Efficient Industrial Control Systems risk assessment using the attack path to the critical device

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ABSTRACT

In cyberattacks against Industrial Control Systems (ICS), one of the final goals of attackers is to impair ICS operations. Recent ICS tend to be connected with other networks and are often implemented with common technologies in order to increase production efficiency and reduce costs. This leads to the creation of new attack surfaces that increase the cyber risks of these systems. Although preventing system intrusion without fault could be difficult, if attacks can be prevented at an early stage before they reach the physical world, damage can be minimized. Thus, appropriate cybersecurity risk assessment methods for ICS are necessary. ICS risk assessment methods proposed in previous research require more time to administer, and they heavily depend on the analysts' particular expertise and skill to efficiently examine attack scenarios and attack paths. In this research, we propose an efficient quantitative risk assessment method to evaluate the risk of possible attacks on critical ICS devices. This method uses packet capture data in the ICS network to automatically enumerate possible attack paths and calculates the risk level of each attack path. It then comprehensively evaluates the risk level of an entire ICS by utilizing multiple metrics such as the severity of vulnerabilities that exist in specific devices or communication methods, security measures that have been taken, and the features of the attack paths to the critical devices.

CCS CONCEPTS

• Security and privacy → Network security.

KEYWORDS

Industrial Control System, cyber security, risk assessment, attack path

*Presently with NTT Secure Platform Laboratories

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1 CYBER RISKS IN INDUSTRIAL CONTROL SYSTEMS

ICS were considered to possess no cybersecurity risks since they were operated in isolated networks. However, in modern ICS, a variety of common technologies are used, and multiple systems are oftentimes interconnected. The use of common technologies makes attack activities easier since an abundance of information and tools are openly available. If an ICS network is connected to another network, there is also the security risk of intrusion into the ICS network through connected adjacent networks.

The Cyber Kill Chain is a part of the Intelligence-Driven Defense model for the identification and prevention of cyber intrusion activities. According to the Cyber Kill Chain of ICS, [2], defined by the SANS Institute, attack activities are divided into attacks against IT systems and attacks against ICS. For example, attackers first intrude into an employee's PC, then expand into the ICS network through a Gateway server, etc. Attackers who make their way into the ICS network tries to compromise ICS devices. Controllers and PLCs are typical targets of attacks [16] [17], thus attackers tend to expand infections to devices that can directly operate controllers or PLCs. The following (1.1,1.2,1.3) are typical methods to expand the intrusion scope and to operate the ICS maliciously.

1.1 Leveraging vulnerabilities

Attackers leverage vulnerabilities for expanding infections, gaining higher privilege, executing malicious code, etc. The impact of a vulnerability is different depending on the type, and one of the most serious vulnerability types is the remote code execution type, which allows arbitrary code execution from remote hosts.

1.2 Leveraging legitimate functions

Attackers sometimes leverage legitimate functions to expand infections. For instance, Pass the hash[8] and Golden Ticket[15] are

two famous attack methods leveraging legitimate accounts of the Windows operating system.

1.3 Leveraging vulnerable communications

Some ICS devices including PLCs use vulnerable communication methods that are not protected with encryption or authentication, and they are vulnerable to replay attacks [17]. A replay attack in this paper is defined as an attack where attackers snoop data transmitted among legitimate ICS devices and then use this data to send unauthorized ICS commands. For instance, attackers can snoop communications between HMIs and PLCs and then send unauthorized commands to PLCs.

2 RELATED RESEARCH

This chapter describes related research on risk assessment methods for analyzing the risk of cyber attacks using attack trees or attack paths that are easy to automate. [7] proposes a method to analyze attack patterns using attack trees. [3] proposes the application of attack trees to an ICS environment. The purpose of research [7][3] is to identify corresponding security measures, thus they are different from the goal of our research. [12] proposes a method to consider appropriate security measures for ICS based on attack paths, but it does not focus on ICS specific security risks.

