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Enhancing Cybersecurity against Stuxnet in the Future of Cyberwarfare: A Combined Approach Using Firewalls and Intrusion Detection Systems

Zina Balani & Mohammed Nasseh Mohammed

Abstract

Stuxnet is a highly customized malware developed to destroy centrifuges used in the Iranian nuclear program through SCADA systems. It infects a computer through a USB drive, making it effective for targeting air-gapped networks. Stuxnet is larger and more complex than an equivalent worm; it is created in several different programming languages, and some components are encrypted. The malware utilizes four unprecedented zero-day vulnerability attacks that exploit application security vulnerabilities before developers become aware of the vulnerability. Additionally, it employs advanced rootkit technology to conceal itself from users and antimalware software on both Windows and the control computer it targets. To strengthen cybersecurity, this study implemented and configured a combination of firewalls and intrusion detection systems (IDS) to enhance security against the Stuxnet malware. By integrating these security measures, the aim was to establish a robust defense against the sophisticated attack methods employed by Stuxnet. It is essential to continuously update and adapt these security measures as the threat landscape evolves. By remaining vigilant and proactive, organizations can effectively safeguard their systems from sophisticated threats like Stuxnet, bolstering their cybersecurity defenses.

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About Author (s)

Zina Balani (Corresponding author), Department of Software Engineering, Lebanese French University, Erbil, Iraq.

Mohammed Nasseh Mohammed, Department of Software and Informatics, college of Engineering, Salahaddin University, Erbil, Iraq.

1. Introduction

Stuxnet is a sophisticated piece of malware, believed to be 20 times more advanced than any previous virus code, including its namesake 'Stuxnet.' This malicious software targets USB drives and other computers connected to the internet, and it has impacted hundreds of computers, particularly those associated with Iran's mechanical systems. Stuxnet has various functions, some of which involve increasing pressure inside the reactor, closing the oil pipeline, and providing misleading information to the controllers to make them believe that everything is operating normally. The primary target of the virus is the centrifuge used in Iran's nuclear program to enrich uranium. Without reaching its specific goal, the virus remains dormant or inactive. As a response to the Stuxnet attack, Iran has taken measures to strengthen its cybersecurity and has been known for its efforts in building a formidable digital defense. This includes creating one of the world's largest digital armies to protect against future cyber threats (Sahu et al., 2016).

Stuxnet represents the beginning instance of a cyber-attack aimed at causing physical damage, challenging the conventional understanding of the cyber-attack scope. This sophisticated malicious software, often referred to as a computer worm, effectively targeted and compromised sensitive military cyber missiles, particularly those in Iran's "Olympic Games" code. It successfully destroyed over a thousand centrifuges at the Natanz uranium enrichment facility in 2010. The incident marked a significant milestone as it became the first documented case of a computer system attack causing physical destruction beyond international borders. Stuxnet's impact goes beyond mere destruction, as it brought to light a new type of warfare capable of posing threats to even the most potent military forces. A cyber-revolution paper suggests that the Internet provides militarily weaker actors with asymmetrical advantages, making defense challenging and attackers able to exploit anonymity to their advantage. However, empirical evidence from Stuxnet's case contradicts this perspective, as it demonstrated how a well-executed cyber-attack could achieve its objectives despite facing significant challenges and maintaining anonymity (Chen, 2010).

Unlike its predecessors, Stuxnet is unique in its specific objective of directly targeting and controlling real-world machines. While previous worms, such as Slammer, caused material consequences like interfering with ATMs and airline reservation systems, these effects were unintentional and arose from network congestion resulting from the worms' rapid spread through computer systems. In contrast, Stuxnet diverges from these earlier cases by intentionally seeking to gain control over physical infrastructure (Baezner & Robin, 2017). Stuxnet initially exploited security vulnerabilities in embedded systems processing PLCs. However, modern cyber threats have expanded to encompass various systems integrated into vehicles, handheld computers, mobile devices, and electric computers. Public threat assessments, which outline risks faced by countries, have evolved. Before 2008, these assessments did not include cyber-related terms, but within two years, they incorporated cyber-related language, reflecting the growing importance of cyber threats in the contemporary landscape. As technology advances, cyber threats have risen to the top of the threat list, becoming a major concern for authorities (Sahu et al., 2016).

