# ICS$^3$Fuzzer: A Framework for Discovering Protocol Implementation Bugs in ICS Supervisory Software by Fuzzing

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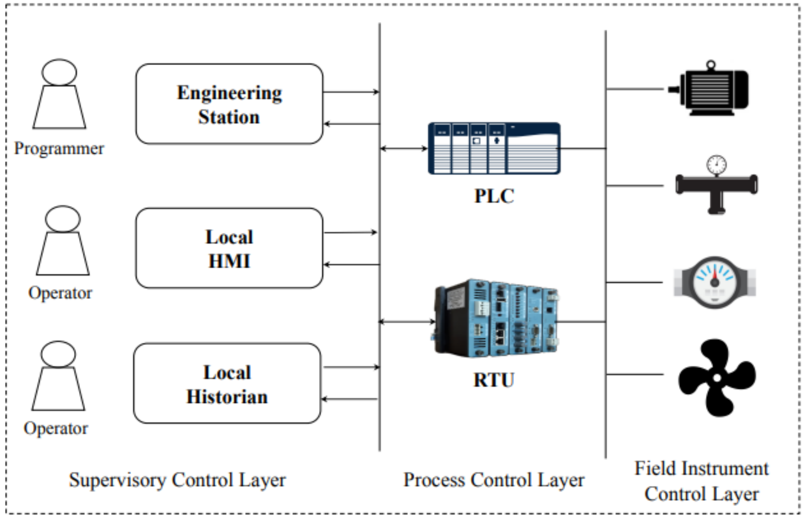
# Outline

- Background
- Fuzzing Supervisory Software
- Design
- Evaluation
- Conclusion

# Background

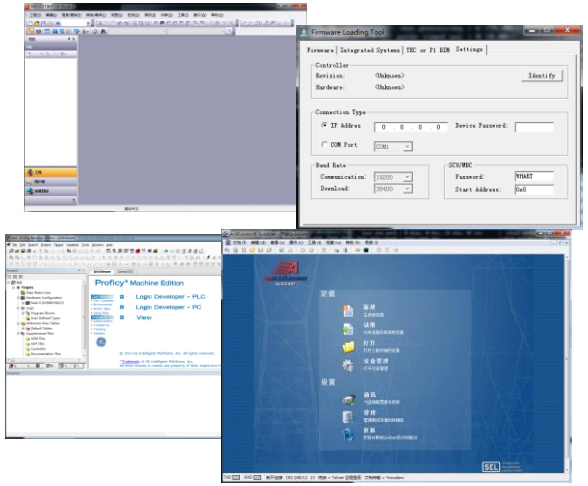
- **Industrial Control Systems (ICS)**
  - ICSs are widely used in critical infrastructures (e.g., chemical industry, power grid, nuclear plant, etc.)
  - Integration of IT and OT — multiple layers