Some research propose methods to analyze the threat of attacks using attack paths based on system architectures. [11] proposes a method for creating attack paths based on vulnerabilities, network information, account information, etc. [1] extends the research [11] to other network attacks such as ARP spoofing and route hijacking. [6] proposes an efficient method for creating attack paths for large networks based on vulnerabilities and network information. They focus on specific attack methods against generic IT systems and do not focus on attacks against ICS.

[13] proposes a risk assessment method for ICS considering multiple aspects such as attacks leveraging legitimate functions in addition to vulnerabilities. It is a comprehensive risk assessment method, but it takes a lot of time and depends on the analyst's skill since it creates attack paths based on each attack scenario analyzed by an analyst. We refer to [13], then propose a more efficient risk assessment method.

3 PROPOSED METHOD

We propose an efficient quantitative risk assessment method to evaluate the risk of attacks reaching critical ICS devices. Our method calculates the risk level of attack reachability to the critical devices from a specific computer (e.g. a computer that a security alert is detected). Critical devices indicate the most important ICS devices that need to be protected, and they should be defined in each organization. In this research, we choose PLCs as critical devices. The contribution of our research is as follows.

- The proposed method considers cyber risks specific to ICS and can evaluate the cyber risk level mechanically without depending on human skill.
- The proposed method can reduce the time cost of risk assessment since it analyzes communication traffic to automatically generate possible attack paths, and iterates through each of the paths.

Figure 1: Conceptual diagram of the attack paths

- The proposed method can identify an attack path to a critical device with the highest risk factor and can simulate the effectiveness of implementing security measures.

3.1 Hypotheses

We assume that a successful attack depends on the following elements.

- Vulnerabilities that exist on each host
- The number of remote access services available
- The number of vulnerable communications among hosts
- Security measures taken on each computer and network

3.2 Enumeration method of the attack path

All possible network attack paths should first be enumerated. Figure 1 is a conceptual diagram that shows an example of possible attack paths. *startNode* is an arbitrary computer where the attack paths initiate. This is oftentimes a compromised computer where a security alert is detected. *intermediateNode* are devices that exist on the route between the *startNode* and the critical devices. *criticaldevice* is the most important ICS device that needs to be protected. The proposed method enumerates all paths that can reach from *startNode* to *criticaldevice* by identifying network reachability by using passive network scanning among hosts.

- (1) Extract all destination hosts for the specified host from packets. This step should start from *startNode*.
- (2) Repeat step 1 for every host until *criticaldevice* is reached.

For efficient automated risk assessment, the proposed method narrows down attack activities to unauthorized manipulation and DoS attacks against ICS devices, since they lead to critical physical damages of ICSs. For *criticaldevice*, the proposed method assesses attack activities that could affect the behavior of the *criticaldevice*. In the case of *intermediateNode*, since these hosts can be leveraged as stepping stones to *criticaldevice*, the proposed method mainly assesses attack activities that allow the expansion of infections.

3.3 Risk assessment metrics

3.3.1 Vulnerabilities. Vulnerabilities that exist on each host are one of the metrics of assessing possibilities of successful attacks. Since analyzing all existing vulnerabilities could be very costly, we narrow down the vulnerabilities that are analyzed to the ones below.

Table 1: Metrics for vulnerabilities

Score	CVSS3 metrics	Value	Critical device	Intermediate node
1	Attack Complexity	Low	Evaluate	Evaluate
1	Privileges Required	None	Evaluate	Evaluate
1	User Interaction	None	Evaluate	Evaluate
1	Integrity Impact	High	Evaluate	-
1	Availability Impact	High	Evaluate	-

Table 2: Metrics for remote access services

Score	Service	Description
1	Secure Shell (SSH)	A cryptographic protocol generally used to access Unix-like operating systems
2	Telnet	A protocol generally used to access Unix-like operating systems. Data does not encrypt by default.
2	Remote Shell (rsh)/rlogin	A protocol used to execute remote shell or access remote computers. Data does not encrypted.
2	Server Message Block (SMB)	A protocol generally used to access Windows system. Since there are common attack methods such as Pass the hash, the score is set to 2.
1	Remote Desktop Protocol (RDP)	A cryptographic protocol generally used to access the Windows system using GUI
2	Kerberos	A cryptographic protocol generally used in Active Directory. Since there are common attack methods such as Golden Tickets, the score is set to 2.