Among the three types of cyber-attacks or threats highlighted by Sahu et al. (2016) and that concern countries, the following are significant:
1. Intellectual Property Theft - Such actions have the potential to negatively impact the economic state of a country, similar to the recent incident involving JP Morgan.
2. Attacks like the one from USNSA (United States National Security Agency) can cause significant disruption to our daily lives through mass surveillance.

3. Security breaches of this nature may lead to the degradation or even destruction of a nation's military capabilities.

In this study, a comprehensive approach has been adopted to enhance cybersecurity measures against the notorious Stuxnet malware. Both firewalls and intrusion detection systems (IDS) have been implemented to protect the network's defense mechanisms. By incorporating firewalls, the study aims to establish a formidable first line of defense, preventing unauthorized access and well-filtering incoming and outgoing traffic. The intrusion detection systems, on the other hand, play an essential role in actively monitoring the network's traffic, tirelessly examining any indications of suspicious activities or potential Stuxnet threats. The combination of these two robust security measures creates a powerful communion, significantly bolstering the network's resistance to Stuxnet and other cyber threats. the study emphasizes the importance of updating and patching the system regularly. By staying observant and proactive in implementing timely security updates, the network maintains a continuous and ever-observant watchfulness, effectively mitigating the risks posed by the persistent Stuxnet malware. This proactive stance ensures that the system remains secure with the latest defenses and security protocols, keeping potential vulnerabilities at bay and instilling confidence in the system's ability to put off and prevent Stuxnet from penetrating critical infrastructure.

2.1 Literature Review

The detection and impact of Stuxnet raised global awareness about cybersecurity issues significantly. This malware incident served as a wake-up call for countries, making them realize that their critical infrastructure is vulnerable to cyber-attacks, and the potential consequences of such attacks can be devastating (Baezner, 2019). In December 2009, a cyber-operation named Arora successfully infiltrated Google's corporate networks, aiming to steal sensitive information. The operation involved the collaboration of Chinese hackers and targeted various aspects, including email accounts and potentially even computer source code. Arora managed to exploit a zero-day vulnerability in Microsoft Internet Explorer to carry out the attack (Tian et al., 2019). In late 2010, the Stuxnet malware was discovered in an Iranian computer system. Before this detection, Iran had completely halted its uranium enrichment activities at the Natanz nuclear power plant. However, both the manager of Iran's nuclear organization and the acting foreign minister admitted that the Stuxnet computer malware had infected the nuclear power plant. It was suspected that the United States, with support from Israel, orchestrated the creation of Stuxnet to hinder or delay Iran's nuclear program. Stuxnet was designed to propagate through infected USB drives, enabling it to infiltrate the network at the Natanz power plant. These technology worms usually infiltrate networks that are isolated from other networks (Baezner, 2019). In 2012, there were concerns that Israel or the United States might resort to air strikes to deal with the escalating issue. However, the remarkable technical capabilities demonstrated by Stuxnet highlighted that cyber weapons are not just theoretical concepts but have physical real-world implications (Chen, 2010). Researchers conducted analyses on the classification, composition, and impact of Stuxnet-like (SL) attacks within the CPS (Cyber-Physical Systems) control loop. As a result, a proactive defense strategy called Moving Target Defense (MTD) was developed. The MTD approach involves dynamically changing the system configuration to detect and counter SL attacks effectively. The reason for adopting such an approach is that these types of attacks typically rely on knowing the target system's configuration (Yang et al., 2015). By constantly altering the system's setup, potential attackers find it more challenging to exploit specific vulnerabilities, enhancing the overall security of the system.

Providing security assurance to a cyber-physical system is a challenge since cyberspace is subject to zero-day attacks. It needs a method to safeguard critical infrastructure from damage with possible long-term effects. TSM is created for improving the assurance of preventing cyber-induced physical damage even when operating systems and devices are compromised (Clark et al., 2013). Advanced novel pre-defense system framework, in which bidding from the system operator to the PLC is verified using a random sequence of encryption keys. The framework uses cryptographic analysis and control game theoretical techniques to measure the impact of malicious bidding on the performance of physical facilities (Clark et al., 2013). comprehensive graphical representations of Stuxnet attacks modeled their mechanisms and quantified outcomes for all potential attack sequences. These representations showcase BDMP's ability to model attack stages and global progress, serving as a measurement tool for attack probabilities and sequences contributing to overall success. Additionally, the model enables attackers to penetrate the system, exploit access points, and gain control over the representative system (Kriaa et al., 2012). Randomizing internal system structures as safety measures is an evolving field in cybersecurity. For instance, modern operating systems employ address space randomization to prevent code injection attacks. However, these defenses are yet to be utilized in cyber-physical systems to safeguard control systems in critical infrastructure (Clark et al., 2013).