- **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**

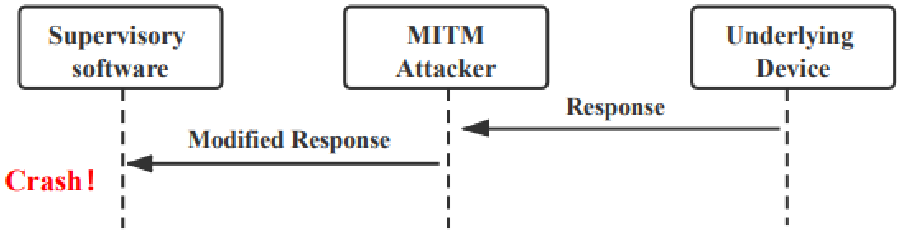



Figure 2: Crashing the supervisory software

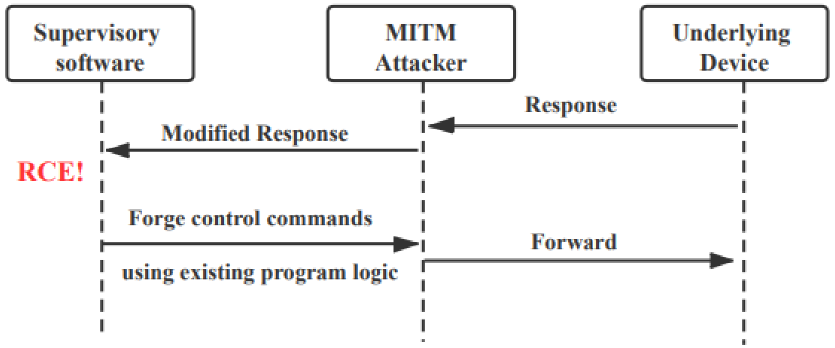



Figure 3: Forging malicious commands with RCE

# 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**

| Study | closed binary | client-role | GUI-management | Proprietary-protocols? |
|---|---|---|---|---|
| AFLNet [35] | ✗ | ✗ | ✗ | ✗ |
| PripFuzz [32] | ✓ | ✗ | ✗ | ✓ |
| Pulsar [15] | ✓ | ✓ | ✗ | ✓ |
| Polar [25] | ✗ | ✗ | ✗ | ✗ |
| Peach* [26] | ✗ | ✗ | ✗ | ✗ |
| Kif [1] | ✓ | ✗ | ✗ | ✓ |
| Achilles [41] | ✓ | ✗ | ✗ | ✗ |

# Fuzzing Supervisory Software

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

| Study | closed binary | client-role | GUI-management | Proprietary-protocols? |
|---|---|---|---|---|
| AFLNet [35] | ✗ | ✗ | ✗ | ✗ |
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| Kif [1] | ✓ | ✗ | ✗ | ✓ |
| Achilles [41] | ✓ | ✗ | ✗ | ✗ |

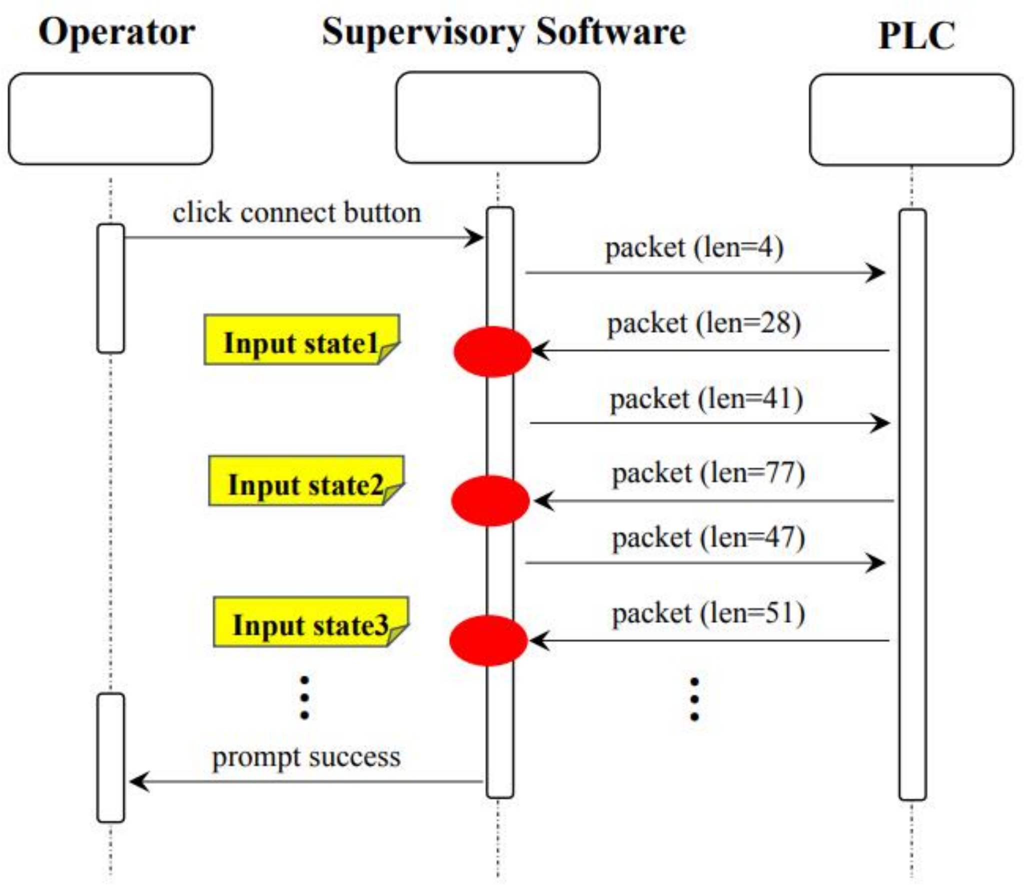
- **Writing a harness is extremely difficult**
  - Not general and requires many manual work
  - WINNIE supports writing harness within ONLY two components
  - Difficult to fuzz deep state-space of a proprietary protocol

