TRITON: The First ICS Cyber Attack on Safety Instrument Systems

Understanding the Malware, Its Communications and Its OT Payload

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Table of Contents

1. Abstract

In December 2017 it was reported that a Middle Eastern oil and gas petrochemical facility [1] had undergone a safety system shutdown as the result of a malware attack. The malware, named TRITON (also known as TRISIS or HatMan), went beyond other industrial cyber attacks by directly interacting with a Safety Instrumented System (SIS). SIS are the last line of automated safety defense for industrial facilities, designed to prevent equipment failure and catastrophic incidents such as explosions or fire.

Based on the significance of this industrial cyber attack, it warranted an in-depth analysis. We were determined to understand the TRITON malware itself, as well as the resources it took to create it. We also sought to gain insights that would help industrial operators defend their control systems from such attacks in the future.

Our challenge was to learn how to turn an undocumented device – the Triconex controller from Schneider Electric, which was the target of the attack – into malicious code. To do so we first focused on obtaining the TRITON engineering toolset. We combined Internet sleuthing with asking the right people the right questions, to obtain the information we needed.

Our next hurdle was obtaining the Triconex controller. Employing a variety of global ecommerce websites, we purchased the components needed and assembled them into a working environment. We were unable to find one key component – the marshalling cables, but we overcame that problem by using brute force to directly connect two panels.

Now that we had a working system, we proceeded to reverse engineer the TriStation suite of software used on the engineering workstation that communicates with the SIS controller. That activity, combined with malware analysis, allowed us to deeply dissect the TriStation proprietary communication protocol used by the Triconex controller.

Our findings allowed us to develop two new tools [2] to help the ICS community secure Triconex SIS. The first tool, the ***TriStation Protocol Plug-in for Wireshark***, allows an engineer to visually see and comprehend TriStation communications. It also identifies hardware connected to the safety controller and passively detects TRITON activity in network communications.

The second tool, the ***Triconex Honeypot Tool,*** can be used by defense teams to simulate SIS controllers on the network, using them like a honeypot [12] to detect reconnaissance scans and capture malicious payloads.

While the TRITON malware attack failed to deliver a malicious OT payload, we successfully used its capabilities to implement new programs in the Triconex controller and to execute a malicious payload.

Our research shows that the effort, skills and financial resources needed to create the TRITON malware are not that high – certainly not at the level where nation state-sponsored resources are required. Knowing this, industrial asset owners should act immediately to monitor their SIS and secure them against external attacks. We also urge SIS equipment makers to provide more robust built-in security for these vitally important systems.

2. Introducing SIS and the TRITON cyber attack

2.1. SIS (Safety Instrumented Systems)

Safety Instrumented Systems (SIS), also known as *Industrial Safety Systems,* are designed to prevent industrial incidents, such as equipment or operational failures, from causing damage, injury, loss of life, or serious environmental harm. Examples of extreme consequences would be explosions, fires, oil spills, floods or even nuclear system meltdowns.

The equipment used in SIS are a special type of PLC (Programmable Logic Controllers) designed with predictability and reliability in mind. They include multiple main processors, built-in diagnostics, redundancy management systems, and failure detection for inputs and outputs [3]. Best practices for securing SIS include running them on isolated networks and carefully restricting access rights.

If out-of-range operating conditions occur, SIS perform control functions that shut the process down in a safe, predictable way. Also, while designed to never fail, should an SIS failure actually occur, it will do so in a predictable manner. Thus, the worst-case scenario is known and planned for ahead of time.

SIS are the last line of automated defense for industrial facilities, though it should be noted that mechanical fail-safes also exist.

2.2. The TRITON cyber attack and why it is important

In December 2017, FireEye reported [4] that it had recently worked with an industrial operator whose facility was attacked by a new type of ICS malware, which they named *TRITON* (other organizations have named it *TRISIS* or *HatMan*). [5]

The attack reprogrammed the facility's SIS controllers, causing them to enter a failed state, and resulting in an automatic shutdown of the industrial process. The investigation following the shutdown led to the detection of the hacking attempt.

The targeted facility was subsequently identified as a Saudi Arabian petrochemical processing plant [5], while the SIS that was attacked was a Triconex Safety Instrumented System from Schneider Electric. This type of SIS is commissioned in a consistent way across many industries and is widely used. [6]

TRITON is one of only a handful of malware with the ability to impact the physical process of an industrial control system. Previous examples include *Stuxnet* [7] (Iran, uranium enrichment centrifuges, 2010) and *Industroyer*/*Crash Override* [8] (Ukraine, power grids, 2015 and 2016).

TRITON goes well beyond earlier attacks and is considered a milestone industrial cyber attack because it directly interacts with, and controls, SIS. It raises the possibility of a cyber attack leading to unpredictable and dangerous plant outcomes, without the protection of a last line of safety defense.

Based on the significance of this industrial cyber attack, the Nozomi Networks security research group decided to do an in-depth analysis of it. We were determined to understand TRITON and the resources needed to create it. We also sought to gain insights that would help industrial operators defend their control systems from such attacks in the future.

2.3. The key components of the attack

The attack began with penetration of the IT network using well-documented [9], easily-detected attack methods. The attackers moved to the OT (Operational Technology) network through systems that were accessible to both environments.

Once on the OT network, the threat actors were able to infect the engineering workstation for the SIS system, usually situated in an isolated network segment. The infection probably used a social engineering technique whereby the engineer received or downloaded a file with a legitimate file name, in this case “trilog.exe”. The name suggests that the dropper file is a clean executable dealing with something related to Triconex and its logging capabilities (TRIconex LOGging filename).

The main purpose of the dropper file was to deliver the malicious payload into the target, in this case the SIS controller. Soon after the execution, the dropper connected to the targeted Triconex, injecting the real malware payload inside its memory.

The malware payload was contained in two separate binary files called *inject.bin* and *imain.bin*. One of the actions taken by the dropper was to read, inject and execute these files into the memory of the Triconex.

- **inject.bin** contained the code which exploits a specific 0-day in order to execute the content of the file "imain.bin".
- **imain.bin** contained the final code that allows a remote user to gain full control of the SIS device.

Following is reported information about the malicious files involved in the infection phase:

Filename	MD5	Component
trilog.exe	6c39c3f4a08d3d78f2eb973a94bd7718	Dropper
inject.bin	0544d425c7555dc4e9d76b571f31f500	Backdoor injector
imain.bin	437f135ba179959a580412e564d3107f	Backdoor code

The dropper was developed in Python and compiled inside the trilog.exe executable. It contains the implementation of the TriStation protocol reverse-engineered by the threat actors and used to interact with the targeted device.

The first action performed by the researchers who got the TRITON sample was to decompile the executable, extract the Python code, and use it as the starting point for the further analysis.

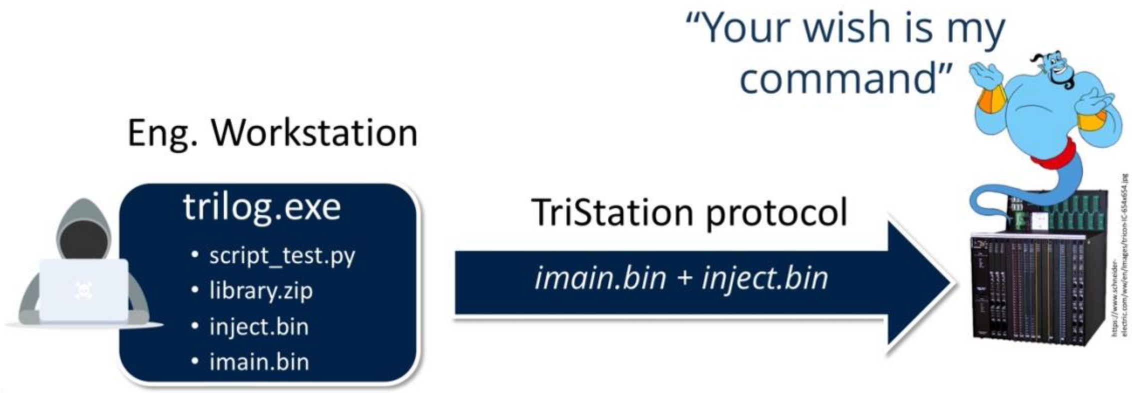


Figure 1 - A schematic view of the dropper phase of TRITON

3. Understanding TRITON through Reverse Engineering

3.1. Turning an 'Undocumented Device' into malicious code

Despite the routine techniques employed to gain access to the victim's OT environment, the threat actors behind the TRITON malware attack had to go through a significant learning curve. They had to learn about the Triconex SIS controller itself and *TriStation*, the proprietary network communication protocol it uses.