Table 3: Metrics for communications

Score	Metrics	Description
1	Encryption	None
1	Authentication	None
1	Protocol	Standard protocol

- Vulnerabilities on *criticaldevice*: Vulnerabilities that affect integrity and availability.
- Vulnerabilities on *intermediateNode*: Vulnerabilities that allow arbitrary code execution remotely (Remote Code Execution vulnerabilities).

Furthermore, the proposed method narrows down the analyzed vulnerabilities to those where the difficulty level of leveraging them is rather low. The existence of Proof Of Concepts and CVSS3 metrics [9] are used to decide on the difficulty level of each vulnerability. The procedure is as follows.

- (1) Pick up vulnerabilities where Proof Of Concepts (exploit code) are published on the Internet. The proposed method searches for Proof Of Concepts of each vulnerability from the Exploit Database [14] and reference URLs published in the NATIONAL VULNERABILITY DATABASE [10].
- (2) Pick up remotely exploitable vulnerabilities where the CVSS3 metric of "Attack Vector" is "Network" or "Adjoin".
- (3) Add score to vulnerabilities that meet conditions shown in Table 1.

3.3.2 Available remote access services. In addition to exploitable vulnerabilities, a successful attack also depends on the number of remote access services available. For efficient analysis, only remote access services that allow remote login to the system is considered as part of the proposed method. The metrics indicate the possibility of whether *intermediateNode* could be exploited as a stepping-stone. Table 2 lists remote access services and their risk score.

3.3.3 Vulnerable communications. Table 3 shows the metrics for vulnerable communication. A "Standard protocol" is defined as a protocol, including common ICS protocols, that meet the following conditions.

- The protocol uses Internet standard protocols such as TCP, UDP, IP, etc.
- The specification of the protocol is published.

3.3.4 Asset priority. The asset priority metric indicates how much potential damage there could be if the specific asset is compromised. It is based on what functions the asset is responsible for in the ICS and is also dependent on what kind of attack activities could be initiated on the asset. The asset priority level is shown in Table 4.

3.3.5 Security level. A successful attack also depends on security measures taken on each computer and network. The security level is calculated based on the security measures taken on the source host and destination host in each attack route.

The proposed method selected security measures shown in Table 5 from the ICS security guidelines[5] and incorporated them in as

Table 4: Asset priority level

Score	Description	Examples
3	Devices that can change the physical state of an ICS	OPC Server, HMI, Engineering Workstation
2	Devices that can retrieve ICS data but cannot change data	Read only OPC Server and HMI, historian
1	Other ICS related devices	Production control server
0	Other devices	Business PC, Web server

Table 5: Security level

Score	Security measure
1	Anti virus software
1	Password is more than 8 characters and includes upper and lowercase letters, numbers, and special characters. A unique password is set on each host
1	Minimize account privileges
1	Memory protection (e.g. LSA protection, Credential Guard: Windows memory protection methods against unauthorized access to credentials)
1	Encryption and access control against ICS data
1	Authentication and authentication of ICS application
1	Application whitelist
1	Appropriate encryption key management
1	Network security solution (e.g. ICS firewall, IPS)

metrics. If the security measures defined in Table 5 are taken, the corresponding score is subtracted from the risk level.

3.4 Procedure for calculating the risk level

Figure 2 shows an example of calculating the risk level. (1) is the formula to calculate the total risk level of each attack path ($attackpathx$).

$$risklevel_{pathX} = \prod_{i=startNode}^{critical} risklevel_i \quad (1)$$

The risk level of the entire system is defined as (2), and is the highest risk level of all the attack path risk levels.

$$\max\{risklevel_{pathX}, X = 1, 2, \dots, n\} \quad (2)$$

The risk level of each attack path ($risklevel_{pathX}$) is the product of the risk level of each network route ($risklevel_i$) on the attack path. Related research [13] defined that the risk level of each attack path is the minimum value of the risk level of each network route. However, our evaluation results showed that that method does not properly evaluate the risk levels under some conditions.