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

# Idea

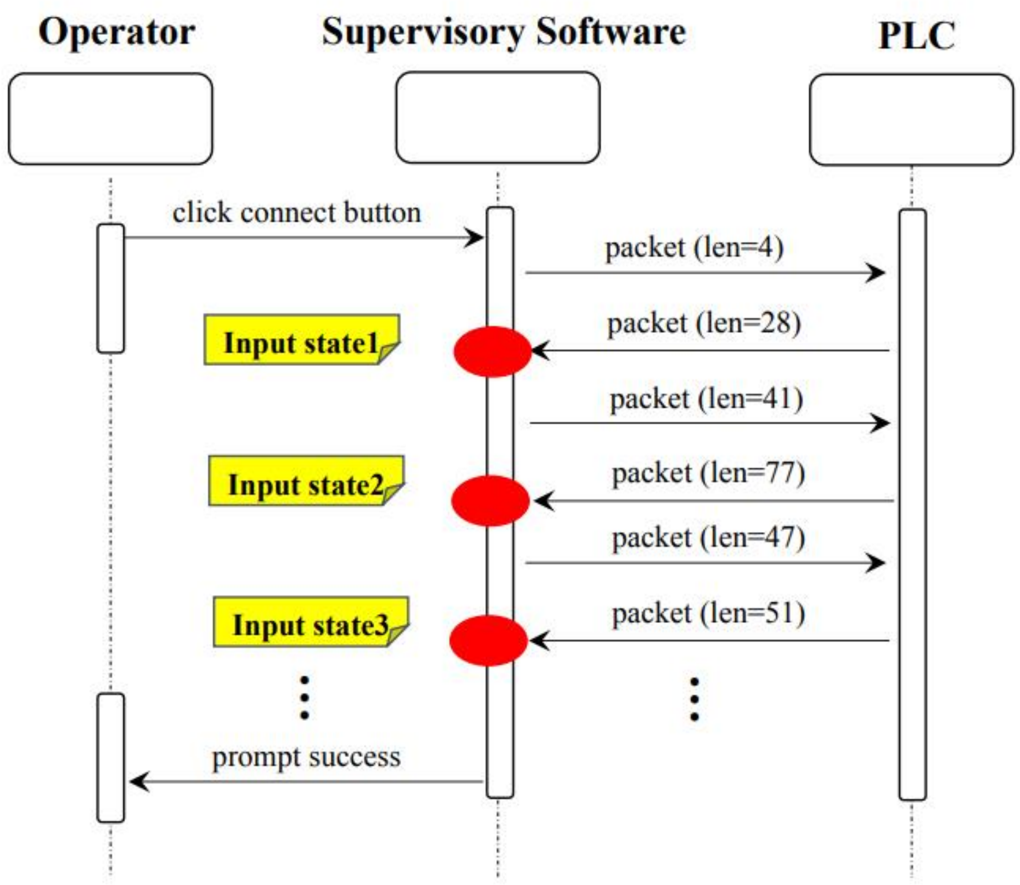
- **Example: protocol states involved in a function**
  - **Start:** click the button, and then the packet are exchanged in both directions
  - **Middle:** additional button-pushing operations
  - **End:** Periodically exchanging heartbeat message or stopping the message exchanges.

