Learning-based Attacks in Cyber-Physical Systems

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Cloud robots and automation systems

Security

We need to address physical security in addition to cyber security

News reports

Port of San Diego suffers cyber-attack, second port in a week after Barcelona

Hacker jailed for revenge sewage attacks

Job rejection caused a bit of a stink

HACKERS REMOTELY KILL A JEEP ON THE HIGHWAY—WITH ME IN IT

News reports

The Stuxnet outbreak

A worm in the centrifuge

The Economist

An unusually sophisticated cyber-weapon is mysterious but important

Computer virus Stuxnet a 'game changer,' DHS official tells Senate

CNN

"It has changed the way we view the security threat"

Proof of concept, Symantec

Zero Days Documentary (2016)

The man in the middle

A fictitious plant for the controller

A malicious controller for the plant

Mathematical formulation

- Linear dynamical system

$$X_{k+1} = aX_k + U_k + W_k$$

$$\{W_k\} \text{ are i.i.d. } \mathcal{N}(0, Var[W])$$

- The controller, at time k, observes Y_k and generates a control signal U_k as a function of all past observations Y_1^k.

$Y_k = X_k$ Under normal operation

$Y_k = V_k$ Under attack

- The attacker feeds a malicious input $\tilde{U}_k$ to the plant.

- How can the controller detect that the system is under attack?

Anomaly detection

- The controller is armed with a detector that tests for anomalies in the observed history Y_1^k.

$$X_{k+1} = aX_k + U_k + W_k \qquad \{W_k\} \text{ are i.i.d. } \mathcal{N}(0, Var[W])$$

- Under legitimate system operation $(Y_k = X_k)$ we expect

$$Y_{k+1} - aY_k - U_k(Y_1^k) \sim \quad \text{i.i.d.} \quad \mathcal{N}(0, Var[W])$$

- The detector performs the variance test

$$Var[W] = \mathbb{E}[W^2]$$

Anomaly detection

- Under legitimate system operation we expect

$$Y_{k+1} - aY_k - U_k(Y_1^k) \sim \quad \text{i.i.d.} \quad \mathcal{N}(0, Var[W])$$

- The controller performs a threshold-based detection

$$\frac{1}{T}\sum_{k=1}^{T}\left[Y_{k+1} - aY_k - U_k(Y_1^k)\right]^2 \in (Var[W] - \delta, Var[W] + \delta).$$

- What kind of attacks can we detect?