Obtaining both the Triconex hardware and software related to it was essential for recreating the full working environment needed for experimenting and writing malicious code. With a working system, the threat actors were able to intercept and analyze traffic transmitted on the wire. They were also able to reverse engineer the TriStation software.

Both methods were needed to dissect the proprietary protocol, extracting information from it and re-implementing it inside TRITON.

To study TRITON ourselves, we needed to recreate the targeted SIS in our lab environment and obtain as much documented information as possible about its functioning and communications. The following sections describe how we went about this.

3.2. Obtaining the TRITON engineering toolset

We used multiple channels to procure the necessary components, as follows:

- Vendor website – the Schneider Electric website contains useful information
- Consultation with key experts – sometimes asking the right person, nicely, is effective
- Asset owners – operations and security staff are our friends – and the best sources of information!
- Internet searches – there is a lot of freely available information, such as:
  - Installation CDs sold on e-commerce sites
  - Loose executables & archives on forum sites
  - Open directories, FTP servers, etc.

In short, a combination of Internet sleuthing and asking the right people the right questions allowed us to obtain a great deal of the information required.

3.3. Obtaining the Triconex controller

Of course, the key item we needed was a Triconex controller. This is where “free” ended and we had to spend some money. A budget of $5-10K is required – the reality is that most ICS equipment is expensive.

Another thing we took into consideration was getting multiple copies of the controller for teardown purposes – and in case we bricked (damaged) one, and it no longer worked.

Here are some of the sources we considered for acquiring the SIS controller:

- From the vendor – it’s possible to buy new equipment directly from Schneider Electric, but it is not the least expensive way.
- From online e-commerce sites such as eBay or Alibaba – we found components and used devices on these sites. In some cases, new ones were listed for sale, including full-warranties.

We needed to keep in mind that the systems had to be compatible for everything to work together, and we needed the same model that was used in the TRITON attack. The TRITON vulnerable SIS controllers are:

- Triconex *MP3008* main processor modules running firmware versions 10.0–10.4 [3]

Note that these models of the Triconex use a *MPC860 PowerPC processor*. Newer models use a different processor (ARM) and are thus not vulnerable to the version of TRITON we studied.

The equipment used for our research is described below.

Main Low-Density Chassis:

- 1.02 3008/N Tricon Enhanced Main Processor v10.3 - Firmware Meta Number: ETSX6236
- 1.05 4329/N/G NCM (Network Communications Module)
- 1.09 3503/E/EN Discrete Input, 24 V, 32 points
- 1.10 Marshalling Connector 2652 -310 DO
- 1.12 3604/E/EN Discrete Output, 24 VDC, 16 points
- Terminator Panel 2652-1

We also tested the injection phase and did some analysis with the 3008/N Tricon Enhanced Main Processor v9.10 BUILD 66.

One item needed was the marshalling cables, which are used to connect the terminal panel to the connector module. This allows communication with field devices through the digital output module.

- We wanted to get this communication to work so that we could test variations of TRITON that would succeed in delivering commands that disrupt the safety process, as described in Section 5.

It turned out to be the only equipment challenge we had – it seems marshalling cables are *very* hard to find.

Figure 2 - Marshalling cables were impossible to locate

Since we were unable to locate the cables, the only solution was to manually, using brute force, connect the terminal panel directly to the connector module. Fortunately, it worked!