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



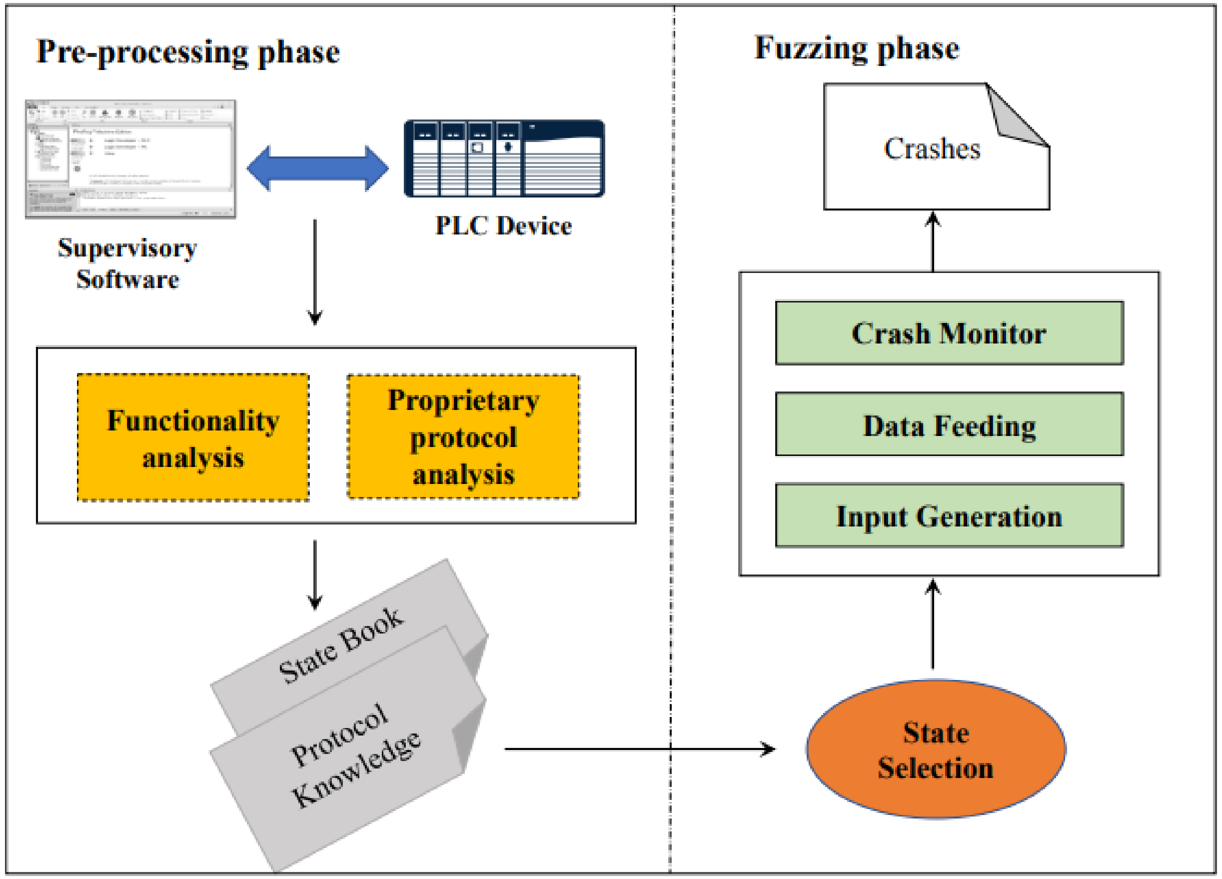
# Design Challenges

- **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

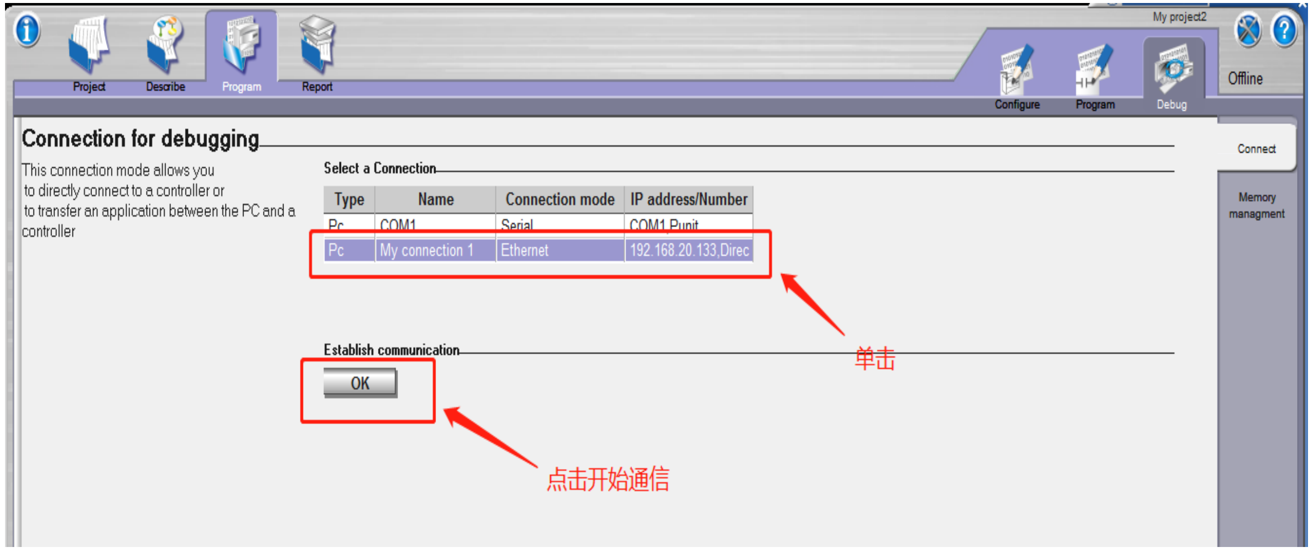
- **Two phases**
  - Pre-processing phase
    - ✓ functionality analysis
    - ✓ Proprietary protocol analysis
  - Fuzzing phase — Fully automated
    - ✓ State selection
    - ✓ Input generation
    - ✓ Data Feeding
    - ✓ Crash monitor
- **Design choice: blackbox vs greybox**
  - We support both
  - 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 (guiautolits)




```
Local $choose_windw = WinWaitActive("TwidoSuite","", 1)
If $choose_windw Then
    ControlClick("[TITLE:TwidoSuite;CLASS:#32770]","CAS_Button", "Button212")
EndIf
Sleep(800)
ControlClick("[TITLE:TwidoSuite;CLASS:#32770]","CAS_Button", "Button212")
ControlClick("[TITLE:TwidoSuite;CLASS:#32770]","CAS_Button", "Button16")

ControlClick("[TITLE:TwidoSuite;CLASS:#32770]","CAS_Button", "Button22")
; choose project
Local $bPos = WinGetPos("TwidoSuit", "")
Local $bx = $bPos[0] + 68 + 33
Local $by = $bPos[1] + 415 + 50
MouseClick($MOUSE_CLICK_LEFT, $bx, $by, 1, 1)
ControlClick("[TITLE:TwidoSuite;CLASS:#32770]","CAS_Button", "Button25")
Sleep(300)
ControlClick("[TITLE:TwidoSuite;CLASS:#32770]","CAS_Button", "Button680")
ControlClick("[TITLE:TwidoSuite;CLASS:#32770]","CAS_Button", "Button692")
```