The man in the middle attack types

Stuxnet

Replay attack

Y. Mo, B. Sinopoli (2009)

Statistical-duplicate attack

$$X_{k+1} = aX_k + U_k + W_k$$

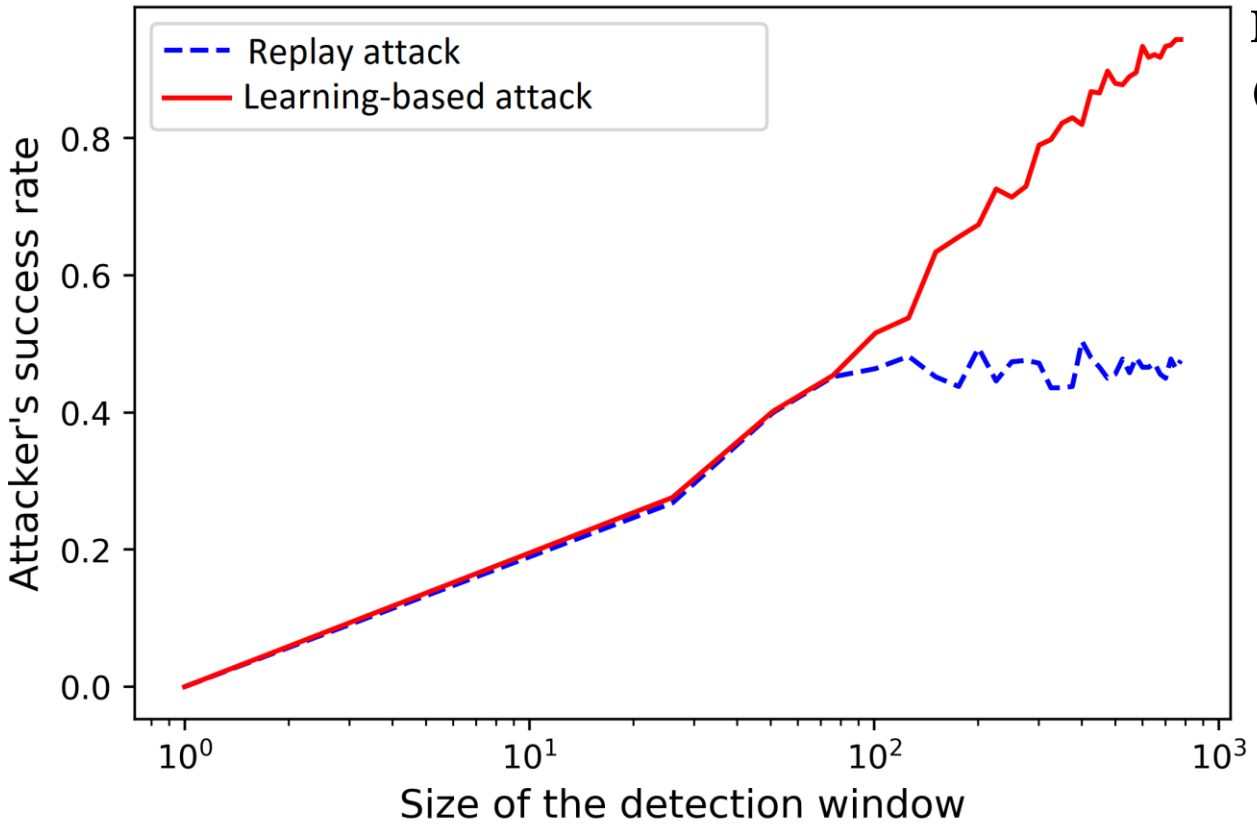
B. Satchidanandan,
P. R. Kumar (2017)
R. S. Smith (2011)

Learning-based attack

$$X_{k+1} = aX_k + U_k + W_k$$

MJ Khojasteh et al. (2020)

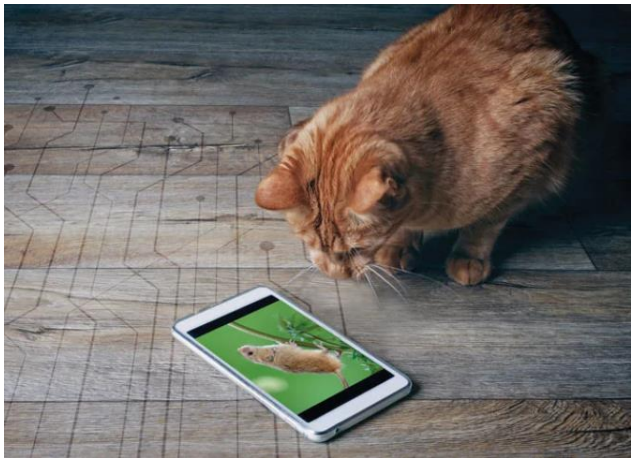
Comparison with a replay attack



MJ Khojasteh et al. (2020)

