ICS³Fuzzer: A Framework for Discovering Protocol Implementation Bugs in ICS Supervisory Software by Fuzzing

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Outline

• Background
• Fuzzing Supervisory Software
• Design
• Evaluation
• Conclusion
Background

- **Industrial Control Systems (ICS)**
  - ICSs are widely used in critical infrastructures (e.g., chemical industry, power grid, nuclear plant, etc.)
  - Integration of IT and OT — multiple layers

- **ICS trends: isolated -> openness**
  - Standardized solutions
  - More connections -> larger attack surface
  - Facing the rapidly growing threats from cyber-attacks
    - Stuxnet (2010)
    - Ukraine Blackout (2015)
    - TSMC Ransomware (2018)
    - ......
Background

• **Two targets in an ICS attack**
  – **Supervisory software**
    • Manage the physical devices, e.g., monitoring status, start/stop control, compile/download programs, etc.
    • E.g., management software such as Human Machine Interface (HMI), Engineering Software, and Configuration Software.
  – **Physical devices**
    • Directly interact with the physical world, e.g., accepting input from sensors, controlling on/off of switches, etc.
    • E.g., programmable Logic Controller (PLC), Remote Terminal Unit (RTU), and Programmable Automation Controller (PAC)

• **Existing research is geared towards embedded systems/devices; less has been studied on supervisory software**
Background

- Assumption – a powerful attacker who can ...
  - Access the inner network (e.g., via USB, insider attacker, etc.)
  - Monitor, intercept, and modify the network communication based on MITM attack
    - MITM attacks are commonly used in real-world ICS exploit, such as Stuxnet, IRONGATE.

- Consequences when the supervisory software is compromised
  - Present false data to the operator
  - Crash the supervisory software, making the control process out of monitor/control, real-time status cannot be updated
  - RCE by reusing existing control logic and existing authorizations

- We focus on identifying the protocol implementation flaws within supervisory software
Fuzzing Supervisory Software

- It is difficult to directly fuzz the commercial supervisory software
  - Bulky size of executables (closed binary) running on the Windows System
  - GUI-driven
  - Client-role in the communication
  - Proprietary protocol involved

- Existing solutions

<table>
<thead>
<tr>
<th>Study</th>
<th>closed binary</th>
<th>client-role</th>
<th>GUI-management</th>
<th>Proprietary-protocols?</th>
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Fuzzing Supervisory Software

- **Major challenge: the tightly coupled** of GUI and proprietary protocol implementation

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- **Writing a harness is extremely difficult**
  - Not general and requires many manual work
  - WINNIE supports writing harness within ONLY two components
  - Difficult to fuzz deep state-space of a proprietary protocol

- **Our approach:** we run and fuzz the whole supervisory software, with the synchronized controls of GUI operations and network communication
Idea

- **Example: protocol states involved in a function**
  - **Start:** click the button, and then the packet are exchanged in both directions
  - **Middle:** additional button-pushing operations
  - **End:** Periodically exchanging heartbeat message or stopping the message exchanges.

- **Input state≈protocol state**
  - An input state is determined by the previous button-pushing operations and the previous input states.
Design Challenges

• **C1**: How to enter a specific input state
  - Each input state is reachable and testable

• **C2**: Unknown message frame format and state-space in proprietary protocols
  - Producing effective inputs and fuzzing valuable input states with higher priority

• **C3**: Real device involved
  - Simulate the session of proprietary protocol to making the fuzzing process scalable
Design Overview

• **Two phases**
  - Pre-processing phase
    ✓ functionality analysis
    ✓ Proprietary protocol analysis
  - Fuzzing phase — Fully automated
    ✓ State selection
    ✓ Input generation
    ✓ Data Feeding
    ✓ Crash monitor

• **Design choice: blackbox vs greybox**
  - We support both
  - However, instrumenting bulky GUI-driven executables incurs huge overhead (~30X)
Functionality analysis

- **Identify UI triggers of functionality**
  - Find GUI operations that lead to the network events
  - Capture the corresponding messages

- **Prepare the GUI operation triggers**
  - Record the GUI operation orders
  - Preparing the UI elements triggers (guiautolitos)
Proprietary Protocol analysis

- **Infer Protocol Formats** – generate effective inputs
  - Leveraging an existing tool Netzob

- **Obtain State-space** – switch more valuable input states
  - Identify and distinguish input states
  - Filter repeated behaviors (e.g., the input states related to the heartbeat messages)
  - Each input state is distinguished/measured by
    - origin message
    - input index
    - the corresponding execution trace (based on DynamoRIO framework)

- **Device Emulation** – make fuzzing more scalable
  - The Fuzzer needs to act as a PLC device role to feed the test cases
  - For each request from the supervisory software, simulating a response needs to
    - Identify the corresponding response message in the captured traffic
    - Adjust the dynamic field such as session ID, sequence number, etc
State Selection

- Select the most promising input state to fuzz against
  - "deeper" network communication
  - More basic block executed under the state
  - More complex the input

- Calculate a weight for each state
  - depth: message index in an interaction
  - bb_cnt: execution trace when handling a packet
  - fld_cnt: the count of reverse-engineered field in a message (to represent the complexity of the input)

\[
w_i = \frac{1}{N} \left( \frac{\text{depth}_i}{\sum_{j=0}^{N-1} \text{depth}_j} + \frac{\text{bb}_\text{cnt}_i}{\sum_{j=0}^{N-1} \text{bb}_\text{cnt}_j} + \frac{\text{fld}_\text{cnt}_i}{\sum_{j=0}^{N-1} \text{fld}_\text{cnt}_j} \right)
\]