# 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)

$$w_i = \frac{1}{3}\left(\frac{depth_i}{\sum_{j=0}^{N-1} depth_j} + \frac{bb\_cnt_i}{\sum_{j=0}^{N-1} bb\_cnt_j} + \frac{fld\_cnt\_i}{\sum_{j=0}^{N-1} fld\_cnt\_j}\right)$$

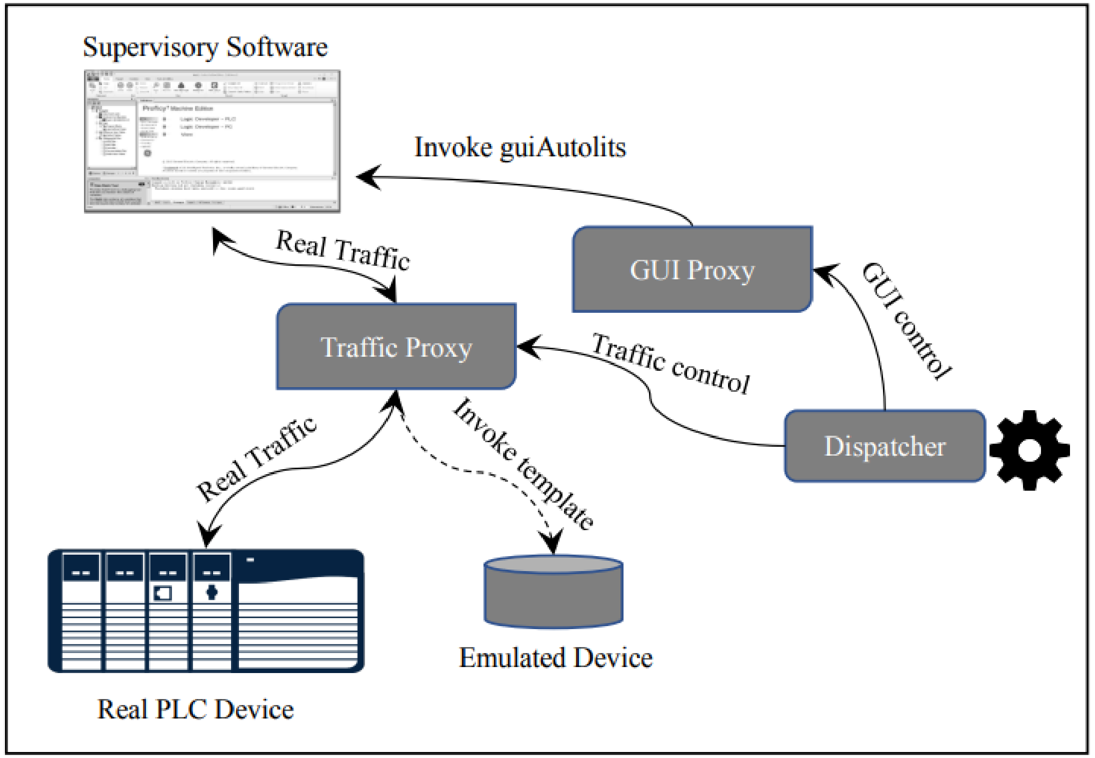
**Algorithm 1** State-selection based fuzzing loop