2.2 Stuxnet Malware

In the present scenario, there is digital competition among attackers and potentially aggressive groups, including terrorists and nations. Instead of traditional methods like firearms and explosives, they employ digital codes to launch attacks on other states. By utilizing a single computer, they can target vital infrastructures such as SCADA and PLC systems, which are responsible for overseeing and organizing various industries (Sahu et al., 2016). Stuxnet is the first malicious threat directed at the industrial control system like gas pipelines, power plants, etc. There are four functions for Stuxnet malware (Sahu et al., 2016):

1. Control: Stuxnet was designed to take control of programmable logic controllers (PLCs) used in industrial systems. By gaining control of these PLCs, the attackers could manipulate the operations of the targeted industrial facilities (Sahu et al., 2016).
2. Theft of VeriSign Driver Certificate: Stuxnet stole a legitimate digital certificate issued by VeriSign, a renowned certificate authority. By using this stolen certificate, Stuxnet could bypass security measures and appear as a trusted application, making it more challenging to detect and block (Kim et al., 2017).
3. Multiple Propagation Methods: Stuxnet employed various methods to propagate itself within a system or across networks. This allowed it to spread and infect multiple devices and systems, increasing its reach and impact (Sahu et al., 2016).
4. Rootkit: A rootkit is a type of malicious software that provides unauthorized access to a computer or network. Stuxnet utilized a rootkit to conceal its presence and activities on infected systems, making it difficult for security software to detect and remove the malware.

Stuxnet contains four primary files: payload.dll, encoded by selecting other files such as. LNK files, ~ WTR4141.tmp, ~ WTR4132.tmp, .dll, .exe, .dat, .sys, .tmp. These files are all wrapped as .dll files, also called UPX compressed .dll files (Faisal & Ibrahim, 2012). The main purpose of Stuxnet is to disrupt the system by upgrading the programmable logic controller (PLC), therefor attackers manage PLCs easily. Stuxnet was also created to transfer data from Iran’s industrial facilities to external network nodes for production lines (Goyal et al., 2012).

2.3 Stuxnet's Propagation Techniques and Their Impact on Industrial Control Systems

Stuxnet stands out from typical malicious software in industrial settings due to its extensive array of features. These features include exploiting multiple zero-day vulnerabilities, modifying system libraries, targeting Siemens SCADA control software (Step7 installations), running an RPC server, and installing signed drivers on Windows operating systems (Falliere et al., 2011).

To infect the target PLC, Stuxnet utilizes various propagation vectors. It can update itself automatically, replacing the older version with a newer one on the local network. Additionally, it communicates with a command-and-control server, allowing it to transmit information back to its creator and receive further updates. Stuxnet conceals its presence and destructive impact, perplexing installation personnel who may not fully understand the root cause of the unexplained issues, the following methods are provided for transmitting Stuxnet to the machine (Mueller & Yadegari, 2012):

- With USB flash drives, Stuxnet's ultimate goal is to control the centrifuge. This is called a programmable logic controller (PLC) and is a dedicated computer used to control the system like electronic devices or industrial systems. A computer-based PLC that manages and controls the computer, usually not connected to the Internet. So Stuxnet needs another vector to access these computers, so they can be spread via USB flash drives. In the case of Natanz, an external contractor operating in the field allows the infected flash drive to be inserted into the control computer. Different versions of Stuxnet do this in different ways. The latest version uses the Windows LNK vulnerability and the previous version uses the autorun.inf file vulnerability. As shown in Figure 1. Stuxnet uses several methods to propagate itself.