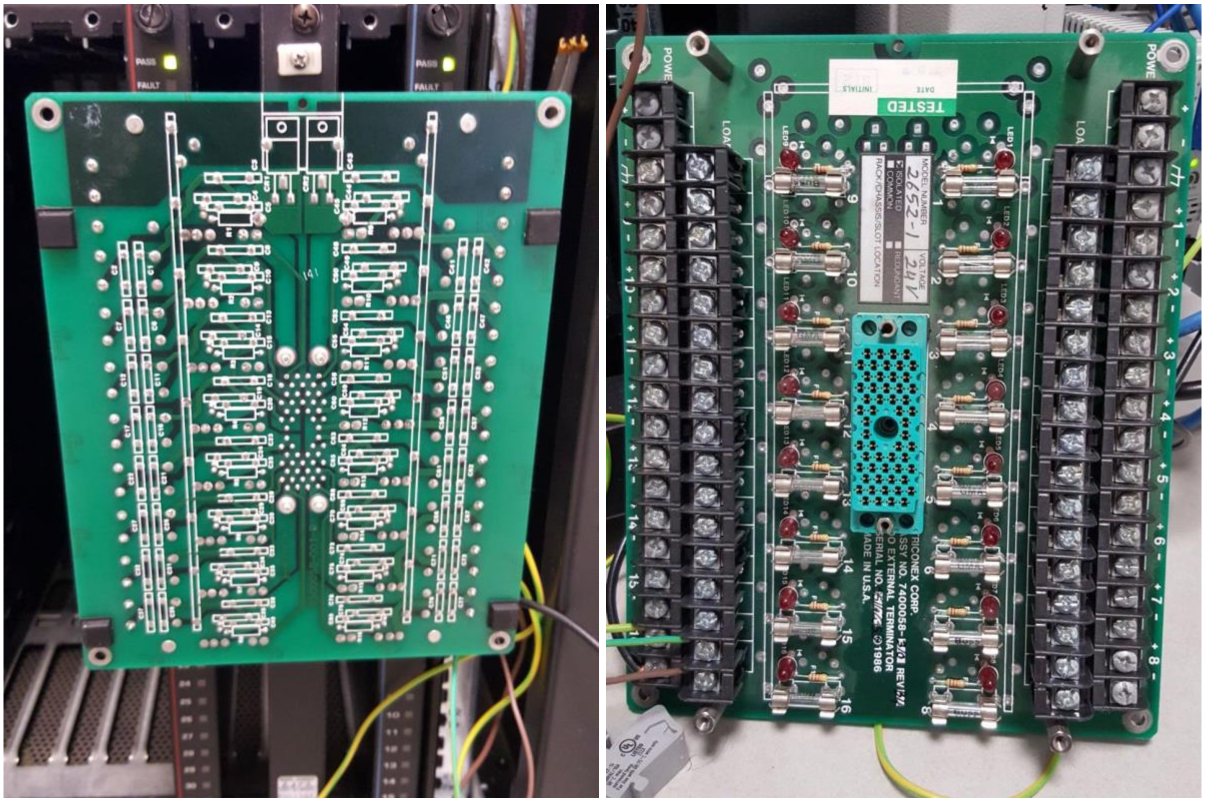


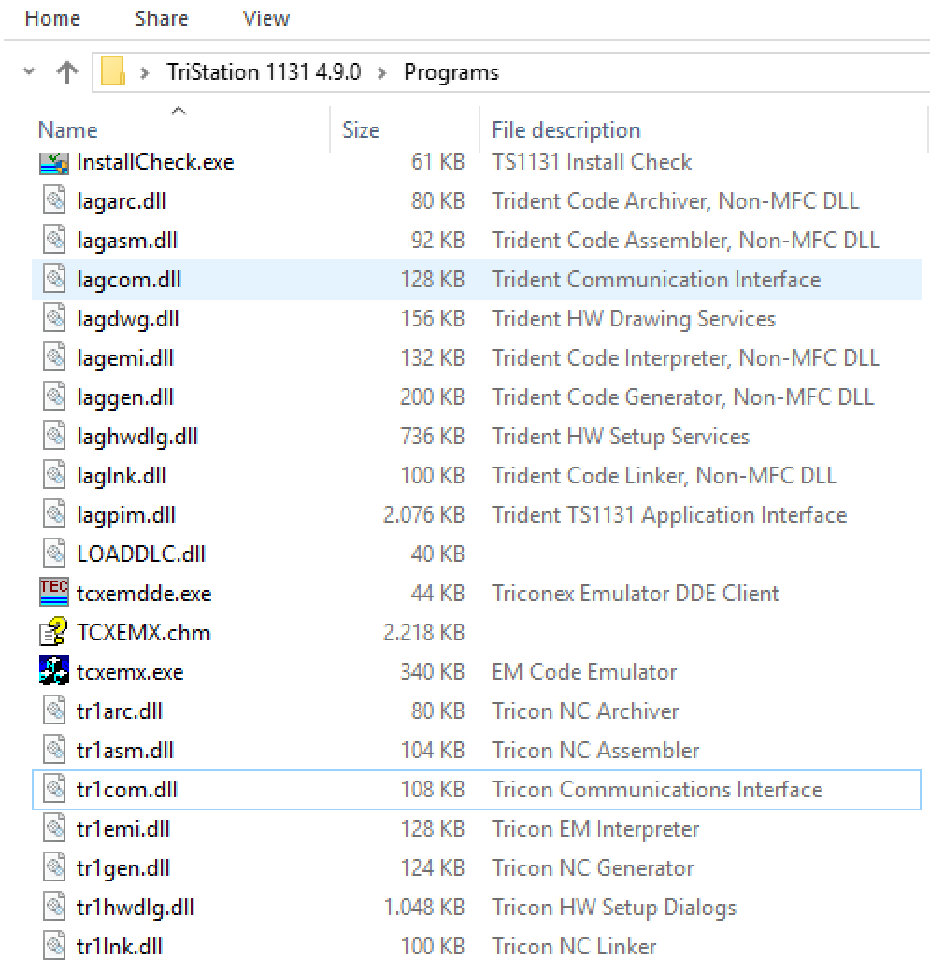
Figure 3 - Lacking the marshalling cables, these two boards were directly connected.

3.4. Reverse engineering the TriStation suite

The software installed on the engineering workstation is a gold mine for threat actors because it contains all the information needed to interact with the controller, including how to recognize different statuses and attached modules. *TriStation 1131 v4.9.0 (build 117)* is able to connect with the hardware version targeted by the malware, and all of our analysis has been performed on that version.

The Schneider Development Team has kindly included useful information about their files – which unfortunately can also be used by an attacker to better understand the software architecture and its general structure.

Starting with a detailed description of every file installed by the software, it is quite simple to understand where to look for different components.



Name	Size	File description
InstallCheck.exe	61 KB	TS1131 Install Check
lagarc.dll	80 KB	Trident Code Archiver, Non-MFC DLL
lagasm.dll	92 KB	Trident Code Assembler, Non-MFC DLL
lagcom.dll	128 KB	Trident Communication Interface
lagdwg.dll	156 KB	Trident HW Drawing Services
lagemi.dll	132 KB	Trident Code Interpreter, Non-MFC DLL
laggen.dll	200 KB	Trident Code Generator, Non-MFC DLL
laghwdlg.dll	736 KB	Trident HW Setup Services
laglnk.dll	100 KB	Trident Code Linker, Non-MFC DLL
lagpim.dll	2.076 KB	Trident TS1131 Application Interface
LOADDLC.dll	40 KB	
tcxemdde.exe	44 KB	Triconex Emulator DDE Client
TCXEMX.chm	2.218 KB	
tcxemx.exe	340 KB	EM Code Emulator
tr1arc.dll	80 KB	Tricon NC Archiver
tr1asm.dll	104 KB	Tricon NC Assembler
tr1com.dll	108 KB	Tricon Communications Interface
tr1emi.dll	128 KB	Tricon EM Interpreter
tr1gen.dll	124 KB	Tricon NC Generator
tr1hwdlg.dll	1.048 KB	Tricon HW Setup Dialogs
tr1lnk.dll	100 KB	Tricon NC Linker

Figure 4 - The TriStation suite files are nicely identified

3.5. Undocumented power users

The TriStation software also stores project files containing key information about the Triconex program, configuration and behavior inside a password-protected file with .PT2 extension. The assumption is that only authorized engineers can access the project files containing the proprietary code executed inside the SIS devices.

However, the TriStation software v4.9.0 (and prior versions), also contain two undocumented power users able to open any project file regardless of the robustness of its password. These users are likely used by the product support team to help customers with technical issues. While having operational value, these users can also be abused by threat actors to access password-protected project documents without the proper credentials.

The two undocumented users are:
*T****FD*
*T****BD*

For user *T****FD*, the login requires a password that is available through reverse engineering and additional authentication in the form of a support ticket number. This confirms that the role of the user is for customer support purposes.

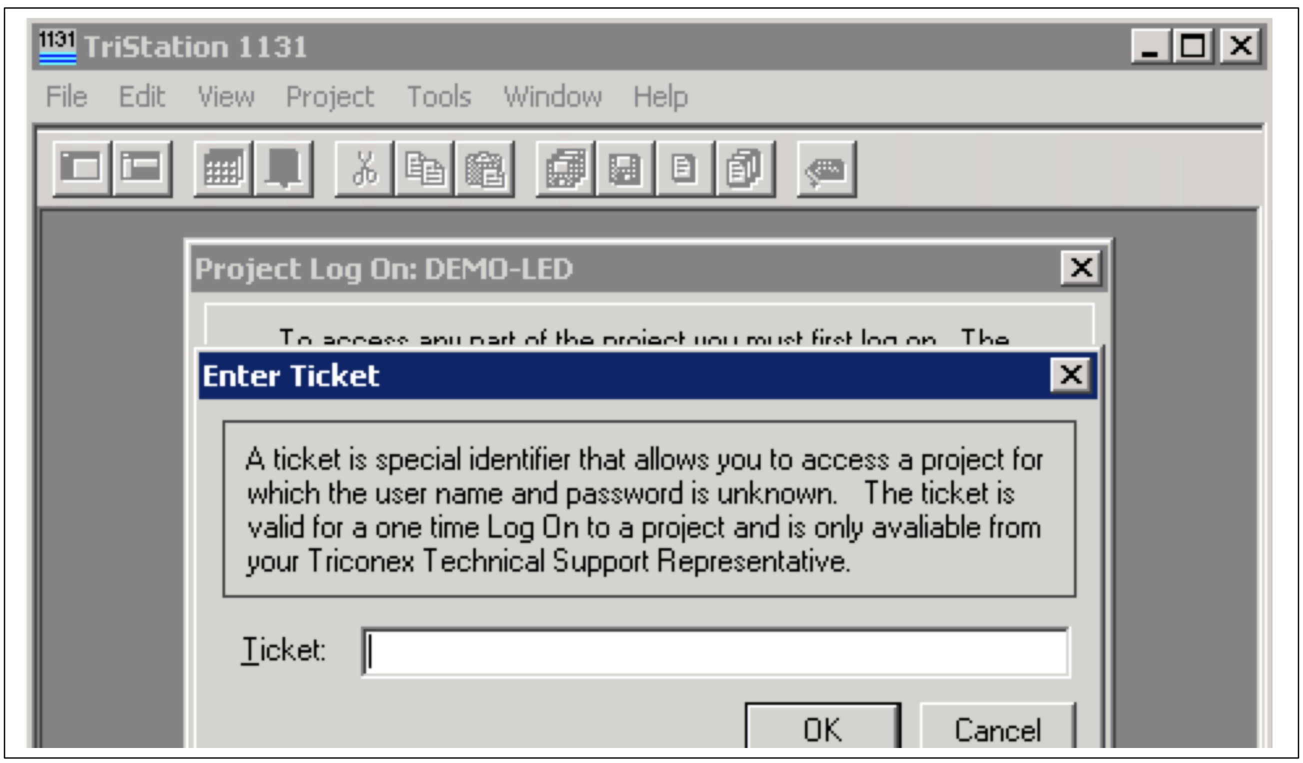


*Figure 5 – Undocumented user T****FD requires the extra step of a support ticket number to login*

User *T****BD* however, has the capability to access a project file just by inserting the hard-coded credentials extracted from the TriStation software.