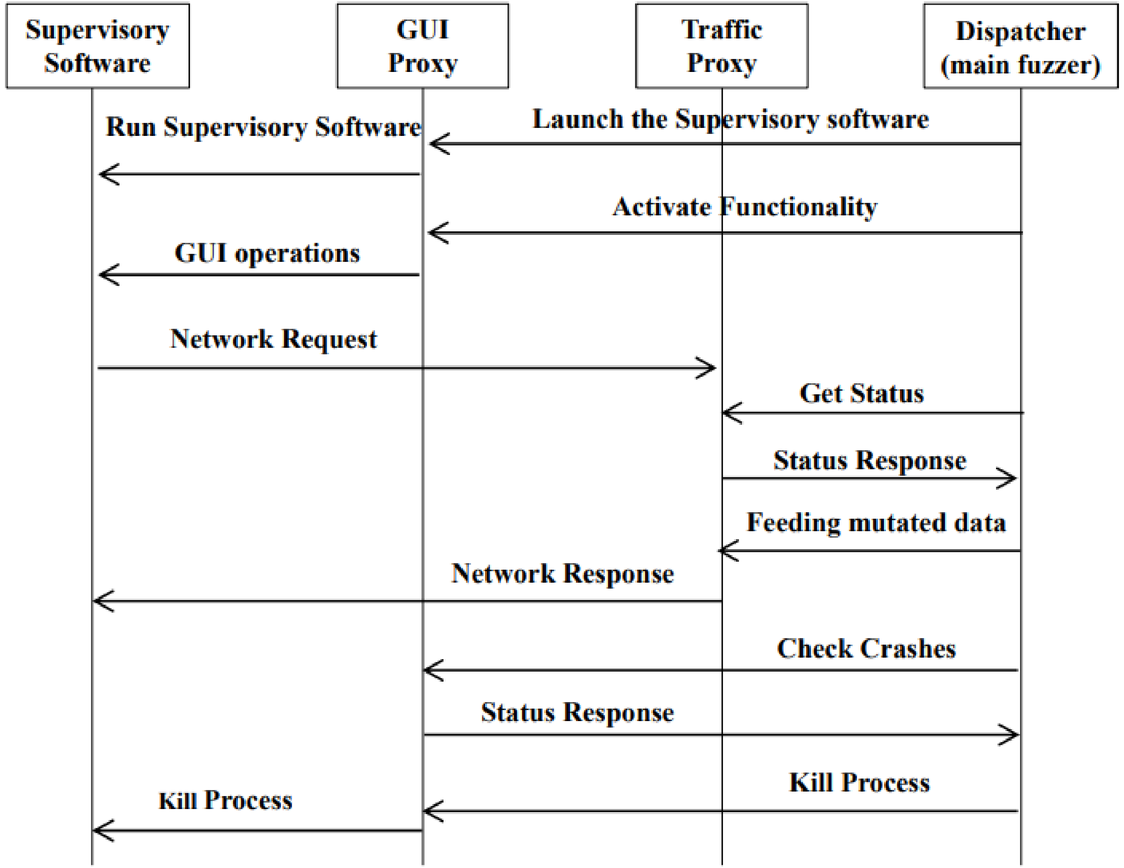
**Input:** Limited state count for a functionality, $N$
Limited test case for a specific input state, $M$
State book of a functionality, $S$
**Output:** Crashes Record, $C$

```
states ← FILTERED(S)
weights ← GETWEIGHTS(states)
for i ← 0; i < N; i++ do
  cur_state ← CHOOSE(states, weights)
  j ← 0
  while j < M do
    mutated_input ← GENERATE(cur_state)
    result ← RUN(cur_state, mutated_input)
    if IsCrash(result) then
      item ← TUPLE(cur_state, mutated_input)
      C ← APPEND(C, item)
    end if
    j ← j + 1
  end while
end for
return C
```

