Generation of Applicative Attacks Scenarios Against Industrial Systems

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MTV2/MFDL

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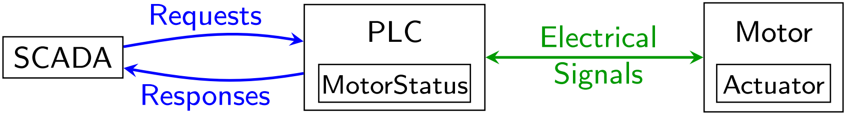
Industrial Systems 1/2

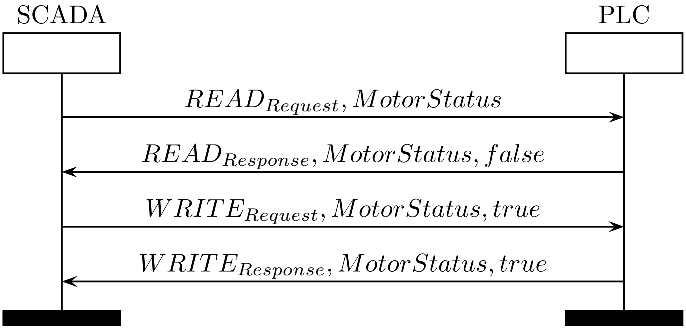
Hot topic

- Since Stuxnet (2009):
  - Complex attack ending up in increasing speed of Iranian centrifuges to damage them.
  - Also attacked the process monitoring to trick operators.
- Protection becoming a priority for government agencies.

Industrial Systems 2/2

- A SCADA controls a PLC which controls a motor.
- Variable *MotorStatus* on the PLC.





Industrial Communication Protocols

MODBUS (1979)

- No security at all.
- Some academic works to secure it (not used in practice):
  - Cryptographic asymmetric signatures [FCMT09]
  - Message Authentication Codes [HEK13]

OPC-UA (2006)

- Security layer: OPC-UA SecureConversation (similar to TLS).
- Three security modes:
  - None, Sign, SignAndEncrypt.

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Cryptographic Protocols Verification

Mutual Authentication Protocol: Needham-Schroeder

1. A $\rightarrow$ B : $\{A, N_A\}_{KB}$
2. A $\leftarrow$ B : $\{N_A, N_B\}_{KA}$
3. A $\rightarrow$ B : $\{N_B\}_{KB}$

Designed and **proved** in 1978.
Broken in 1995 (17 years after) **with an automated tool**.

Man-In-The-Middle attack

1. A $\rightarrow$ I : $\{A, N_A\}_{KI}$

    1. I $\rightarrow$ B : $\{A, N_A\}_{KB}$
    2. I $\leftarrow$ B : $\{N_A, N_B\}_{KA}$

2. A $\leftarrow$ I : $\{N_A, N_B\}_{KA}$
3. A $\rightarrow$ I : $\{N_B\}_{KI}$

    3. I $\rightarrow$ B : $\{N_B\}_{KB}$

$\Rightarrow$ Need for automation: numerous tools exist (e.g.: Tamarin [MSCB13] or ProVerif [Bla01]).

Related Works on Verification of Industrial Protocols

Ref	Year	Studied Protocols	Analysis
[CRW04]	2004	DNP3, ICCP	Informal
[DNvHC05]	2005	OPC, MMS, IEC 61850 ICCP, EtherNet/IP	Informal
[GP05]	2005	DNP3	Formal (OFMC)
[IEC15]	2006	OPC-UA	Informal
[PY07]	2007	DNP3	Informal
[FCMT09]	2009	MODBUS	Informal
[HEK13]	2013	MODBUS	Informal
[WWSY15]	2015	MODBUS, DNP3, OPC-UA	Informal
[Amo16]	2016	DNP3	Formal (Petri nets)
[PPL16]	2016	OPC-UA	Formal (ProVerif)
[DPP+17]	2017	MODBUS, OPC-UA	Formal (Tamarin)

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Motivations on Studying OPC-UA Security

Probably next standard for industrial communications:

- Recent (2006).
- Designed by a consortium of key stakeholders.

Official specifications: 978 pages:

- Several terms redefined afterward.
- Highly context dependent.

$\Rightarrow$ Unclear on the use of some security features.

Objective: Propose a formal model of the handshake from the specifications.

- Published in SAFECOMP'16, Trondheim, Norway.

Modeling Credentials in ProVerif

Login

Takes as parameter the public key of a host.
$\Rightarrow$ Anybody can usurp a login.

Passwd

Takes as parameter the private key of its owner.
Takes as parameter the public key of the server.

Equational Theory Added to ProVerif

verifyCreds(pk(S), Login(pk(C)),Passwd(sk(C), pk(S))) = true.
Allows to verify if a password and a login are matching and if password is the one the server knows (using its public key).

Key Takeaways on OPC-UA Analysis

Two attacks found when security features are removed

Possible reuse of cryptographic signatures (leads to replay attacks).
Possible attacks on passwords in absence of key-wrapping.
Specifications are elusive on purpose for interoperability.

Next steps

Test real implementations.
Application to other industrial protocols.
Model properties such as flow integrity, important for industry.

