruct the original G-code file that is cut off from a chess piece from among the (b) three candidates.

Fig. 7. If one views the 3D QR code embedded in the chess base for HACK3D Challenge 3 from a random direction, it looks like a group of spheres like (a). However, viewed from the correct angle, it is a scannable QR code shown in (b).

Fig. 7. If one views the 3D QR code embedded in the chess base for HACK3D Challenge 3 from a random direction, it looks like a group of spheres like (a). However, viewed from the correct angle, it is a scannable QR code shown in (b).

One of the teams exploited the discrepancy in the metadata in the G-code file. They noticed that the filament length in the original piece (4290.7 mm) was different from that shown by the G-code viewer (3198.14 mm). This gave them insight into the cut off design and they concluded that all pieces had a square cross-section. Next, using the provided z-heights and the extracted height of the base piece from the G-code, they determined where the chess piece was cut off. They cropped the tops off of each chess piece and used computer vision algorithms to measure the pixel dimensions. They scaled the dimensions using information from the G-code. They reconstructed the G-code for the top of all three pieces. Since they knew the height difference between the original and the damaged piece, they were able to deduce the Queen as the target piece, as it matched closest in height. The final result had an error of 1%.

A second red team processed the image and created a profile of the edges of the different chess pieces. This produced a 1% error in the geometry as the image processing led to a pixelated line. Based on this chess piece edge information, one of the teams created the shell of the Queen with the help of a few reference points in the G-code and filled the top and bottom layers with infill. The third team similarly processed the image. However, they took a different approach and produced a square prism at each point on the profile curve to recreate the pieces. They inferred that the chess piece was the Queen based on the filament length information in the damaged G-code.

Two of the teams were successful in recognizing the presence of a QR code embedded in the chess base. This embedded QR code was segmented into small pieces and appeared like a bundle of spheres as shown in Figure 7(a). Only when viewed from a certain direction, the QR code could be seen as Figure 7(b). One of the teams extracted this QR code from the G-code. They then extracted the design file of the original chess piece stored on the cloud server.

D. HACK3D Challenge 4

Challenge. This challenge targeted reverse engineering phase in the AM supply chain along with file forensics. The red team participants were given a physical print and a scaled-down version of the STL file of a female connector (yellow parts in Figure 8). The challenge entailed construction of a male connector with appropriate design and dimensions compatible with the female connector. Similar to Challenge 3, the design
of the female connector had a 3D data matrix embedded within its body. This data matrix, when viewed from the correct orientation, had the password of an online server, while the IP address and username were stored within the header of the STL file. The challenge aimed to have the red team participants wrangle with the structure of a typical STL file and understand the challenge of viewing 2D codes converted to 3D. Once both pieces of data were obtained, the participants would find the design file of the male connector on the server.

**Attacks.** Under a tight time constraint of 6 hours, one red team was able to extract the data matrix and get the password. They studied the header of the STL file and accessed the correct design file stored in the server. The male part was designed with a snap fit and arms to prevent rotation (the left one in Figure 8). Another red team took a geometric approach and recreated a tight slide fit male part of the female part along with the scale factor. While they were able to get the data matrix, they could not recover the hidden message in the STL file. Hence they were did not access the file stored on the server. Their final design is the right most one in Figure 8.

Finally, one team manipulated the STL file and isolated a single cross-section of triangles to create a profile of the female part. After fine-tuning the profile, they created multiple iterations of a snug fit to slide on the male connector (the middle one in Figure 8).

### E. Lessons Learned

The threat taxonomy in Figure 3 serves as a guide while designing the HACK3D challenges. The challenge problems are mapped to this taxonomy in Table II. Moreover, the attacking approaches taken by the challenge participants are summarized in Table III. The attackers may have explored other attack vectors as well but the challenges only measured their success in achieving the goals set by the problem. By analyzing and summarizing the performance of the participating teams, the following lessons were learned:

1) **More information can be extracted from leaked files than what is anticipated.** For example, in HACK3D Challenge 3, one team looked into the metadata of the corrupted G-code and extracted valuable information (shown in Figure 9). For example, the first line in Figure 9 shows that the total filament length that will be used for printing the whole chess design is 4290.7 mm. Participants also used the image provided for visualization.

2) **Common sense and CAD experiences can be used in for digital measurements.** This demonstrates that more information can be extracted if the files are obtained by the adversaries. The metadata of files combined with other information such as geometric structure of the design, the measurement on actual physical prints, and pictures of target designs can reveal more information than anticipated and enables reverse engineering.

