DoS Exploitation of Allen-Bradley's Legacy Protocol through Fuzz Testing*

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Introduction

- EtherNet/IP is a TCP/IP-based industrial protocol commonly used in industrial control systems (ICS)
- Using a custom Scapy-based fuzzer, we uncover a previously unreported denial-of-service (DoS) vulnerability in the Ethernet/IP implementation of the Rockwell Automation/Allen-Bradley MicroLogix 1100 PLC
- ICS-CERT recently announces this vulnerability in the security advisory ICSA-17-138-03

Introduction

- Modern industrial network protocols have evolved from serial-based fieldbus protocols to TCP/IP-based protocols that are transported over standard Ethernet links
- Common Industrial Protocol (CIP) [21] and Ethernet/Industrial Protocol (EtherNet/IP) [22] are two well-known Open DeviceNet Vendors Association (ODVA) TCP/IP-based industrial protocols used by large number of industrial automation vendors
- Rockwell Automation/Allen-Bradley (RA/AB) PLCs (e.g., ControlLogix and MicroLogix) implement these protocols

Introduction

- Fuzz testing, or fuzzing, is a penetration testing technique to verify the robustness of target software in handling invalid, malformed, or unexpected input data
- Fuzzing the implementations of control network protocols is an important step towards developing more secure industrial control systems
- Little information has been made publicly available on the vulnerabilities of the EtherNet/IP software used in commercial PLCs
- To examine the robustness of the EtherNet/IP implemenation of select RA/AB devices, we create a fuzz testing tool (ENIP Fuzz) using Scapy, a Python module used for packet parsing and crafting [19]

Introduction

- A Scapy-based fuzzer for exploiting EtherNet/IP security vulnerabilities
- Remote fault detection strategy
- Deficiency in MicroLogix's handling of the Programmable Controller Communication Commands (PCCC) protocol
- Preliminary exploration of potential cross-generational vulnerabilities

EtherNet/IP Protocols

Common Industrial Protocol (CIP)

- `objects`: particular component within a product
- `class`: a set of objects of the same component
- `object instance`: actual representation of particular object
- `instance`: class or object share same attributes, but has own unique values [21]

EtherNet/IP

- Allow CIP communications to be transported over standard Ethernet
- TCP and UDP over port 44818
- Implicit messaging enables exchange of scheduled, time-critical control data [22]
- Explicit messaging provides general request reply/reply communication [22]

EtherNet/IP Protocols

Programmable Controller Communication Commands (PCCC)

- Provides legacy support for older RA/AB PLCs, e.g., PLC5 and SLC500 [7]
- Used with EtherNet/IP, encapsulated in CIP
- Encapsulation is accomplished through "Execute_PCCC" CIP service (service code = 0x4B)
- Each message contains command code and function code

Fuzzing Methodologies

Mutation-based fuzzers

- Apply transformations (mutations) on existing data samples to create test cases
- Brute force testing

Generation-based fuzzers

- Test cases employ rules defining a grammar-based specification for inputs
- Requires up-front understanding of specification or source code

ICS Protocol Fuzzers

Name	Type	Protocol	Availability
Aegis Fuzzer [2, 3]	custom	DNP3, Modbus	commercially licensed, early version open-source
Beyond Security's beSTORM [5]	framework	several, including DNP3	commercially licensed
blackPeer [10]	framework	several, including Modbus	NA
Codenomicon's Defensics [11]	framework	several, including CIP, EtherNet/IP, Modbus, OPC UA Server, Profinet, Scada GOOSE	commercially licensed
ICCP Fuzzer [13]	custom	ICCP	NA
LZFuzz [9]	framework	several, including SNMP [20]	NA
MTF [25]	custom	Modbus	NA
OPC-MFuzzer [26]	custom	OPC, DCOM, RPC [18]	NA
OPC Server Fuzzer [15]	custom	OPC Server	NA
Peach [16]	framework	several, including Modbus, BACNet, DNP3, OPC [16, 26]	open-source
ProFuzz [14]	custom	Profinet	open-source
scada-tools [24, 23]	custom	Profinet	open-source
Sulley [17]	framework	several, including Modbus, DNP3, TPKT, COPT [12]	open-source
Wuldtech's Achilles [1]	custom	several, including EtherNet/IP, Foundation Fieldbus, MMS, Modbus, OPC UA, Profinet, DNP3, MMS, SES-92	commercially licensed

Design and Implementation

Fuzzers operate under two basic assumptions:

