Generation of Applicative Attacks Scenarios Against Industrial Systems

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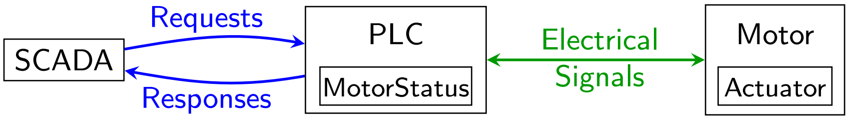
Industrial Systems 1/2

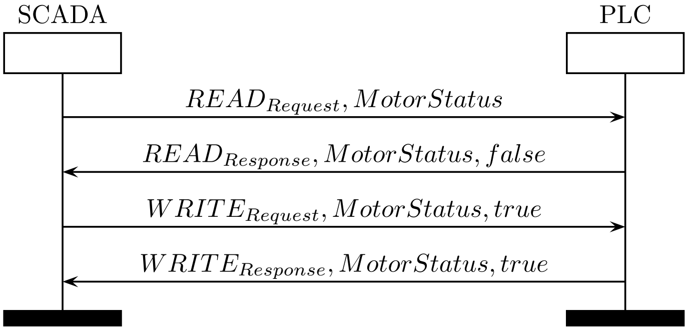
Hot topic

- 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)

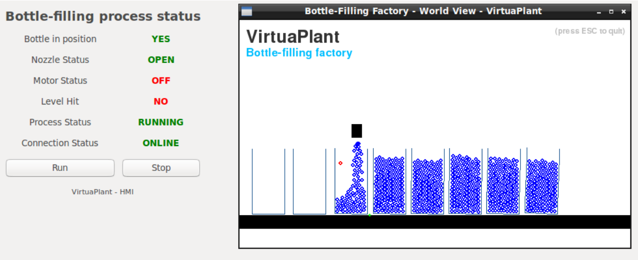
- Security layer: OPC-UA SecureConversation (similar to TLS).
- Three security modes:
  - None, Sign, SignAndEncrypt.

Prior Works on formal verification of security properties

- OPC-UA Handshake, SAFECOMP'16 [PPL16]
- OPC-UA and MODBUS Transport, SECRYPT'17 [DPP^{+}17]

Case Study: Bottle-filling Factory

- Process simulator: `https://github.com/jseidl/virtuaplant`



Variables:

- Conveyor belt
- Nozzle
- Position captor
- Level captor
- On/Off Switch

Properties:

- Nozzle only opens when a bottle is detected.
- Conveyor belt only starts when the bottle is full.
- Nozzle only opens when conveyor belt is stopped.

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.

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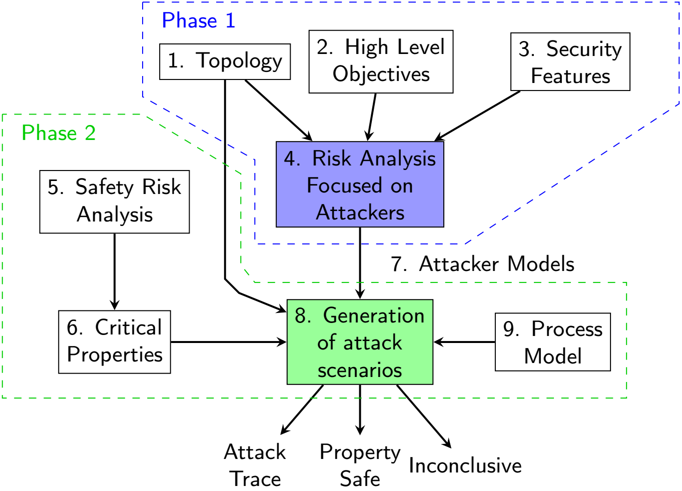
The A^2SPICS Approach

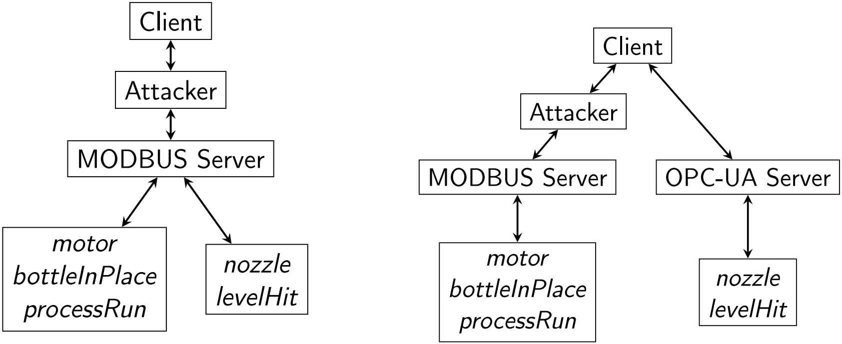


- Phase 1 presented at AFADL 2016, Besançon.

Two examples of topologies

Network topology of the system:

- Communication channels between components;
- Position of attackers.