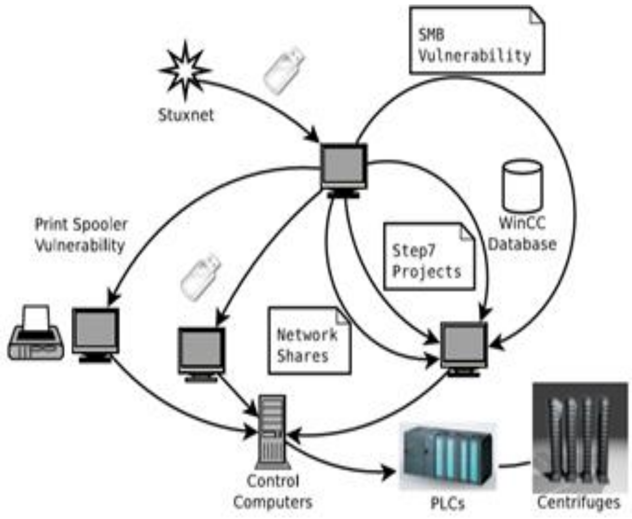

Figure 1. Stuxnet uses many methods to achieve target PLCs.

Through WinCC, Stuxnet searches for computers running Siemens WinCC, an interface for its SCADA systems. It connects using a password coded in WinCC (Baezner & Robin, 2017).

- Through network shares, Stuxnet can use Windows-shared folders to spread itself across a local network. Puts a dropper file on shares on remote computers and important scheduling for implementation.
- Through the 0-day vulnerability of the MS10-061 print queue, Stuxnet copies itself, places the copy on remote computers through this vulnerability, and then runs the copy, thus infecting the remote system (Matrosov et al., 2010).
- Through the MS08-067 SMB vulnerability If a remote computer has this vulnerability, Stuxnet may send an incorrectly formatted route through SMB. This allows you to run arbitrary code on the remote system (Gold, 2012).

- Through the Step 7 project, Stuxnet infects the Siemens SIMATIC Step 7 industrial control project that is open on the infected system (Falliere et al., 2011).

3.1 Zero-day Attack

A zero-day attack refers to software created by an attacker before developers of malware protection software are aware of the actual vulnerability (Goyal et al., 2012). Stuxnet can exploit one or more zero-day vulnerabilities to spread to other computers within the local area network (LAN), as depicted in Figure 2. It employs a specialized method for uploading a .dll file, relying on host intrusion protection technologies that employ behavior blocking and monitor library installation calls (Goyal et al., 2012).

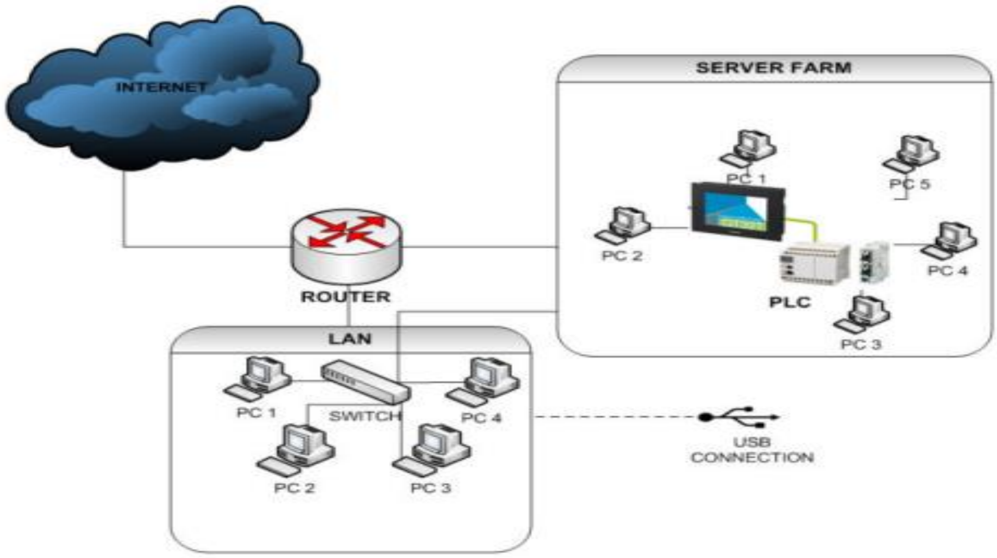

Figure 2. Propagating of Stuxnet.