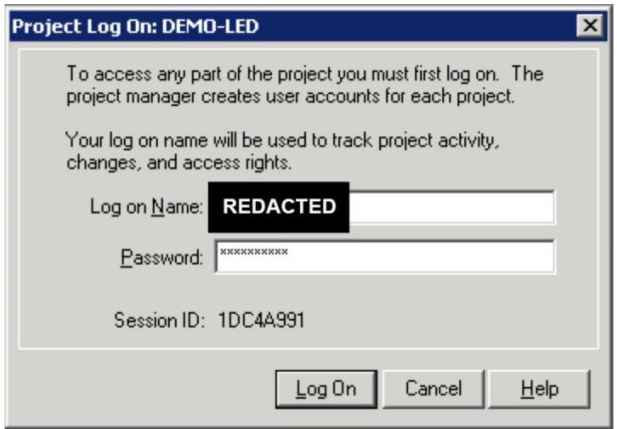


*Figure 6 – Undocumented user T****BD accessing a password protected project file with its static password*

Once user *T****BD* is logged in, a hidden menu is enabled that is not available to other users.

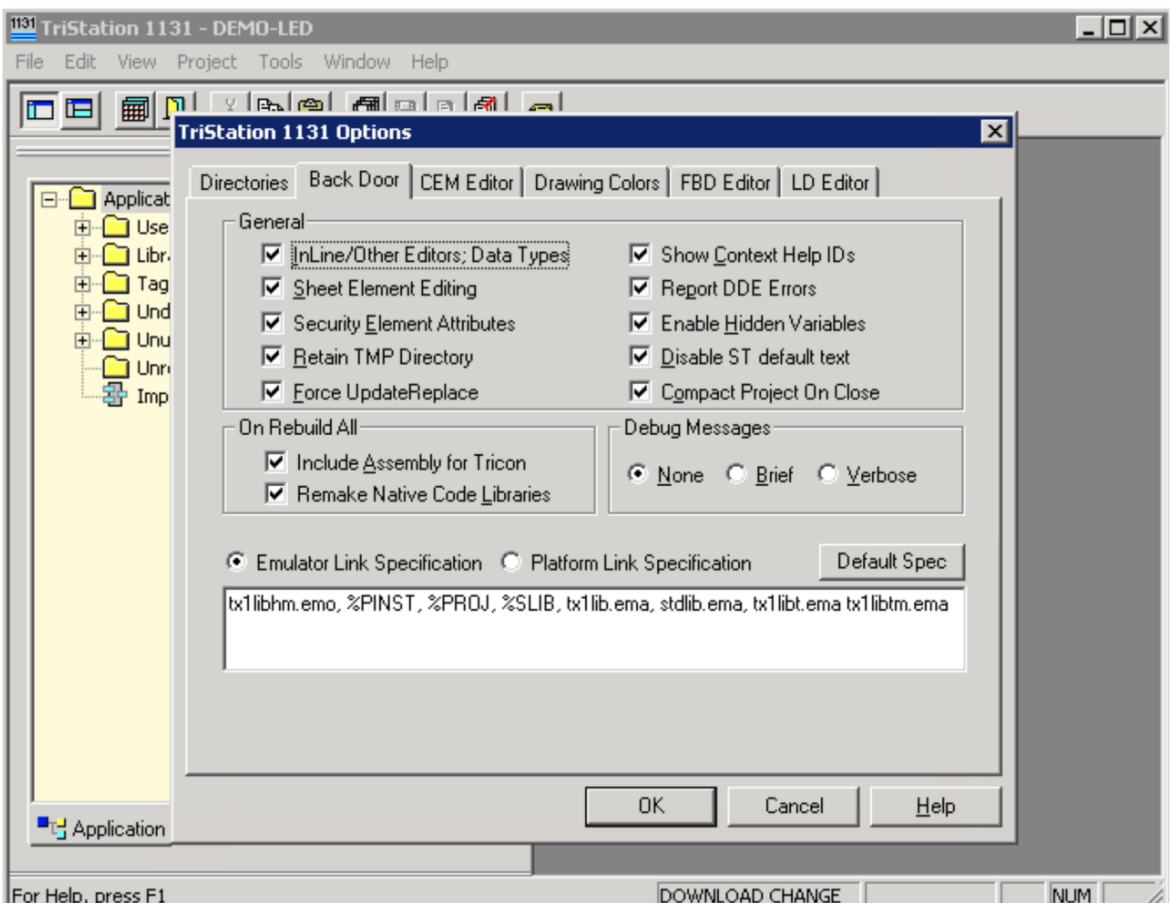
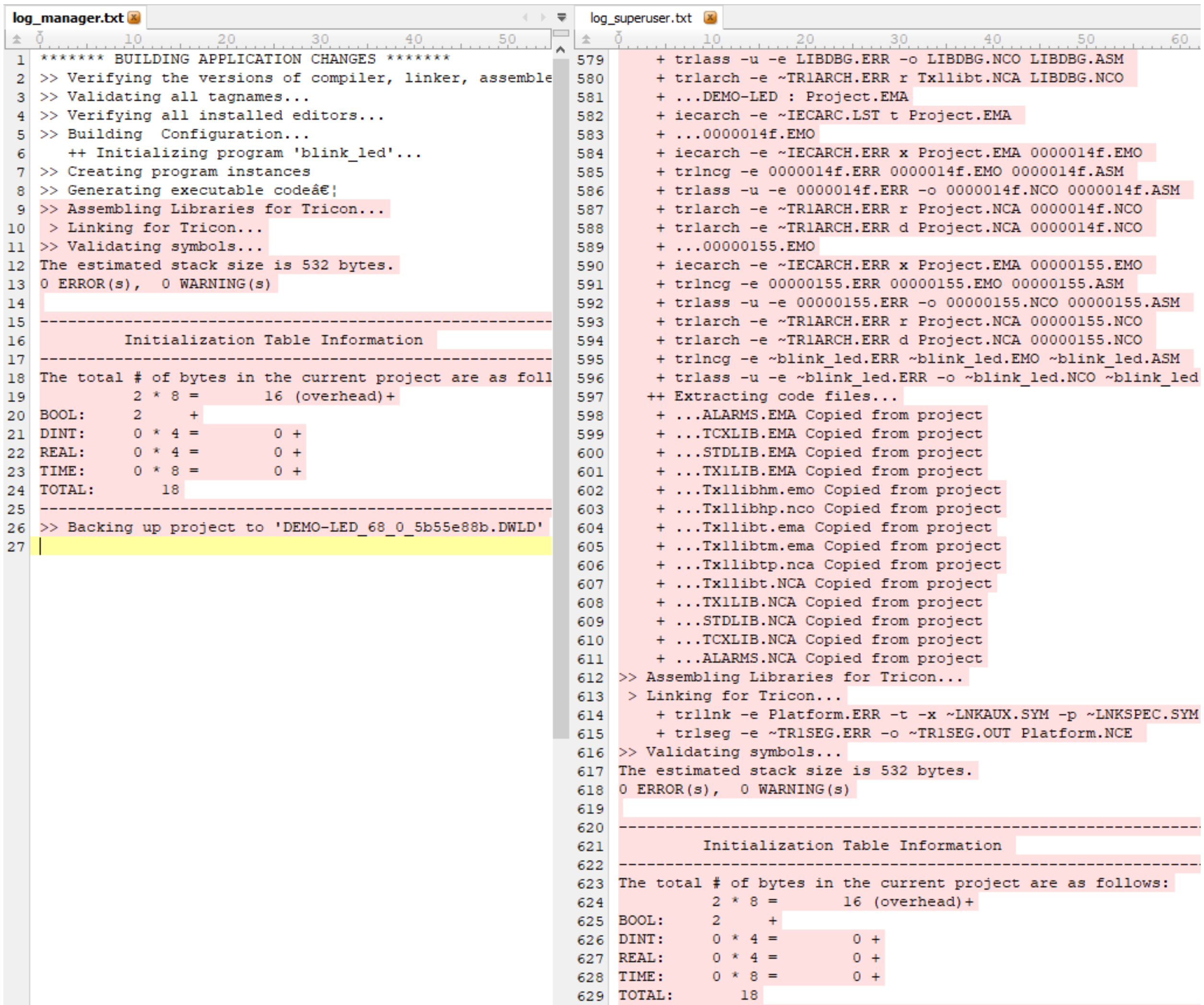


*Figure 7 – A hidden menu is enabled after logging-in as user T****BD*

From an attacker's prospective, this scenario could be useful. The hidden menu provides access to a great number of extra features not available to a normal user.