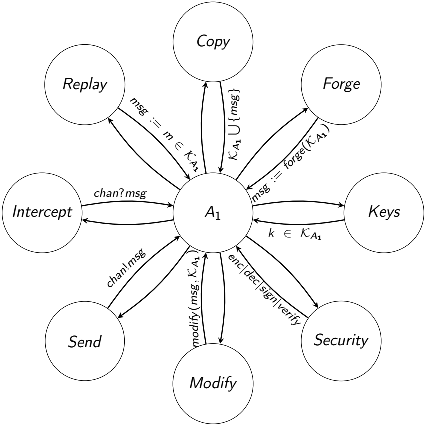


Attackers 1/2

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

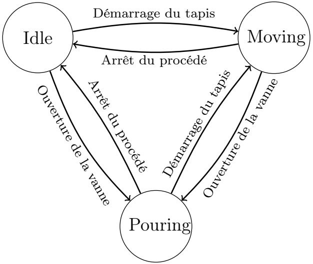


Four attackers:

- 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*).
  $A\Box\neg(nozzle = true \text{ and } bottleInPlace = false)$
- Φ_2: $A\Box\neg(motor = true \text{ and } levelHit = false)$
- Φ_3: $A\Box\neg(nozzle = true \text{ and } motor = true)$

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Analysis tools

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.

UPPAAL

- Model-checker created in 1995 at Aalborg and Uppsala Universities.
- Models specified as automata communicating over channels.
- Outputs an attack trace when falsified properties.

Results on the case study

All attackers on all properties (Intel i5-4590 CPU@3.30GHz, 16GB RAM):

- ✓ = 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	✓	✓	✓	✗

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Timings

Topologies	Properties	A_1	A_2	A_3	A_4
T_1	Φ_1	0.43 s	0.07 s	1.05 s	0.84 s
	Φ_2	0.52 s	0.10 s	0.69 s	0.35 s
	Φ_3	0.47 s	0.04 s	0.37 s	0.42 s
T_2	Φ_1	Out of memory		601 s	31.55 s
	Φ_2	0.66 s	0.23 s	2.17 s	35.20 s
	Φ_3	0.78 s	0.21 s	2.35 s	34.85 s

Observations on results on the POC:

- A_2 obtains same results as A_1 faster (not all capacities of Dolev-Yao are needed to find attacks in this case);
- A_3 globally needs more time but is able to conclude on Φ_1 (less state-space needed);
- A_4 is globally the slowest: as it does not find any attacks, UPPAAL explores all paths.

Conclusion

- 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.

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^{2}SPICS	Model	A,G	Yes	No	Yes

- Rely on Cl-Atse (protocol verification tool)
  - Dolev-Yao intruder ⇒ less precise control on attacker capacities
- A^{2}SPICS 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 model limitation (real state of process).
- Assess example from [RT17] for a better comparison.
- Tentative of automation with ProVerif and Tamarin.
  - Apply formalisms of [RT17].
- Allow collusions between intruders.

Conclusion

Thanks for your attention!

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Differences between Industrial and Business IT

- Really long-term installations, hard to patch, lot of legacy hosts.
- Security objectives are different from traditional systems:
  - Availability, integrity, authentication and non-repudiation.
- Messages are READ/WRITE commands to PLCs.
  - Sometimes SUBSCRIPTIONS, RPCs or grouped commands.
  - Industrial protocols: MODBUS, OPC-UA.
- Attack examples: change the value of a WRITE request to change a temperature, change a READ response to mislead operators.

Disambiguation

Security concepts

- Safety = Protection against identified/natural difficulties.
  - Historic industrial concern.
- Cybersecurity = Protection against malicious adversaries.
  - Often called Security.

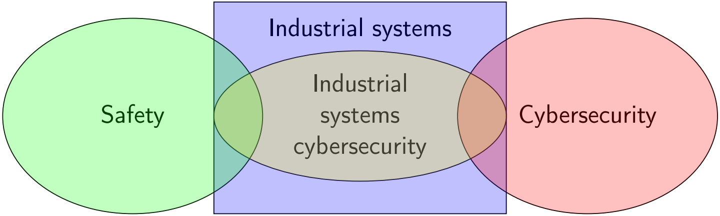


Figure : Relations among security concepts

- Ludovic Pietre-Cambacedes' thesis: On the relationships between safety and security, Telecom ParisTech and EDF, 2010.