Stuxnet

Defense against learning-based attack

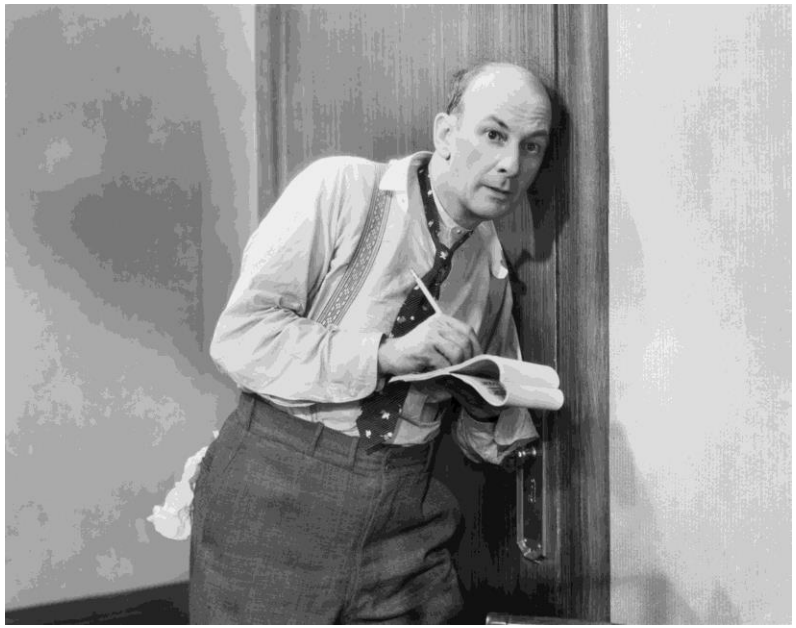


$$X_{k+1} = aX_k + U_k + W_k.$$

- The attacker has access to both X_k and U_k and knows the distribution of W_k and of the initial condition X_0, but it should learn the open loop gain a of the plant.