Moreover, when logged as *T****BD*, the TriStation software exposes internal information about the linking/compilation phases of the system logic. This additional data has a high value for threat actors because it describes in detail the commands involved during program compilation.



log_manager.txt

```
******* BUILDING APPLICATION CHANGES *******
>> Verifying the versions of compiler, linker, assemble
>> Validating all tagnames...
>> Verifying all installed editors...
>> Building  Configuration...
   ++ Initializing program 'blink_led'...
>> Creating program instances
>> Generating executable codeâ€¦
>> Assembling Libraries for Tricon...
 > Linking for Tricon...
>> Validating symbols...
The estimated stack size is 532 bytes.
0 ERROR(s),  0 WARNING(s)

-------------------------------------------------------
         Initialization Table Information
-------------------------------------------------------
The total # of bytes in the current project are as foll
          2 * 8 =        16 (overhead)+
BOOL:     2     +
DINT:     0 * 4 =         0 +
REAL:     0 * 4 =         0 +
TIME:     0 * 8 =         0 +
TOTAL:       18
-------------------------------------------------------
>> Backing up project to 'DEMO-LED_68_0_5b55e88b.DWLD'
```

log_superuser.txt

```
    + trlass -u -e LIBDBG.ERR -o LIBDBG.NCO LIBDBG.ASM
    + trlarch -e ~TRIARCH.ERR r Tx1libt.NCA LIBDBG.NCO
    + ...DEMO-LED : Project.EMA
    + iecarch -e ~IECARC.LST t Project.EMA
    + ...0000014f.EMO
    + iecarch -e ~IECARCH.ERR x Project.EMA 0000014f.EMO
    + trlncg -e 0000014f.ERR 0000014f.EMO 0000014f.ASM
    + trlass -u -e 0000014f.ERR -o 0000014f.NCO 0000014f.ASM
    + trlarch -e ~TRIARCH.ERR r Project.NCA 0000014f.NCO
    + trlarch -e ~TRIARCH.ERR d Project.NCA 0000014f.NCO
    + ...00000155.EMO
    + iecarch -e ~IECARCH.ERR x Project.EMA 00000155.EMO
    + trlncg -e 00000155.ERR 00000155.EMO 00000155.ASM
    + trlass -u -e 00000155.ERR -o 00000155.NCO 00000155.ASM
    + trlarch -e ~TRIARCH.ERR r Project.NCA 00000155.NCO
    + trlarch -e ~TRIARCH.ERR d Project.NCA 00000155.NCO
    + trlncg -e ~blink_led.ERR ~blink_led.EMO ~blink_led.ASM
    + trlass -u -e ~blink_led.ERR -o ~blink_led.NCO ~blink_led
   ++ Extracting code files...
    + ...ALARMS.EMA Copied from project
    + ...TCXLIB.EMA Copied from project
    + ...STDLIB.EMA Copied from project
    + ...TX1LIB.EMA Copied from project
    + ...Tx1libhm.emo Copied from project
    + ...Tx1libhp.nco Copied from project
    + ...Tx1libt.ema Copied from project
    + ...Tx1libtm.ema Copied from project
    + ...Tx1libtp.nca Copied from project
    + ...Tx1libt.NCA Copied from project
    + ...TX1LIB.NCA Copied from project
    + ...STDLIB.NCA Copied from project
    + ...TCXLIB.NCA Copied from project
    + ...ALARMS.NCA Copied from project
>> Assembling Libraries for Tricon...
 > Linking for Tricon...
    + trllnk -e Platform.ERR -t -x ~LNKAUX.SYM -p ~LNKSPEC.SYM
    + trlseg -e ~TR1SEG.ERR -o ~TR1SEG.OUT Platform.NCE
>> Validating symbols...
The estimated stack size is 532 bytes.
0 ERROR(s),  0 WARNING(s)

-------------------------------------------------------------
         Initialization Table Information
-------------------------------------------------------------
The total # of bytes in the current project are as follows:
          2 * 8 =        16 (overhead)+
BOOL:     2     +
DINT:     0 * 4 =         0 +
REAL:     0 * 4 =         0 +
TIME:     0 * 8 =         0 +
TOTAL:       18
```

*Figure 7 – The difference between the information available to a normal user (left) and the undocumented power user T****BD (right)*

The level of information available to this undocumented power user makes it significantly easier for threat actors to create malicious OT payloads. However, our research found no connection between the TRITON malware and this hidden menu, and the malware did not leverage these undocumented users.

It should be noted that these undocumented users exist for *TriStation 1131 v4.9.0* and earlier versions only, according to Schneider Electric.

3.6. Understanding the TriStation protocol

In accordance with the file descriptions, the code delegated to manage the network communication is located inside the DLL “tr1com.dll”. By analyzing this file, we extracted a wealth of information about the protocol’s definition that documents its behavior.

```
int __thiscall CAPLTricon::SendMessageA(CAPLTricon *this, int a2, unsigned __int8 *a3, int a4)
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  v4 = this;
  if ( *((_WORD *)this + 274) >= 1u )
  {
    v5 = sub_100053B0(a2);
    CAPLTricon::DisplayDebugMessage(v4, 1u, aReqS, v5);
  }
  v6 = *((_DWORD *)v4 + 150);
  ++*((_DWORD *)v4 + 151);
  if ( v6 == 2 )
  {
    v10 = 0;
    v11 = (char *)v4 + 1828;
    if ( a4 )
    {
      qmemcpy(v11, a3, a4);
      v10 = 0;
      *((_WORD *)v4 + 918) = a4;
    }
    else
    {
      *((_WORD *)v4 + 918) = 10;
    }
    *((_BYTE *)v4 + 1831) = *((_BYTE *)v4 + 595);
    v12 = *((_WORD *)v4 + 918);
    *((_BYTE *)v4 + 1830) = a2;
    v13 = v12;
    *((_WORD *)v4 + 916) = 0;
    *((_WORD *)v4 + 917) = 0;
    *v11 = 0;
    *((_BYTE *)v4 + 1829) = 0;
    if ( (signed int)v12 > 0 )
    {
      do
        v12 += (unsigned __int8)v11[v10++];
      while ( v10 < v13 );
    }
    *((_WORD *)v4 + 917) = v12;
    *((_BYTE *)v4 + 593) = 2;
    CAPLTricon::SetState(v4, stateRunning|statePaused);
    CAPLTricon::DumpMessage(v4, aSend, (CAPLTricon *)((char *)v4 + 1828));
```

Figure 8 - Decompiled code showing low-level packet management

3.7. Parsing the Triconex hardware definition

The *Low-Density* and *High-Density* chassis used by the Triconex hardware supports several different modules which are described inside a proprietary file called "*TR1HWDEF.HWD*". The malware does not contain any information related to the hardware definition, probably because the threat actors did not invest time to reverse engineer that part.

However, the definition file contains useful information for network traffic analysis that identifies which modules are attached to the remote Triconex hardware.

We invested time in reverse engineering, and successfully parsed the hardware information. The details are given in Appendix A – Triconex Hardware Definition List.

Figure 9 - Automatic parsing of the file that describes Triconex hardware information

We also added this parsing capability to our Wireshark dissector (see section 4.1), which thus provides information about deployed Triconex hardware modules.

3.8. TriStation protocol stack implementation

TriStation is not only the software suite used inside the engineering workstation. There is also a proprietary network protocol called “*TriStation Protocol*” operating on UDP/IP over port 1502.