Safety and Security

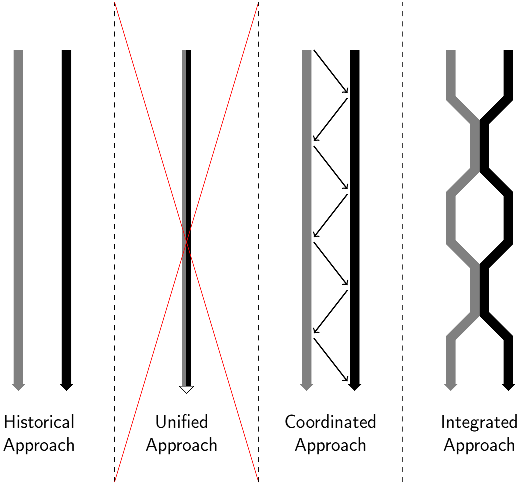


Figure : How to link safety and security [PC10]

Purdue Model

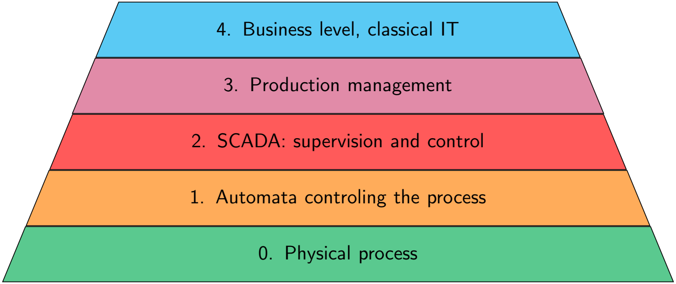


Figure : Purdue model [Wil91]

Motivations on Studying OPC-UA Security

Official specifications: 978 pages.

Several terms redefined afterward:

For this reason, the OpenSecureChannel Service **is not the same as the one specified in the Part 4.** – Part 6, Release 1.02, Page 41.

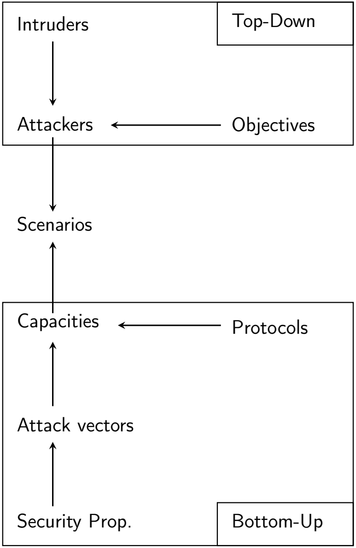
Highly context dependent:

Some SecurityProtocols do not encrypt the entire Message with an asymmetric key. **Instead, they use the AsymmetricKeyWrapAlgorithm to encrypt a symmetric key** [...]. – Part 6, Release 1.02, Page 27.

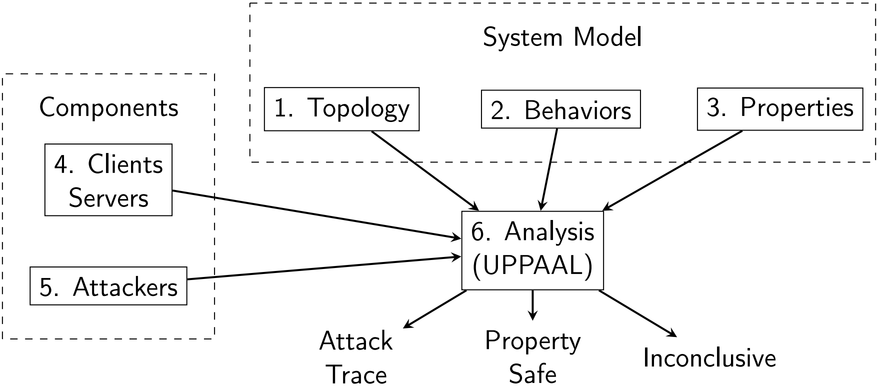
The AsymmetricKeyWrapAlgorithm element of the SecurityPolicy structure defined in Table 22 **is not used by UASC implementations.** – Part 6, Release 1.02, Page 37.

Phase 1: Attacker Models

- Presented at AFADL 2016, Besançon.
- Risk analysis focused on attackers.
- Based on:
  - Topology of the system;
  - Attacker objectives;
  - Security features of protocols.
- Objectives are security vuln., e.g.:
  - Modify a message;
  - Circumvent authentication.
- Yields attacker models in terms of:
  - Position in the topology;
  - Capacities (actions and deduction).



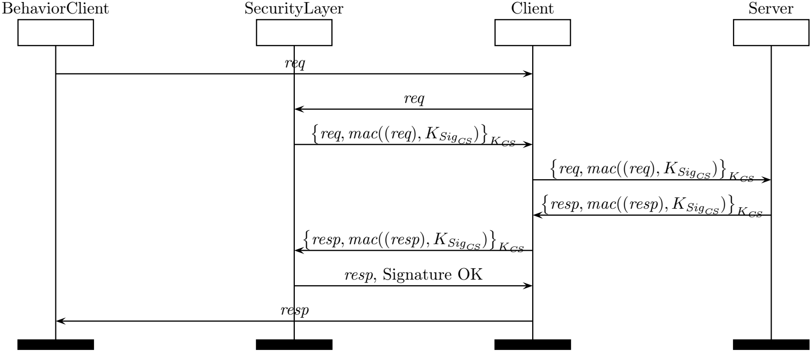
Phase 2: Generation of Attack Scenarios



Clients and Servers

For a transport protocol:

- Encapsulate and decapsulate applicative message into packets.
- Reusable for a model to another.
- BehaviorClient generates applicative messages.
- SecurityLayer performs cryptographic operations.



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