# Input Feeding

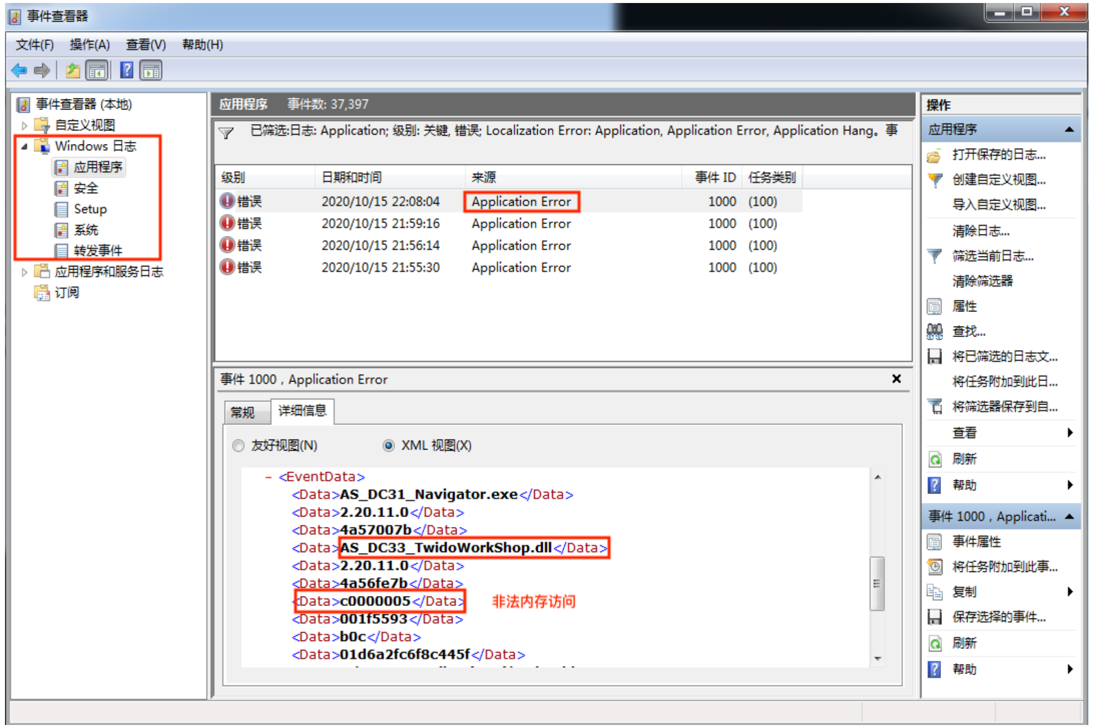
- **Data Feeding**
  - Two proxies: GUI proxy and Traffic proxy
  - A dispatcher commands the two proxies



# 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**

| Vendor | Software | Version | Image Size | Device | Proprietary Protocol? (Yes,No) |
|---|---|---|---|---|---|
| Mitsubishi | GX Works2 | 1.591 | 671M | Q06UDEHCPU | Yes |
| Emerson | Proficy Machine Edition | 9.0 | 1200M | GE RX 7i | Yes |
| Schneider | TwidoSuite | 2.20.11 | 79M | TWDLCAE40DRF | Yes |
| Panasonic | FPWIN GR | 2.95 | 106M | FP-X C60R | Yes |

- **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

| Software | Vulnerability Type | Number | status |
|---|---|---|---|
| GX Works2 | HeapOverflow<br>Unknown crash | 6<br>1 | confirmed |
| Proficy Machine Edition | NullPointer Dereference<br>Unknown crash | 1<br>3 | confirmed |
| TwidoSuit | Unknown crash | 1 | confirmed |
| FPWIN GR | Unknown crash | 1 | confirmed |

# Evaluation - Effectiveness

- **Effectiveness of pruning input states**

| Software | # Selected session | # Origin states | # Post-pruned states |
|---|---|---|---|
| GX Works2 | 8 | 326 | 93 |
| Proficy Machine Edition | 8 | 842 | 52 |
| TwidoSuit | 2 | 136 | 27 |
| FPWIN GR | 4 | 200 | 31 |
| TOTAL | 22 | 1504 | 203 |

- **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

| Software | Launch | GUI Operations | Network Communication | others |
|---|---|---|---|---|
| GX Works2 | 1.095 | 2.363 | 1.850 | 3.415 |
| Proficy Machine Edition | 4.115 | 4.349 | 9.374 | 5.356 |
| FPWIN GR | 1.114 | 0.361 | 1.274 | 2.371 |
| TwidoSuite | 6.765 | 0.592 | 5.444 | 2.157 |

- **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

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