The malware files related to TriStation implementation are found inside these files:

Filename	MD5	Compilation time
TsBase.pyc	288166952f934146be172f6353e9a1f5	2017-08-03 16:52:33
TsHi.pyc	27c69aa39024d21ea109cc9c9d944a04	2017-08-04 08:04:01
TsLow.pyc	f6b3a73c8c87506acda430671360ce15	2017-08-03 16:46:51
TS_cnames.pyc	e98f4f3505f05bf90e17554fbc97bba9	2017-08-03 12:26:36

All the protocol definitions are contained inside the Python-compiled file “*TS_cnames.pyc*” and can be easily decompiled and extracted as shown in the image below. The code contained in the file is a great explanation of the function codes implemented by the TriStation protocol, showing how deep the threat actors went during reverse engineering.

```
TS_cst = {1: 'CONNECT REQUEST',
    2: 'CONNECT REPLY',
    3: 'DISCONN REPLY',
    4: 'DISCONN REQUEST',
    5: 'COMMAND REPLY',
    6: 'PING',
    7: 'CONN LIMIT REACHED',
    8: 'NOT CONNECTED',
    9: 'MPS ARE DEAD',
    10: 'ACCESS DENIED',
    11: 'CONNECTION FAILED'
    }
TS_keystate = {0: 'STOP',
    1: 'PROG',
    2: 'RUN',
    3: 'REMOTE',
    4: 'INVALID'
    }
TS_progstate = {0: 'RUNNING',
    1: 'HALTED',
    2: 'PAUSED',
    3: 'EXCEPTION'
    }
```

Figure 10 - Part of TRITON’s Python code, showing TriStation protocol states

Combining the malware analysis with reverse engineering activity performed with the workstation software, we were able to deeply dissect the TriStation protocol. It allows for communications between engineering workstations (master) and Triconex controllers (slave), equipped with specific network modules (NCM).

Through our reverse engineering of the Triconex we were able to develop tools for helping industrial organizations and researchers understand SIS communications (section 3.6), and create and demonstrate a malicious TRITON payload (section 5).

4. Defending against TRITON: new tools to help

4.1. Wireshark dissector (LUA script) for TriStation protocol

During our analysis, we developed an extended Wireshark dissector using Lua script, called the ***TriStation Protocol Plug-in for Wireshark.*** [2]

It offers several useful features for engineers working with the TriStation protocol:

- Indication of the direction of communication
- Function codes translated as descriptive text
- Extraction of transmitted PLC programs
- Identification of connected hardware
- Detection of the TRITON malware in network communications
- […]

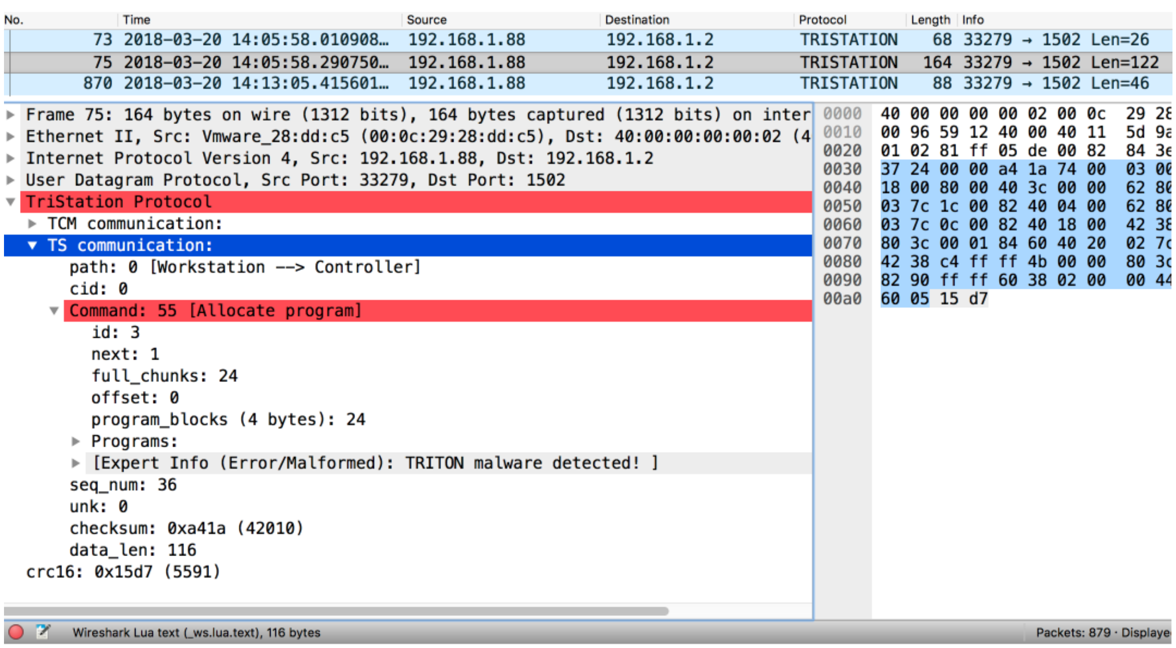


Figure 11 - The TriStation protocol plug-in for Wireshark detects a sample of TRITON during the injection phase

Our Wireshark dissector allows an ICS engineer to see useful information during a network packet inspection. This includes the direction of the packet and the name associated with the function code (also known as a "command"). It also easily parses the packets, extracting the PLC programs/functions downloaded to the Triconex devices, and presenting them in the Wireshark GUI.

Furthermore, the dissector automatically detects TRITON malware using specific indicators obtained during malware analysis performed in the laboratory. This feature was developed **only** with the purpose of demonstrating that it's possible to identify ICS malware on the network using passive techniques.

We strongly recommend that organizations do not depend on Wireshark for intrusion detection. If the threat actors change just one byte of the malware, it will not be detected. Instead, applications specifically designed for detecting ICS malware intrusion, which use multiple techniques for identifying irregularities, should be employed.

4.2. Triconex Honeypot Tool: simulating a real Triconex Controller

The extensive knowledge we gained during our analysis allowed us to develop a tool [2] that simulates a Triconex controller. This tool was created to help us during the deep inspection of specific packets related to how the hardware modules and the modules' LEDs information are encoded inside the packets.

The main goal was to create a script that simulates a Triconex controller and responds to the TriStation diagnostic software developed by Schneider Electric. This diagnostic tool can be used by an OT engineer to query a specific controller deployed in the field and obtain its information.

Using our script, we simulated the controller's behavior, convincing the diagnostic tool that we are a real controller sending its status, including:

- Controller version
- Controller status
- Controller memory
- Chassis type
- Connected modules
- Status LEDs
- LED type and color
- Hardware key position (RUN/STOP/PROGRAM)
- Project name
- Modules configuration match/mismatch (project ⇔ chassis)

Although the script is currently only a proof-of-concept, it can be expanded to support an extensive number of functions. Its realism can be increased to the point where it is indistinguishable from a real controller. In addition, the script can be executed by a regular, inexpensive computer attached to the network.

The ***Triconex Honeypot Tool*** can be used by defense teams to simulate SIS controllers with particular system configurations, using them like a honeypot [12] to detect reconnaissance scans and capture malicious payloads. It can therefore play a useful role in detecting unknown traffic targeting a SIS network.

5. Demonstrating a working malicious TRITON payload

5.1. TRITON's malicious payload was missing

TRITON gave the threat actor the ability to read, write and execute code directly inside the controller's memory. The main advantage of this architecture was its modularity, providing the attackers the means to dynamically send a specific payload inside the memory and execute it.

But this approach also assists the security analyst or researcher, as the malware itself exposes the basic capabilities for low-level interaction with the OT device.

In the case of TRITON, the final stage of the attack is missing [10]. Soon after the targeted Triconex was implanted with the malware, one of the main processors triggered a redundancy alarm. This forced all three main processors to start the safety shutdown process. It is unclear whether the issue was triggered by the dropper injecting the malware in memory, or by an unexpected fault generated while executing the OT payload.

The targeted version of the Triconex hardware is running a CPU based on the PowerPC architecture. During program updates, the code is sent directly in machine code. The malware author followed this technique, developing the ability to write and execute directly in the memory itself.

One of the more likely assumptions is that the attacker injected a specific OT payload containing an invalid memory access which resulted in a crash.