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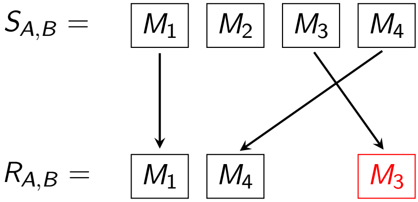
Contributions

⇒ Main Objective: add properties adapted to industrial systems in automatic verification tools.

- Published in SECRYPT'17, Madrid, Spain.

Contributions

- Formalization and implementation of properties for industrial systems in Tamarin
- Tested on 2 real industrial protocols and academic works



Properties and relations among them

$$
\begin{array}{ccccc}
(\mathrm{FD} & \wedge & \mathrm{FA}) & \Longleftrightarrow & \mathrm{FI} \\
\Downarrow & & \Downarrow & & \Downarrow \\
(\mathrm{IMD} & \wedge & \mathrm{IMA}) & \Longleftrightarrow & \mathrm{IMI} \\
\Downarrow & & \Downarrow & & \Downarrow \\
(\mathrm{NIMD} & \wedge & \mathrm{NIMA}) & \Longleftrightarrow & \mathrm{NIMI}
\end{array}
$$

Figure : Relationships: $A \Rightarrow B$ if a protocol ensuring A also ensures B.

- Classical network properties (e.g.: TCP sequence numbers)
  $\Rightarrow$ Never implemented in protocol verification tools
- Can an intruder tamper with these sequence numbers?

Flow Authenticity (FA)

Property

« *All messages are received in the same order they have been sent.* »

$$
\begin{aligned}
&\forall i, j : time, A, B : agent, m, m_2 : msg.(\\
&\quad Received(A, B, m)@i \wedge Received(A, B, m_2)@j \wedge i \lessdot j\\
&) \Rightarrow (\exists k, l : time.\\
&\quad Sent(A, B, m)@k \wedge Sent(A, B, m_2)@l \wedge k \lessdot l\\
&)
\end{aligned}
$$

Key Takeaways on Flow Integrity

- Formalization of 9 Flow Integrity properties with various security levels

- Implementation in Tamarin
- No modification to Tamarin source code

- Tested on 2 real industrial protocols and academic works (16 models total)
- All models and attacks publicly available

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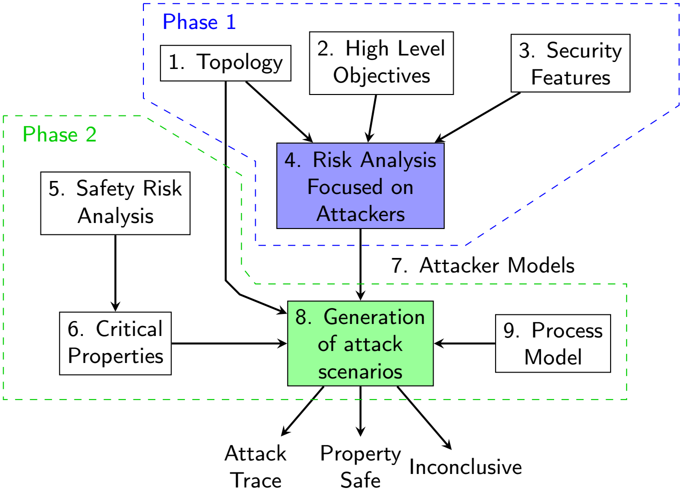
Idea & Contributions

- A^2SPICS: Find applicative attacks on industrial systems:
  - Considering an attacker already in the system;
  - What possible actions on the industrial process.
  - E.g.: Nozzle opens with no bottles under it.
- Implementation using the UPPAAL model-checker;
- Proof-of-concept on a case study.
- Published in FPS'17, Nancy, France.

Generic verification tools vs. Protocol verification tools

- Generic tools: model-checkers, smt-solvers, etc.
- Protocol verification tools: embed attacker logic.
- Trade-off: tool optimized for verification with attackers vs. granularity.

The A²SPICS Approach

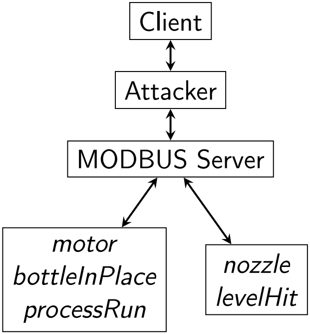


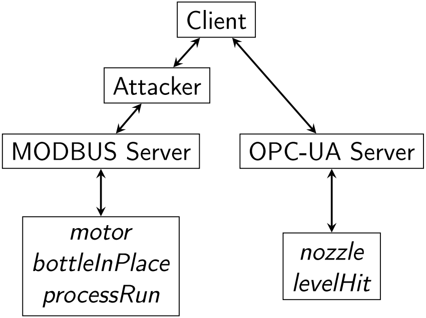
Phase 1 presented at AFADL/MTV2/MFDL 2016 in Besançon.

Topologies

Network topology of the system (expressed in CSP, π-calculus, etc):

- Communication channels between components;
- Position of attackers.