- Faults in a target application can be triggered through input controlled by the user
- The execution of a faulty portion of an application will result in some behavioral manifestation (e.g., bricking the device or producing unexpected output)

Implementation of Support Library

- Library uses Scapy, a Python module used for packet crafting and manipulation
- Library conforms to EtherNet/IP specifications [22, 21]
- ENIP Fuzz is complete in its support of EtherNet/IP and one fourth of CIP specification
- EtherNet/IP traffic characterized from ICS lab environment, which included the AB/RA MicroLogix 1100 and ControlLogix 5570

Implementation of Fuzzer

EtherNet/IP Register Session Request

- Used for establishing a session between an originator and a target
- Originator sends Register Session Request on port 0xAF12, the target shall assign and reply with a Session Handle [22]

CIP NOP Request

- CIP common service request that generates a No Operation Response [21, §A-4.17]
- Receiver does not execute any other internal action

Implementation of Fuzzer

Execute PCCC Service

- PCCC is a vendor specific application layer protocol used for communication between certain RA/AB processors
- Used primarily to "ease communication between legacy networks and the new CIP networks" [6, p. 7.17]
- The Protected Typed Logical Read with Three Address Fields command is the specific Execute PCCC Service function chosen for fuzzing; function is used to read data from a logical address [6, p. 7.17].

Fault Monitoring

Liveness Check

- Remote analysis to determine crashes occurred
- TCP RST Flag for indicating target device has crashed [20]
- Socket timeout, reset, or close; failure in reopening a closed socket; and failure in opening a new socket [25]

Unexpected responses

- Filter for responses outside of specification

Performance degradation

- Malformed packets impacting timely delivery of responses may be considered soft failure
- Records captured during fuzzing are compared to baseline and analyzed for irregularities in response times

Test Environment

SUT

- MicroLogix 1100

Fuzzer

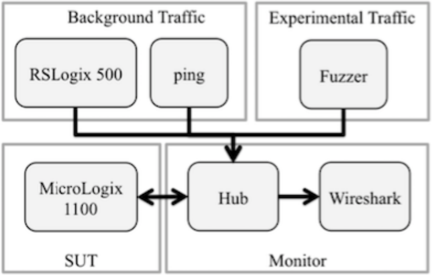
- Kali 2.0 VM with the fuzzer

Background traffic generators

- Windows 7 Virtual Machine with RSLinx
- Kali 2.0 VM with the Ping Utility

Monitor

- Mac OS X running Wireshark



Experimentation

- A liveness check is performed using the Ping utility to determine that the target is still responsive
- Monitor the latency in responses to both ICMP Echo requests and EtherNet/IP requests made by the RSLinx
- SUT is also monitored for unexpected responses, i.e., responses outside the EtherNet/IP specification or otherwise incorrect (e.g., responses that contain erroneous data).

Results and Analysis

- Three metrics were used for analysis: the deltas between ICMP Echo requests from Ping, List Identity requests from RSLinx, and the response from the service request being fuzzed
- SUT interacts with the traffic generators during "warm-up period," fuzzer sends either correctly formed packets (during baseline) or malformed packets (during testing) for a period of approximately 20 minutes
- Wireshark packet capture of the fuzzing session is then truncated into a 10 minute window, after which each of the metrics is analyzed
- Each delta is calculated by taking the difference between the timestamp of the response and the request.

Results and Analysis

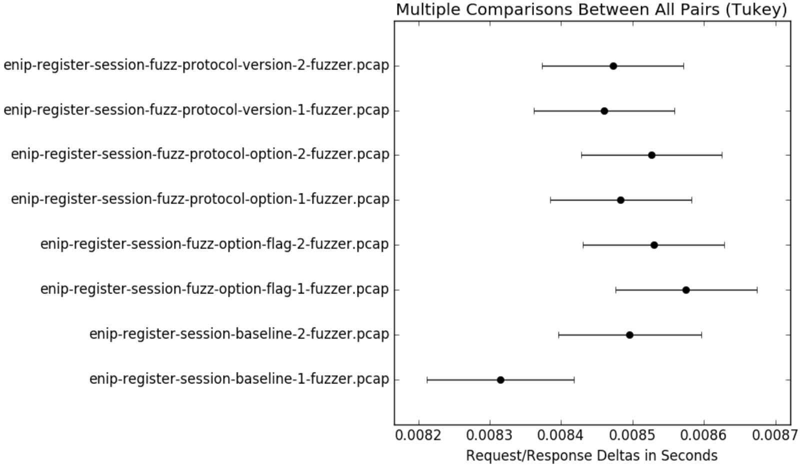
- Three baseline measurements and fourteen trials were performed
- Each baseline and trial was repeated twice