Once Stuxnet infiltrates the intranet, it utilizes a download server to update its definitions (Miyachi et al., 2011). In cases where an earlier version of Stuxnet already exists on the intranet, the new version informs it and proceeds to propagate itself to the ICS (Industrial Control System) PLC (Falliere et al., 2011). For a successful installation, Stuxnet actively seeks administrator privileges on the targeted system. If these privileges are not already present, it will attempt to acquire them by exploiting one of the two zero-day vulnerabilities. Once installed, Stuxnet verifies the detailed ICS configuration to ensure it serves its intended purpose. Following the installation, the malware collects information from the system and other sources through HTTP, sending this data to the attacker/hacker (Goyal et al., 2012).

3.2 Stuxnet and SCADA

Stuxnet was a malicious software explicitly created to disrupt the centrifuges used in Iran's nuclear program by targeting SCADA systems. SCADA systems are IT mechanisms responsible for monitoring and overseeing physical processes (Collins & McCombie, 2012). These systems typically consist of network devices like sensors, actuators, controllers, and communication devices. The exploitation of SCADA systems involves centrally acquiring and controlling data from dispersed assets (Moteff et al., 2004). These distributed systems can include power grids, water distribution and waste collection systems, oil and gas pipelines, rail transportation control, and, in the case of Stuxnet, nuclear facilities (Collins & McCombie, 2012).

Stuxnet's specific objective within the SCADA system was to target Programmable Logic Controllers (PLCs). PLCs are small computers responsible for supervising the operations of electrical equipment, such as switches, relays, and timers/counters (Tsang, 2010). The PLC sought by Stuxnet was that of the control centrifuges used to enrich uranium (Collins & McCombie, 2012).

3.3 Methodology

The combination of Intrusion Detection Systems (IDS) and Firewalls creates a powerful and synergistic cybersecurity defense. This integration enhances the overall network security posture, providing both proactive threat detection and real-time traffic filtering capabilities. As shown in Figure 3. The structure of the combined system typically follows these key components:

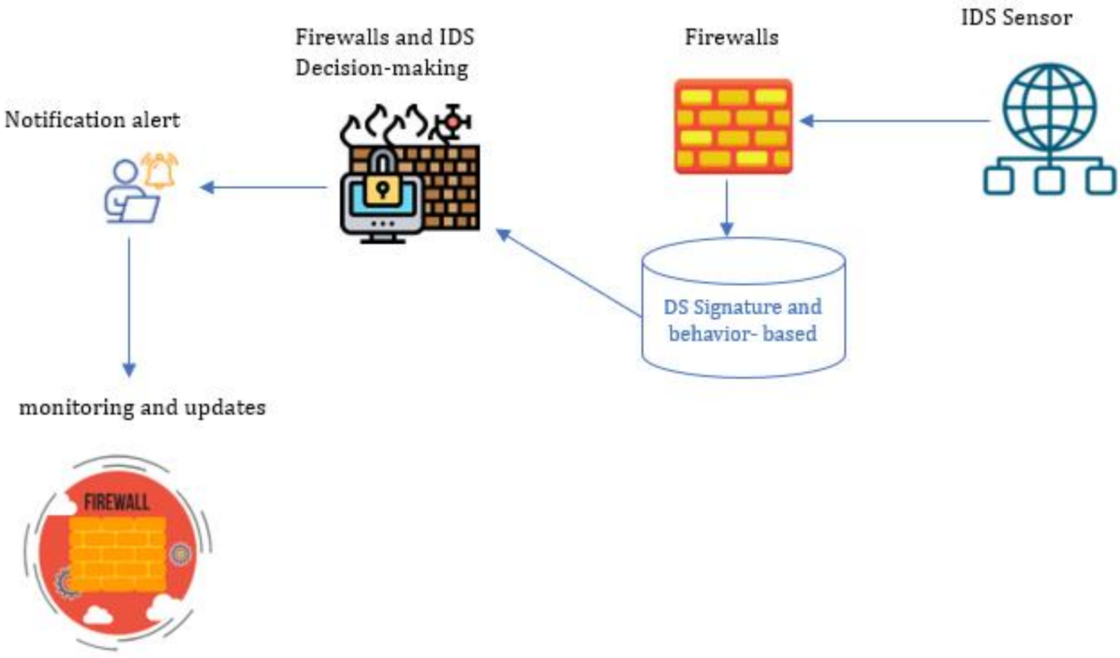

Figure 3. Combination of both Intrusion Detection System IDS against Stuxnet.