5.2. Demonstrating a working TRITON malicious payload

Figure 3 – Working Triconex infrastructure used to demonstrate successful TRITON OT infection

During our research we recreated a fully working Triconex infrastructure, including connecting a field device to the controller. We attached a compressor and a balloon, similar to the set-up first used to demonstrate the Stuxnet ICS malware. [11]

The program run by the controller supervises the compressor executing an inflating and deflating process in a specific, synchronized and ongoing way. Then we used the TRITON capabilities to inject a command that modified the behavior of the security supervisor, causing the balloon to overinflate and finally generate an explosion.

This achieved the final goal of our research, showing how we were able to use the knowledge we obtained through reverse engineering TRITON to compromise the safe functioning of the Triconex controller.

6. What TRITON means for securing Industrial Control Systems

Over the last twenty years it has become easier and easier for threat actors to launch ICS cyber attacks. More and more tools and examples are readily available, lowering the bar for the knowledge and skills needed by intruders.

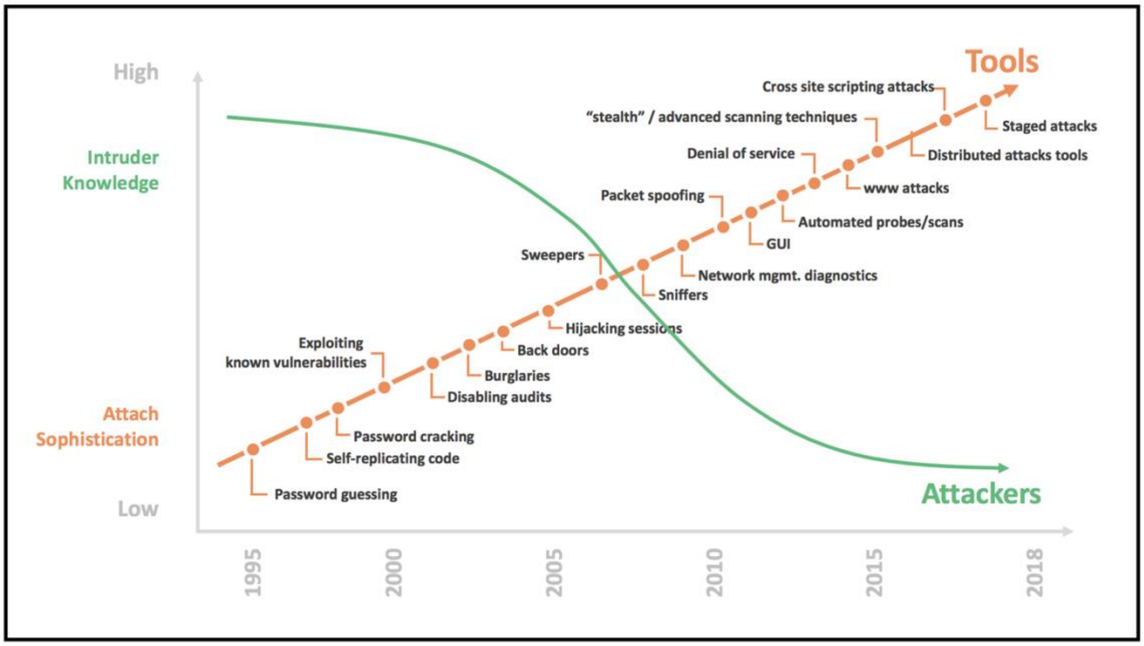


Figure 14 - Developing malware for ICS requires less skills today than it did in the past.

For example, before Stuxnet (2010), there were no example ICS malware frameworks available over the Internet. Now, there are many, including TRITON. Other things that have changed include:

- Global ecommerce platforms that make it easy to buy the documentation and equipment needed to recreate a SIS environment
- A rapid increase in the number of disclosed ICS vulnerabilities
- Shodan and similar search engines which make it easy to find Internet-connected ICS devices
- Increased connectivity with IT and Internet-based systems has greatly increased the attack surface

When we began our research, we were determined to understand TRITON and the resources it took to create it. This paper shows that the effort, skills and financial resources needed to create the TRITON malware framework, while not insignificant, are not that high – certainly not at the level where nation state-sponsored resources are required. While the level of difficulty of executing a cyber attack varies according to the cyber security defenses, networking architecture and equipment of each facility, the development of the malware itself does not require high levels of resources.

Knowing this, industrial asset owners should act immediately to monitor their SIS and secure them against external attacks. We also urge SIS equipment makers to provide more robust built-in security for these vitally important systems.

Appendix A – Triconex Hardware Definition List

1	3501/E/T/TN Discrete Input, 115 V, 32 points
2	3502/E/EN Discrete Input, 48 V, 32 points
3	3503/E/EN Discrete Input, 24 V, 32 points
7	3505/E/EN Discrete Input, 24 V, Low Threshold, 32 points
11	3508/E Discrete Input, 230 V, 32 points
17	3601/E/T/TN Discrete Output, 115 VAC, 16 points
19	3603/B/E/T/TN Discrete Output, 120 VDC, 16 points
20	3604/E/EN Discrete Output, 24 VDC, 16 points
23	3608/E Discrete Output, 48 VAC, 16 points
24	3607/E/EN Discrete Output, 48 VDC, 16 points
29	6603 Discrete Output, 24 VDC, 16 points
30	6602 Discrete Output, 48 VDC, 16 points
31	6601 Discrete Output, 115 VAC, 16 points
32	3701/N Analog Input, 10 V input, 32 points
33	3700/A/AN Analog Input, 5 V input, 32 points
38	3510/N Pulse Input, 8 points
40	3801 Analog I/O, 10 V inp, 4-20ma out, 8 inputs, 4 outputs
41	3800 Analog I/O, 5 V inp, 4-20ma out, 8 inputs, 4 outputs
42	6810 Analog Output, 4-20ma, 4 points; Pulse Input, 4 points
45	3511 Enhanced Pulse Input, 8 points
47	3515 Pulse Totalizer Input, 32 Data points, 32 Reset points
48	4119/A/AN EICM (Intelligent Communications Module)
49	420-/N,421-/N Remote Extender Module, Primary/Remote
50	6211 ICM (Intelligent Communications Module)
51	4509 Honeywell Data Highway Interface Module (HIM)
52	4409 Safety Manager Module
53	6215 Honeywell Data Highway Interface Module (HIM)"
54	GPSI Global Positioning System Interface
55	4329/N/G NCM (Network Communications Module)
56	4609/N ACM (Advanced Communications Module)
57	4351B TCM-B (Tricon Communication Module/B - Copper)

58	4352B TCM-B (Tricon Communication Module/B - Fiber)
59	4353 TCM/OPC (Tricon Communication Module OPC - Copper)
60	4354 TCM/OPC (Tricon Communication Module OPC - Fiber)
71	3531 Discrete Input (simplx), 115 V, 32 points
72	3532 Discrete Input (simplx), 48 V, 32 points
73	3533 Discrete Input (simplx), 24 V, 32 points
84	4351 TCM (Tricon Communications Module - Copper)
85	4352 TCM (Tricon Communications Module - Fiber)
86	4351A TCM-A (Tricon Communication Module/A - Copper)
87	4352A/N TCM-A (Tricon Communication Module/A - Fiber)
88	3664 Dual Discrete Output, 24 V, 32 points, Serial
89	3674 Dual Discrete Output, 24 V, 32 points, Fail-Safe
90	3667 Dual Discrete Output, 48 V, 32 points, Serial
91	3677 Dual Discrete Output, 48 V, 32 points, Parallel
92	3663 Dual Discrete Output, 120V, 32 points, Serial
93	3673 Dual Discrete Output, 120V, 32 points, Parallel
94	3720 Enh Analog Input, 5V, 64 points, Configurable
95	3721/N Enh Differential Analog Input, +/-5V, 32 points, Configurable
104	3805/E/H/EN Analog Output, 4-20ma, 8 points
105	3807 Servo Control Analog Output, -60 to +60mA
107	6613 Supv Disc Output, 24 V, 16 points
106	3806 Analog Output, 4-20ma (6 pts), 4-320ma (2 pts)
108	6612 Supv Disc Output, 48 V, 16 points
109	6617 Supv Disc Output, 120 V, 16 points
110	6703 Analog Input (isolated), 2 V, 16 points
111	3635/E Discrete Output (simplx), Relay Cntct, Norm clsd, 32 pts
112	3636/R/T/TN Discrete Output (simplx), Relay Cntct, Norm open, 32 pts
113	3611/E Supv Discrete Output, 115 VAC, 8 points
129	6507 Discrete Input, 120 VDC, 32 points
130	6502 Discrete Input, 48 VDC, 32 points
133	6503 Discrete Input, 24 VDC, 32 points
134	6501 Discrete Input, 115 VAC, 32 points