Trial Name	Field Fuzzed
enip-register-session-baseline	NA
enip-register-session-fuzz-protocol-version	Version
enip-register-session-fuzz-option-flag	Options
enip-register-session-fuzz-protocol-option	Version,Options
cip-nop-baseline	NA
cip-nop-fuzz-class	Class
cip-nop-fuzz-instance	Instance
cip-nop-fuzz-class-instance	Class,Instance
pccc-exec-baseline	NA
pccc-exec-fuzz-byte	Byte Size
pccc-exec-fuzz-file-no	File Number
pccc-exec-fuzz-file-type	File Type
pccc-exec-fuzz-element	Element No.
pccc-exec-fuzz-all	File No., File Type, Element No.

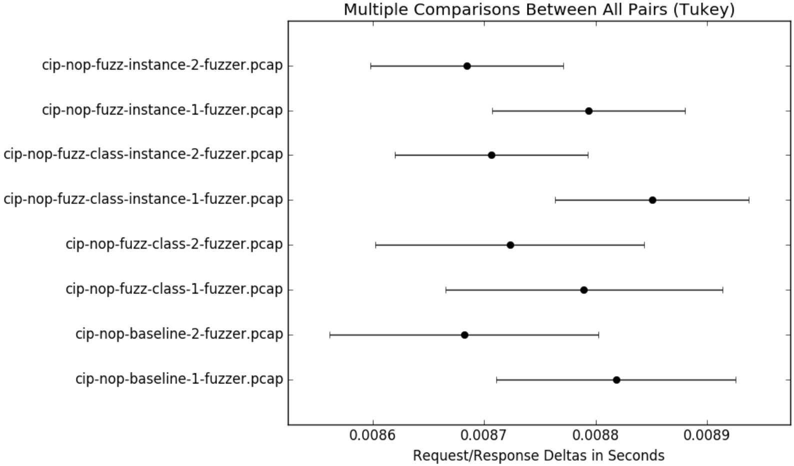
Response Time Analysis

- Deltas in response times from ICMP Echo requests and List Identity requests may not be meaningful metrics
- Using Tukey's Honest Significant Difference (HSD) test there is no significant difference in response times when fuzzing compared to when sending non-malformed traffic

Response Time Analysis



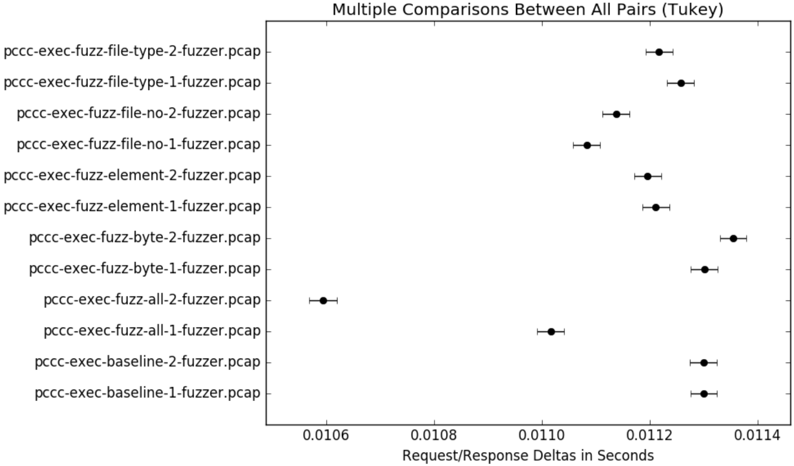
Response Time Analysis



Response Time Analysis

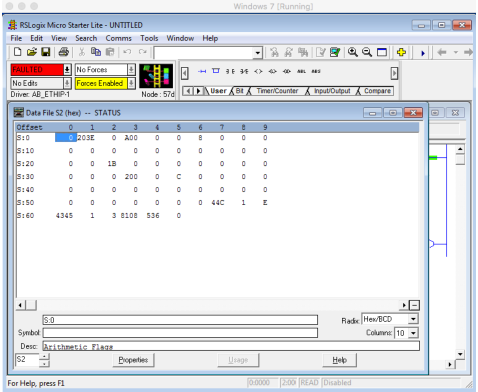
- Tests against Execute PCCC Service shows some sensitivity with performance metrics
- More testing warranted to claim fuzzed inputs were responsible for performance degradation