(3) shows the formula for calculating the risk level of each route.

$$risklevel_i = (threatlevel_d + prioritylevel_s - (securitylevel_s + securitylevel_d)) / MAXRISKLEVEL \quad (3)$$

The risk level of each route is calculated using the threat level ($threatlevel_d$), asset priority level ($prioritylevel_s$), and security level ($securitylevel_s$, $securitylevel_d$).

Figure 2: Example of calculating risk level

3.4.1 Threat level. The threat level is calculated as (4).

$$threatlevel = vullevel_d + remoteservicecnt + vulcomcnt \quad (4)$$

$vullevel_d$ is the risk level that indicates the existence of vulnerabilities on the destination host in each attack route. If the destination host has vulnerabilities that meet the conditions defined in section 3.3.1, the corresponding score is added. The maximum $vullevel_d$ is 3. If the $vullevel_d$ exceeds 3, $vullevel_d$ is set to 3.

$remoteservicecnt$ is the accessible remote access services of the destination host in each attack route. If the destination host has

Figure 3: ICS testbed for evaluation

accessible remote access services defined in Table 2, the corresponding risk level is added per remote access service. The maximum *remoteservicecnt* is 3. If the *remoteservicecnt* exceeds 3, *remoteservicecnt* is set to 3.

vulcomcnt is the vulnerable communications between the source host and destination host in each attack route. If vulnerable communications that meet any conditions in Table 3 exist, the risk level is added per condition. The maximum *vulcomcnt* is 3. If the *vulcomcnt* exceeds 3, *vulcomcnt* is set to 3.

3.4.2 Asset priority level. The asset priority level(*prioritylevel_s*) indicates the damage level of each computer on an attack path if it is compromised. Thus it is evaluated with the asset priority level of the source host in each attack route.

3.4.3 Security level. The security level(*securitylevel_s*, *securitylevel_d*) is the security measures taken on the source host and destination host in each attack route. If the security measures defined in Table 5 are taken, the corresponding risk level is subtracted per security measure. The maximum-security level(*securitylevel_s* + *securitylevel_d*) is 3. If the security level exceeds 3, it is set to 3.

3.4.4 Normalizing and scoring. The maximum score of *vullevel_d*, *remoteservicecnt*, *vulcomcnt* and security level(*securitylevel_s* + *securitylevel_d*) are adjustable. In this paper, we define the maximum score based on previous research[13]. *MAXRISKLEVEL* is the maximum risk level that is allowed per attack route. To normalize the risk level between 0 to 1, the risk level is divided by *MAXRISKLEVEL*.

4 EVALUATION OF THE PROPOSED METHOD

We compare the result (successful or failure) of an attack in the penetration test with the risk level of each attack path calculated by the proposed method. For the evaluation, we use an ICS testbed that operates on actual machinery. The testbed is a water pump system that provides water to consumers with flow control and temperature control (Figure 3 and Table 6). It is divided into several network segments based on the reference architecture in IEC 62443[4].

We evaluate whether the proposed method can simulate the risk level of each attack path and the effectiveness of security measures correctly upon the following patterns.

Figure 4: Evaluation result (Without security measures)

4.1 Evaluation without security measures

Almost all security measures shown in Table 5 are disabled on many computers, and ICS communications meet the condition in Table 3.

4.2 Evaluation with security measures

We place security measures on networks and devices that exist on the attack path with the highest risk factor as calculated in evaluation pattern 1, then evaluate whether the proposed method can rate the effect of security measures correctly.

4.3 Evaluation result

We compared the result of the penetration test with the risk level of each attack path calculated by the proposed method shown in Table 7.