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3 using brute force.
**TABLE II**

| Challenge   | XYZ Coordinates | STL file | Partial G-code & An image | STL file & A physical print of a female part |
|-------------|-----------------|----------|---------------------------|---------------------------------------------|
| Information Exploited | Metadata of G-code & Geometric Information | Physical Measurement & Geometric Information | Metadata of Files, Geometric Information | Metadata of Files, Measurement on Designs |

**TABLE III**

| Information Exploited            | Skills                  | Tools                                      | # of Teams |
|-----------------------------------|-------------------------|--------------------------------------------|------------|
| Geometric Information             | Reverse Engineering     | CAD Software & Self-developed Scripts      | 2          |
| Metadata of G-code & Geometric Information | Image Processing   | Self-developed Scripts                     | 1          |
| Metadata of G-code & Geometric Information | Image Processing | CAD Software & Self-developed Scripts | 2          |
| Hidden Code Embedded              | File Manipulation       | Self-developed Scripts                     | 2          |
| Physical Measurement & Hidden Code Embedded | File Manipulation | Self-developed Scripts | 2          |
| Hidden Code Embedded & Header of STL | File Manipulation     | Self-developed Scripts                     | 1          |
| Physical Measurement & Geometric Information | CAD                 | Commercial CAD Software                    | 2          |

**IV. CONCLUSIONS**

Securing the additive manufacturing cyber-physical system is a challenging task. A number of methods have been developed for embedding security features in the CAD designs,

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**reverse engineering attacks.** In HACK3D challenge 1, after one connects multiple adjacent coordinates to create polygons, a doughnut-like shape, as shown in Figure 10, can be observed. It is most likely that the shape is two concentric circles in the CAD model. Although in the digital file, there is no information to guarantee that this shape is a circle, common sense and experiences in designing CAD models can help the attackers realize the functionality of the design and fine tune its shape.

Another example that shows common sense and past 3D printing experiences is useful for attacking, happened in HACK3D Challenge 2. Theoretically, there are around 50 million possible angle combinations, but an attacker with rich printing experiences can quickly rule out many combinations. For example, to print a high-quality product, one would prefer to select the surface with a larger area and mass towards the bottom of the printing toolpath. This principle guides the attackers to choose the bottom surface and prioritize rotations around the relevant axes.

3) **Attackers need not necessarily be experts in AM to launch a successful attack.** In HACK3D Challenge 1, one team had no programming experience. So they could not develop scripts to automate the generation of the corresponding 3D model. However, they tried many commercial CAD tools and found one add-on tool that could provide an exact solution to the challenge. This shows that the technical barrier to become an attacker is indeed very low, and almost anyone can be an attacker in an AM supply chain with little training. The capabilities of CAD and other AM related tools will progressively become better and can support complex designs and tasks. This increasing sophistication will add to the attackers tool box enabling, for example, reverse engineering.

4) **Multi-disciplinary knowledge and skills are useful both from an attacker and a defenders perspective.** Although one does not require a deep understanding of cyber security to launch an attack on AM systems and supply chains, more sophisticated and novel attacks can be developed if one can combine knowledge and expertise from different disciplines like computer science, electrical engineering, mechanical engineering, and material science. This is also why HACK3D challenges strongly encourage participants who had different technical backgrounds to join forces with each other and form cross-disciplinary teams. The skills employed by the teams in the attacks are listed in Table III. Image processing and file manipulation are skills that computer science experts always have, while 3D model reverse engineering and CAD skills are a part of the training for mechanical engineers. We are certain that the listed attack methods are a partial list, and novel attack methods will emerge as the security countermeasures become more and more sophisticated. This also implies that to develop secure defense mechanisms in AM supply chains, AM security researchers need multi-disciplinary knowledge.

5) **Attacks can originate in any stage in the AM supply chain.** The HACK3D challenges show that attackers can launch attacks from almost any stage in the AM supply chain, including STL files, G-code files, and physical prints. AM security researchers should design and deploy security measures to protect the whole AM supply chain. A weakness in any stage can compromise the design resulting in real-world consequences and monetary loss.

6) **The taxonomy outlines numerous defenses and even more number of attack pathways.** Since we had only two iterations of HACK3D, we explored a small set of pathways through the taxonomy and several other pathways remain to be explored.
QR codes for identification of genuine products and cybersecurity of design and manufacturing files. We are conducting an annual crowdsourcing approach to assess the strength of some of the security methods yielding novel attacks. While it is only in its formative years, HACK3D showed that red-teams with a range of skills—with minimal knowledge in AM and Cyber security to expert interdisciplinary knowledge—developed innovative attacks in defeating the embedded security. The defenses and the attacks can be used to benchmark both future defenses and attacks for the AM community. The approaches documented by HACK3D will provide an insight into developing next generation security methods and applying them to manufacturing processes. Consistently, we noticed that the participants were able to obtain more information from the files than was anticipated and this informed effective attacks. Despite a stringent timeline for solving the challenges, several red teams made significant advancements and many of them solved the challenges. It is clear that multi-disciplinary training is important for the emerging AM workforce to develop security methods for AM CPS. Otherwise they may not anticipate many of the impending attack vectors.

From our 20/20 hindsight of organizing CSAW CTF and CSAW embedded security challenges [16], we are optimistic that the HACK3D attacks and defenses will become the basis for an open, community-accessible benchmark resource that the AM community can use, add onto, and improve AM cybersecurity.

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