Response Time Analysis



Denial-of-Service Fault

- When fuzzing the Execute PCCC Service, we discover a previously unreported DoS vulnerability
- To clear fault, device must be power-cycled and reset using RSLogix Clear Major Fault utility
- SUT used to test fault condition is a MicroLogix 1100 PLC (1763-L16BWA Series B, FRN 14)



Denial-of-Service Fault

- To exploit the vulnerability, the attacker sends a single Execute PCCC Service - Protected Typed Logical Read with Three Address Fields packet with a File Number of 0x02–0x08 and File Type 0x48 or 0x47. Any combination of File Number 0x02–0x08 and File Type 0x48 or 0x47 will trigger a Major Error (0x08)
- Data files store status and data information associated with instructions used in ladder subroutines [8, p. 40–41]

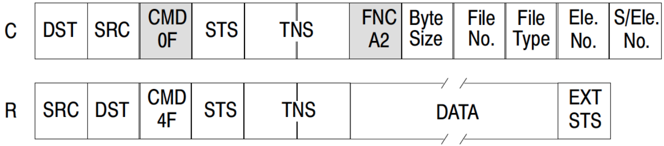
```
###[ ENIP TCP ]###
           Command   = Send Unit Data (0x0070)
           Length    = 45
           Session_Handle= 0x6077596d
           Status    = Success
           Sender_Context= 0
           Options   = 0
###[ Send Unit Data ]###
              Interface_Handle= 0
              Timeout   = 20
###[ ENIP_CommonPacketFormat ]###
                 Item_Count= 2
                 \Items     \
                  |###[ Common Packet Format Item ]###
                  |  Address_Data_Item= Connection-Based (0x00A1)
                  |  Address_Length= 4
                  |  Connection_Identifier= 0x6d596902
                  |###[ Common Packet Format Item ]###
                  |  Address_Data_Item= Connected Transport Packet (0x00B1)
                  |  Data_Length= 25
                  |  Sequence_Number= 0x1
###[ Common_Industrial_Protocol ]###
                    Request_Response= Request
                    Common_Service= Execute_PCCC_Service
                    Request_Path_Size= 2
                    \Words     \
                     |###[ CIP Request Path ]###
                     |  Path_Segment_Type= Logical Segment
                     |  Logical_Segment_Type= Class ID
                     |  Logical_Segment_Format= 8-bit logical address
                     |  Class     = 0x67
                     |###[ CIP Request Path ]###
                     |  Path_Segment_Type= Logical Segment
                     |  Logical_Segment_Type= Instance ID
                     |  Logical_Segment_Format= 8-bit logical address
                     |  Eight_bit_Instance= 0x1
###[ CIP Execute PCCC Service Request ]###
                       Length_of_Requestor_ID= 7
                       CIP_Vendor_ID_of_Requestor= Rockwell Software, Inc.
                       CIP_Serial_Number= 90180339
                       CMD       = 0x0F
                       Status    = 0x0
                       Transaction_Word= 2
                       Function  = Protected Typed Logical Read Three Address Fields
                       Byte_Size = 0x0
                       File_No   = 0x5
                       File_Type = 0x47
```

ControlLogix Experiment

- We speculate that the same PCCC vulnerability could potentially exist in newer RA/AB PLC models
- Same PCCC stress tests on the ControlLogix 5570 did not cause expected DoS fault
- Experiment yields insight into the differences in the way MicroLogix and ControlLogix respond to the Protected Typed Logical Read with Three Address Fields PCCC command

ControlLogix Experiment

- A PCCC reply always has a `status (STS)` byte, and for some commands, an `extended status (EXT STS)` byte
- MicroLogix only returns the STS byte (0x10= "Illegal command or format") whereas ControlLogix returns both STS and EXT STS bytes– STS = 0xF0 ("Error code in the EXT STS byte") and EXT STS = 0x06 ("Address doesn't point to something usable")[6]
- Functional difference indicates that it may be more valuable to fingerprint PLCs using information at the application level



Future Work

- EtherNet/IP support library can be expanded so that is fully compliant with specifications
- Testing TCP and IP layers may expose vulnerabilities in the ENIP/IP implementation
- Explore EtherNet/IP implementations across related products, i.e., products that conforms to the ODVA specification or deemed interoperable with related models
- OpENer is a POSIX-compliant implementation of ENIP that is partially supported by Rockwell Automation [4]

Questions

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