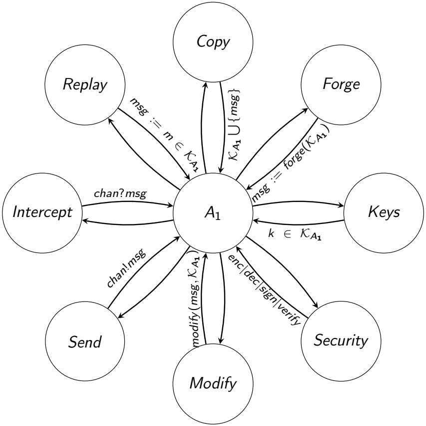


Attackers 1/2

Characterized by:

- Position in the topology:
  - On a channel (Man-In-The-Middle);
  - On a corrupted component (virus, malicious operator, etc).
- Capacities:
  - Possible actions on messages (intercept, modify, replay, etc);
  - Deduction system (deduce new information from knowledge, e.g.: encrypt/decrypt).
- Initial knowledge:
  - Other components;
  - Process behavior;
  - Cryptographic keys, etc.

Attackers 2/2

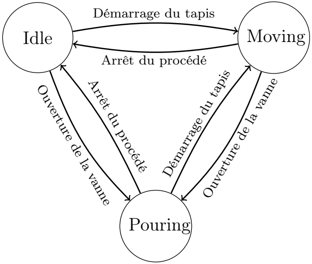


Four attackers:

- A_1 = close to Dolev-Yao;
- Other are subsets of A_1.

Attacker	Modify	Forge	Replay
A_1	✓	✓	✓
A_2	✓	✗	✗
A_3	✗	✓	✗
A_4	✗	✗	✓

Behaviors and Safety Properties



(a) Automaton of the behavior of the process

Current State	Next State	Guard	Actions
Idle	Moving	$processRun = true \wedge bottleInPlace = false$	$motor := true$
Idle	Pouring	$processRun = true \wedge bottleInPlace = true$	$nozzle := true$
Moving	Pouring	$bottleInPlace = true$	$motor := false \wedge nozzle := true$
Pouring	Moving	$levelHit = true$	$motor := true \wedge nozzle := false$
Moving	Idle	$processRun = false$	$motor := false \wedge nozzle := false$
Pouring	Idle	$processRun = false$	$motor := false \wedge nozzle := false$

(b) Transitions Details

Properties: CTL formula:

- Φ_1: At all time and on each path, *nozzle* is never *true* if *bottleInPlace* is *false*). $A\square \neg(nozzle = true \text{ and } bottleInPlace = false)$
- Φ_2: $A\square \neg(motor = true \text{ and } levelHit = false)$
- Φ_3: $A\square \neg(nozzle = true \text{ and } motor = true)$

Results on the case study

All attackers on all properties (checked using UPPAAL):

- ✓ = attack found;
- ✗ = no attack found;
- $\mathcal{O}$ = inconclusive (here, out of memory).

Topologies	Properties	A_1	A_2	A_3	A_4
T_1	Φ_1	✓	✓	✓	✗
	Φ_2	✓	✓	✓	✗
	Φ_3	✓	✓	✓	✗
T_2	Φ_1	$\mathcal{O}$	$\mathcal{O}$	✗	✗
	Φ_2	✓	✓	✓	✗
	Φ_3	✓	✓	✓	✗

Related Works

- Survey on assessment of security in industrial system ([CBB+15, PCB13, KPCBH15]).
- Comparison criteria from [KPCBH15, CBB+15]:

Ref.	Type	Focus	Process model	Probabilistic	Automated
[BFM04]	Model	A	No	No	No
[MBFB06]	Model	A	No	Yes (E)	No
[PGR08]	Model	A	No	Yes (E,H)	No
[TML10]	Model	A	No	Yes (H)	Yes
[CAL+11]	Formula	N/A	Yes	Yes (N/C)	Yes
[KBL15]	Model	A	No	Yes (E)	Yes
[RT17]	Model	A,G	Yes	No	Yes
A^2SPICS	Model	A,G	Yes	No	Yes

- Rely on Cl-Atse (protocol verification tool)
  - Dolev-Yao intruder ⇒ less precise control on attacker capacities
- A^2SPICS aims at modeling attackers resulting on risk analysis

Limitations

- Time and state of the process are discretized (e.g.: the bottle is either empty or full).
- Number of actions per attack is bounded (configurable, classical limitation of model-checking).
- Model only considers logical state of variables:
  - real state (i.e.: if a bottle is physically present or not);
  - logical state (i.e.: if the variable *bottleInPlace* is set to *true*);
  - properties are verified on logical state;
  - if a captor is written, a decorrelation is introduced.

    $\Rightarrow$ Can lead to missed attacks (e.g.: Φ_1).

Perspectives

- Study how to address former model limitations.
- Assess example from [RT17] for a better comparison.
- Allow collusions between intruders.
- Consider resilience properties.

- Tentative of automation with ProVerif and Tamarin.
  - Apply formalisms of [RT17].

- Combine protocol and safety properties verification.

Conclusion

Thanks for your attention!

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