4.3.1 Evaluation result (Without security measures). Table 8 shows the result of evaluation pattern 1 (4.1) that places no security measures. The "Attack result" column indicates whether pen-testers were able to attack critical devices (PLCs). As a result, the proposed method found 3 possible attack paths (Figure 4) and rated *attackpath1* as the path with the highest risk factor. This *attackpath1* was the only path where pen-testers successfully attacked the critical devices.

4.3.2 Evaluation result (With security measures). Table 9 shows the evaluation result of evaluation pattern 2 that place security measures (4.2). We placed the following security measures on the networks and devices that existed on the network route *route1* – 2 of *attackpath1* with the highest risk level. As a result, the risk level of *attackpath1* decreased to "0.083", and pen-testers were not able to attack the critical devices.

- Close unnecessary ports (RDP and SMB) in *route1* – 2.
- Protect the memory of the Production control server and OPC server with LSA protection¹.
- Set password to the OPC server application.
- Set a unique and strong password to the Production control server.

¹ Additional protection for the Local Security Authority (LSA) process to prevent Code injection that could compromise credentials

Table 6: Evaluation environment

Device	OS(Level)	Used protocols
Water pump	-	-
PLC	-	Modbus/TCP
OPC Server	Windows Server 2016	OPC DA/Modbus(TCP)
HMI	Windows 10	OPC DA
Engineering workstation	Windows 7	SMB,Modbus/TCP
ICS file server	Windows Server 2016	SMB
Production control server	Windows 7	OPC DA,RDP,SMB
Operator's PC1	Windows 10	RDP,SMB
Operator's PC2	Windows 10	RDP,SMB
Internal web server	CentOS 7	SSH,HTTP
Employee's PC	Windows 7/MacOS	SMB,RDP

Table 7: Risk assessment metrics

Device	Risk level		
	Asset priority	Vulnerability	Security
PLC	3	0	0
OPC Server	3	3	0(2*)
HMI	3	3	0
Engineering workstation	3	3	0
ICS file server	1	3	1
Production control server	1	3	0(2*)
Operator's PC1	0	0	2
Operator's PC2	0	0	3
Internal web server	0	2	0
Employee's PC	0	0	2

*Value in the bracket means the security level upon the evaluation with security measures.

Table 8: Evaluation result(Without security measures)

Path	riskLevel (total)	riskLevel (route1)	riskLevel (route2)	riskLevel (route3)	Attack result
1	0.24 (5)	0.58	0.83	0.50	success
2	0.024 (1)	0.080	0.58	0.50	fail
3	0.021 (1)	0.083	0.50	0.50	fail

Value in the bracket represents the risk value using the previous research[13]

Table 9: Evaluation result(With security measures)

Path	riskLevel (total)	riskLevel (route1)	riskLevel (route2)	riskLevel (route3)	Attack result
1	0.083 (4)	0.50	0.33	0.50	fail
2	0.020 (1)	0.080	0.50	0.50	fail
3	0.021 (1)	0.083	0.5	0.50	fail

Value in the bracket represents the risk value using the previous research[13]

Compared with the previous research[13], the proposed method judged the same path with the previous research as a critical path. However, when applying the security measures and the attack failed, the risk level of the critical path decreased by only 20% while the risk level of the proposed method decreased by 67%. It can be

said that the proposed method can calculate the risk level more accurately.

5 CONCLUSION

In this research, we proposed an efficient cybersecurity risk assessment method for ICS. The proposed method can be utilized for

identifying devices on the high-risk network path or simulating the efficiency of implementing security measures. Furthermore, the proposed method can evaluate the cyber risk level automatically and mechanically without depending on human skill. The method is tested on a small testbed as an example. However, The proposed method can extend to a wider class of environments by using automated assessment. In this paper, we used metrics considered in previous research to define the maximum score of metrics used for calculating the risk level. For future work, we will evaluate more ICS operations and attack patterns, and adjust each score based on the evaluation results. In addition, we will further evaluate how certain security measures affect different threats, and how they should be scored.

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