Algorithm 1 State-selection based fuzzing loop

Input: Limited state count for a functionality, \(N\)
Limited test case for a specific input state, \(M\)
State book of a functionality, \(S\)

Output: Crashes Record, \(C\)

1. \(\text{states} \leftarrow \text{FILTERED}(S)\)
2. \(\text{weights} \leftarrow \text{GETWEIGHTS}(\text{states})\)
3. \(\text{for } i \leftarrow 0; i < N; i++ \text{ do}\)
4. \(\text{cur}\_\text{state} \leftarrow \text{CHOOSE}(\text{states}, \text{weights})\)
5. \(j \leftarrow 0\)
6. \(\text{while } j < M \text{ do}\)
7. \(\text{mutated}\_\text{input} \leftarrow \text{GENERATE}(\text{cur}\_\text{state})\)
8. \(\text{result} \leftarrow \text{RUN}(\text{cur}\_\text{state}, \text{mutated}\_\text{input})\)
9. \(\text{if IsCRASH}\_\text{hit}(\text{result}) \text{ then}\)
10. \(\text{item} \leftarrow \text{TUPLE}(\text{cur}\_\text{state}, \text{mutated}\_\text{input})\)
11. \(\text{C} \leftarrow \text{APPEND}(\text{C}, \text{item})\)
12. \(\text{end if}\)
13. \(j \leftarrow j + 1\)
14. \(\text{end while}\)
15. \(\text{return } \text{C}\)
Input Feeding

- **Data Feeding**
  - Two proxies: GUI proxy and Traffic proxy
  - A dispatcher commands the two proxies
Crash Monitor

- Check the Eventlog after feeding the testcase
  - We do not consider liveness of the connection as an indicator, because the normal communication could close the connection
  - Once an application crashes, a record will be added in the Eventlog of Windows System with a tag “Application Error”

- Program hangs
  - They are not considered as a bug, because whether a long delay should be considered as a bug or not depends on specific scenarios
  - There is no standard to specify the cutoff value to separate a normal response and a delayed response
  - Record the hangs can be easily enabled in the current prototype
Evaluation - Effectiveness

• Four targets

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Software</th>
<th>Version</th>
<th>Image Size</th>
<th>Device</th>
<th>Proprietary Protocol? (Yes, No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitsubishi</td>
<td>GX Works2</td>
<td>1.591</td>
<td>671M</td>
<td>Q06UDEHCPU</td>
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<tr>
<td>Emerson</td>
<td>Proficy Machine Edition</td>
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<td>1200M</td>
<td>GE RX 7i</td>
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<tr>
<td>Schneider</td>
<td>TwidoSuite</td>
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<td>79M</td>
<td>TWDLCAE40DRF</td>
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<td>Panasonic</td>
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<td>2.95</td>
<td>106M</td>
<td>FP-X C60R</td>
<td>Yes</td>
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</table>

• Bug identified
  - 13 0-day bugs and got 3 CVEs
  - Among them, 2 bugs are “CRITICAL” (high risk, basic score is 9.8) and 40 different products are affected

<table>
<thead>
<tr>
<th>Software</th>
<th>Vulnerability Type</th>
<th>Number</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>GX Works2</td>
<td>HeapOverflow</td>
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<tr>
<td></td>
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<td>Proficy Machine Edition</td>
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<tr>
<td></td>
<td>Unknown crash</td>
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<td></td>
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<tr>
<td>TwidoSuite</td>
<td>Unknown crash</td>
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<tr>
<td>FPWIN GR</td>
<td>Unknown crash</td>
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</table>
Evaluation - Effectiveness

• Effectiveness of pruning input states

<table>
<thead>
<tr>
<th>Software</th>
<th># Selected session</th>
<th># Origin states</th>
<th># Post-pruned states</th>
</tr>
</thead>
<tbody>
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<td>GX Works2</td>
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<td>326</td>
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<td>Proficy Machine Edition</td>
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<tr>
<td>TOTAL</td>
<td>22</td>
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</table>

• Effectiveness of state selection
  – There is no fuzzer designed for testing supervisory software
  – We reused the same fuzzing framework and use a random strategy to select a input state during fuzzing
  – ICS3Fuzzer can find 5 more bugs
Evaluation - Performance

• Time-cost breakdown (mainly composed of four parts)
  – Restarting the supervisory software
  – Operating the GUI
  – Network communication
  – The others

<table>
<thead>
<tr>
<th>Software</th>
<th>Launch</th>
<th>GUI Operations</th>
<th>Network Communication</th>
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<td>6.765</td>
<td>0.592</td>
<td>5.444</td>
<td>2.157</td>
</tr>
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</table>

• Why not use feedback-based method?
  – It needs 34.9s to restart the instrumented GX Works2 and the number is 1.1s without instrumentation
  – 48hours can only generate 4.5K testcases, it is hard for the genetic algorithm to make progress
  – Most of the test cases (more than 95%) cannot make through the initial input state

• Why not use snapshot-based method?
  – Snapshot/rollback of a complete Windows system is very slow, and it almost costs 32 seconds for a test case
  – The connection is easy to be closed due to slow network recovery, and it is hard to feed the testcase
Conclusions

• **Contribution**
  – We designed and implemented ICS3Fuzzer, which is an insecurity testing framework specific for the supervisory software in ICS
  – We propose a new fuzzing strategy, which selects input states based on execution trace and corresponding inputs
  – Our tool found 13 real world bugs and received 3 CVEs, 2 of them are classified as critical, 40 different products are affected

• **Feature work**
  – Feedback-based method can be improved in terms of high fuzzing speed (e.g., via parallelization)
  – Better protocol state management mechanisms can be proposed
Thank you!

Q&A