Initially, IDS sensors collect network traffic and system logs, identifying potential security events and anomalies. Firewall sensors monitor incoming and outgoing data packets, inspecting them based on predefined rules and criteria. After Data collected by IDS sensors undergoes preprocessing to remove irrelevant information and prepare it for analysis. The Intrusion Detection System (IDS) and firewall employ their decision-making algorithms to assess whether the observed activities are normal or potential security threats and effectively make decisions by considering the activities and leveraging the benefits derived from the behavior and signature-based approaches. Then, If IDS recognizes a potential security threat, it generates alerts and notifications to inform security administrators. Similarly, the firewall can log and notify administrators about blocked or allowed traffic based on its rule sets. The combination allows for a coordinated response mechanism. When IDS identifies a specific attack pattern or malicious activity, it can communicate with the firewall to block the offending IP addresses or take other protective actions. Both IDS and firewalls maintain logs of detected events, including blocked traffic and suspicious activities. Regular updates, monitoring, and patches for both IDS and firewalls are crucial to ensure their effectiveness against evolving threats. Security experts continuously monitor the system to fine-tune rule sets, adapt to new attack patterns, and maintain a robust defense posture.

4. Result and Discussion

In this study, we implemented a combination of firewalls and intrusion detection systems (IDS) to enhance cybersecurity and protect against the sophisticated Stuxnet malware. The goal was to establish a robust defense strategy to safeguard critical assets and prevent potential vulnerability attacks. The firewalls served as the first line of defense, actively monitoring and filtering incoming and outgoing network traffic. They enforced predefined security policies and rules, effectively blocking unauthorized access attempts and malicious data packets. By controlling data flow, firewalls provided a strong barrier against external threats, reducing potential entry points for malware like Stuxnet. Simultaneously, the intrusion detection systems continuously monitored network activities and system logs, using various detection techniques such as signature-based, behavioral-based, and anomaly detection. Real-time monitoring allowed IDS to identify potential security events and anomalies indicative of Stuxnet or other sophisticated malware. The IDS played a crucial role in identifying and flagging suspicious activities, enabling prompt responses to potential threats. This study demonstrated the effectiveness of using firewalls and IDS together as a defense mechanism against cyber threats like Stuxnet. The collaborative nature of these security measures allows for comprehensive coverage, protecting against both external and internal threats. Firewall deployment ensured that only authorized traffic was allowed, preventing unauthorized access and blocking potentially harmful data packets from entering the network. This proactive approach significantly reduced the attack surface and limited Stuxnet's opportunities to infiltrate the system.

On the other hand, the IDS provided continuous monitoring and analysis of network activities, promptly detecting any suspicious behavior indicative of Stuxnet or similar malware. The IDS enabled immediate responses to potential threats, allowing security administrators to take appropriate actions and mitigate the attacks' impact. Furthermore, the integration of firewalls and IDS created a coordinated response mechanism. When the IDS identified specific attack patterns or malicious activities, it communicated with the firewalls to block offending IP addresses or take other protective measures. This dynamic interaction enhanced the overall security posture, preventing potential threats from spreading within the network.

5. Conclusion

the Stuxnet attacks have marked a significant paradigm shift in the landscape of malware attacks. The unique combination and complexity exhibited by this malware have surprised computer experts worldwide. Its utilization of four zero-day exploits and sophisticated design have made it a remarkable piece of malicious software. The integration of firewalls and IDS techniques brings together two powerful components of cybersecurity defense. Firewalls act as the first line of defense, actively filtering network traffic and enforcing security policies. The IDS techniques, on the other hand, provide continuous monitoring and analysis of network activities, identifying potential threats and anomalies in real time. By combining these two security mechanisms, organizations can establish a robust defense posture against potential vulnerability attacks. The coordinated efforts of firewalls and IDS techniques ensure the timely detection and prevention of malicious activities, reducing the risk of unauthorized access and resource exploitation.

Future Work

Stuxnet is just the historical example of a strategic attacker and the only empirical opportunity to test the current awareness of cyber warfare. Unlike its predecessor of malware, is very straightforward and designed to meet global standards. And also Stuxnet duplicates itself. It may be possible for future attackers to take advantage of the zero-day challenge and launch new types of attacks on key challenges. Therefore, we are trying to provide methods to stop Stuxnet from replication in the future. And develop methods to stop the zero-day attack.

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