136	6508 Discrete Input, 48 VAC, 32 points
138	6708 Isol Thermocouple Input Type E dgC, 16 points
139	6708 Isol Thermocouple Input Type J dgC, 16 points
140	6708 Isol Thermocouple Input Type K dgC, 16 points"
141	6708 Isol Thermocouple Input Type T dgC, 16 points
146	3706/A/AN Non-Isol Thermocouple Input Type J dgF 32 points
147	3706/A/AN Non-Isol Thermocouple Input Type K dgF 32 points
148	3706/A/AN Non-Isol Thermocouple Input Type T dgF 32 points
149	3706/A/AN Non-Isol Thermocouple Input Type J dgC 32 points
150	3706/A/AN Non-Isol Thermocouple Input Type K dgC 32 points
151	3706/A/AN Non-Isol Thermocouple Input Type T dgC 32 points
152	3704/E/EN Analog Input, 5 V, DnS, 64 points
153	3704/E/EN Analog Input, 10 V, DnS, 64 points
154	3704/E/EN Analog Input, 5 V, UpS, 64 points
155	3704/E/EN Analog Input, 10 V, UpS, 64 points
156	3504/E/EN Discrete Input, 24 VDC, 64 points
157	3504/E/EN Discrete Input, 48 VDC, 64 points
158	3625/N Supervised Discrete Output, 24V, 32 points, Configurable
160	6700 Analog Input, 5 V, DnS, 32 points
161	6700 Analog Input, 10 V, DnS, 32 points
162	6700 Analog Input, 5 V, UpS, 32 points
163	6700 Analog Input, 10 V, UpS, 32 points
180	3703/E/EN Enh Isol Analog Input, 5 V, DnS, 16 points
181	3703/E/EN Enh Isol Analog Input, 10 V, DnS, 16 points
182	3703/E/EN 3Enh Isol Analog Input, 5 V, UpS, 16 points
183	3703/E/EN Enh Isol Analog Input, 10 V, UpS, 16 points
184	3708/E/EN Enh Isol Thermocouple Input Type J dgC DnS, 16 points
185	3708/E/EN Enh Isol Thermocouple Input Type K dgC DnS, 16 points
186	3708/E/EN Enh Isol Thermocouple Input Type T dgC DnS, 16 points
187	3708/E/EN Enh Isol Thermocouple Input Type E dgC DnS, 16 points
192	3708/E/EN Enh Isol Thermocouple Input Type J dgF DnS, 16 points
193	3708/E/EN Enh Isol Thermocouple Input Type K dgF DnS, 16 points

194	3708/E/EN Enh Isol Thermocouple Input Type T dgF DnS, 16 points
195	3708/E/EN Enh Isol Thermocouple Input Type E dgF DnS, 16 points
200	3708/E/EN Enh Isol Thermocouple Input Type J dgC UpS, 16 points
201	3708/E/EN Enh Isol Thermocouple Input Type K dgC UpS, 16 points
201	3708/E/EN Enh Isol Thermocouple Input Type T dgC UpS, 16 points
202	3708/E/EN Enh Isol Thermocouple Input Type E dgC UpS, 16 points
208	3708/E/EN Enh Isol Thermocouple Input Type J dgF UpS, 16 points
209	3708/E/EN Enh Isol Thermocouple Input Type K dgF UpS, 16 points
210	3708/E/EN Enh Isol Thermocouple Input Type T dgF UpS, 16 points"
211	3708/E/EN Enh Isol Thermocouple Input Type E dgF UpS, 16 points
216	3614/E Supv Discrete Output, 24 V, OFF STATE SCD, 8 points
217	3614/E Supv Discrete Output, 24 V, 8 points
218	3617/E Supv Discrete Output, 48 V, OFF STATE SCD, 8 points
219	3617/E Supv Discrete Output, 48 V, 8 points
220	3613/E Supv Discrete Output, 120 V, OFF STATE SCD, 8 points
221	3613/E Supv Discrete Output, 120 V, 8 points
222	3615/E Supv Disc Output, 24 V, OFF STATE SCD, Low Power, 8 points
223	3615/E Supv Disc Output, 24 V, Low Power, 8 points
224	3564 Single Discrete Input, 24 V, 64 points
225	3564 Single Discrete Input, 24 V, 64 points, Non-Critical
226	3562 Single Discrete Input, 48 V, 64 points
227	3562 Single Discrete Input, 48 V, 64 points, Non-Critical
228	3561 Single Discrete Input, 120V, 64 points
229	3561 Single Discrete Input, 120V, 64 points, Non-Critical
230	356X Single Discrete Input, 115V, 64 points
231	356X Single Discrete Input, 115V, 64 points, Non-Critical
232	3624/N Supervised Discrete Output, 24 V, 16 points
233	3624 Supervised Discrete Output, 24 V, 16 points, Non-Supervised
234	3627 Supervised Discrete Output, 48 V, 16 points
235	3627 Supervised Discrete Output, 48 V, 16 points, Non-Supervised
236	3623/T/TN Supervised Discrete Output, 120V, 16 points
237	3623 Supervised Discrete Output, 120V, 16 points, Non-Supervised

238	362X Supervised Discrete Output, 115V, 16 points
239	362X Supervised Discrete Output, 115V, 16 points, Non-Supervised
208	3708/E/EN Enh Isol Thermocouple Input Type J dgF UpS, 16 points
209	3708/E/EN Enh Isol Thermocouple Input Type K dgF UpS, 16 points
210	3708/E/EN Enh Isol Thermocouple Input Type T dgF UpS, 16 points"
211	3708/E/EN Enh Isol Thermocouple Input Type E dgF UpS, 16 points
216	3614/E Supv Discrete Output, 24 V, OFF STATE SCD, 8 points
217	3614/E Supv Discrete Output, 24 V, 8 points
218	3617/E Supv Discrete Output, 48 V, OFF STATE SCD, 8 points
219	3617/E Supv Discrete Output, 48 V, 8 points
220	3613/E Supv Discrete Output, 120 V, OFF STATE SCD, 8 points
221	3613/E Supv Discrete Output, 120 V, 8 points
222	3615/E Supv Disc Output, 24 V, OFF STATE SCD, Low Power, 8 points
223	3615/E Supv Disc Output, 24 V, Low Power, 8 points
224	3564 Single Discrete Input, 24 V, 64 points
225	3564 Single Discrete Input, 24 V, 64 points, Non-Critical
226	3562 Single Discrete Input, 48 V, 64 points
227	3562 Single Discrete Input, 48 V, 64 points, Non-Critical
228	3561 Single Discrete Input, 120V, 64 points
229	3561 Single Discrete Input, 120V, 64 points, Non-Critical
230	356X Single Discrete Input, 115V, 64 points
255	3008/N Tricon Enhanced Main Processor

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About Nozomi Networks

Nozomi Networks is the leader of industrial cyber security, delivering the best solution for real-time visibility to manage cyber risk and improve resilience for industrial operations. With one solution, customers gain advanced cyber security, improved operational reliability and easy IT/OT integration. Innovating the use of artificial intelligence, the company helps the largest industrial facilities around the world See and Secure™ their critical industrial control networks. Today Nozomi Networks supports over a quarter of a million devices in sectors such as critical infrastructure, energy, manufacturing, mining, transportation and utilities, making it possible to tackle escalating cyber risks to operational networks (OT).

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