Two phases of the learning-based attack

Learning (exploration) phase



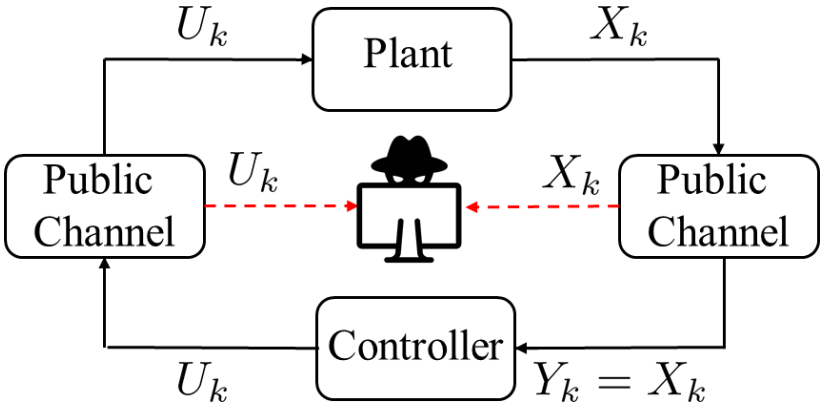
Eavesdropping and learning

Hijacking (exploitation) phase

Hijacking the system

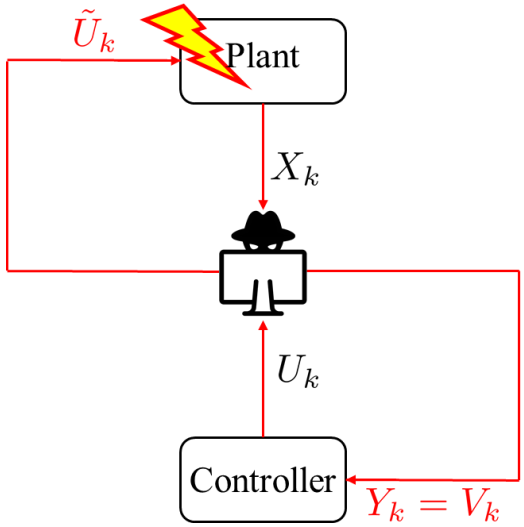
Two phases of the learning-based attack

Learning (exploration) phase



Eavesdropping and learning

Hijacking (exploitation) phase



Hijacking the system

Privacy-enhancing signal

Impede the learning process of the attacker

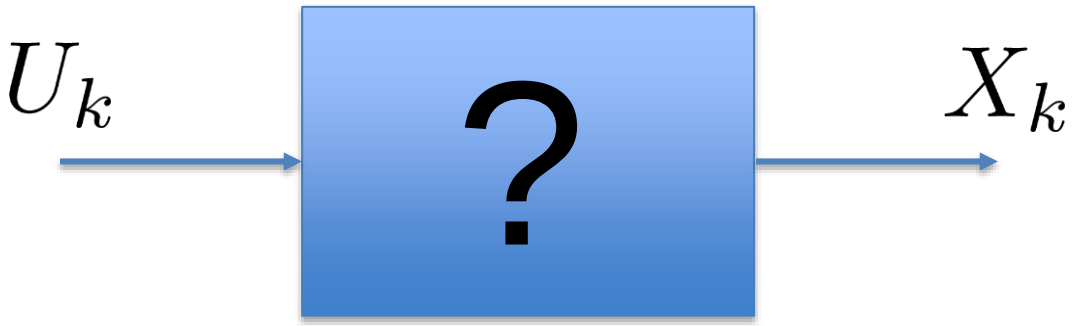
Privacy-enhancing signal

$$U_k = \bar{U}_k + \Gamma_k$$

Nominal control policy

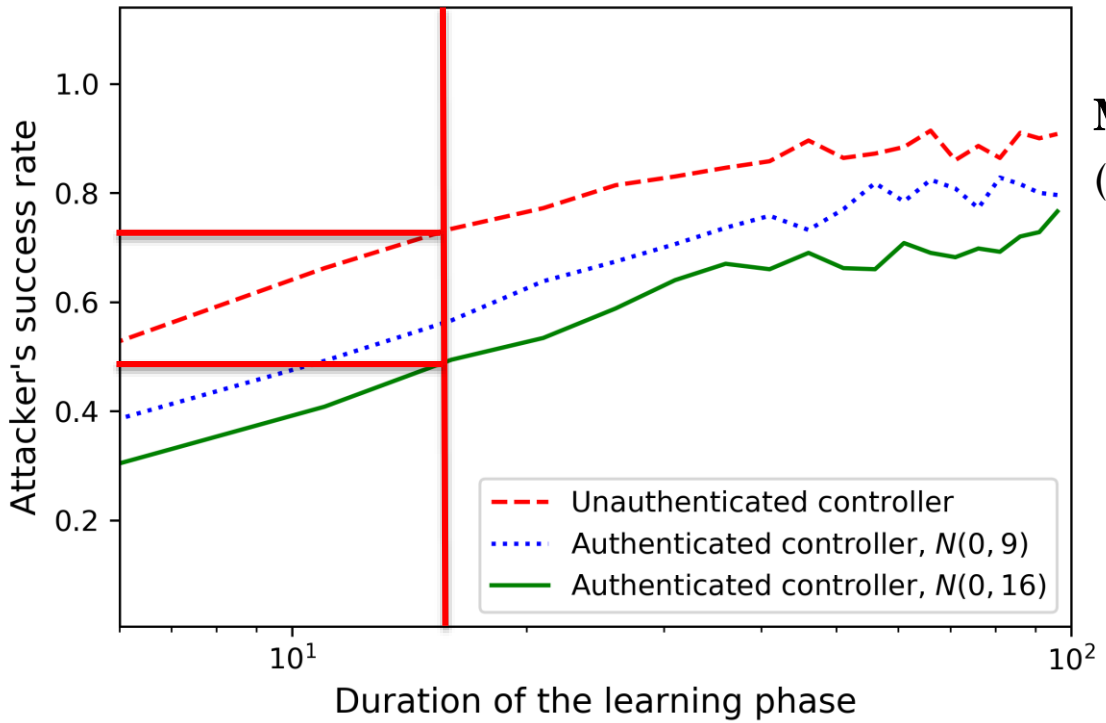
Privacy-enhancing signal

- Injecting a strong noise may in fact speed up the learning process



- Carefully crafted privacy-enhancing signals provide better guarantees on the deception probability

Privacy-enhancing signal

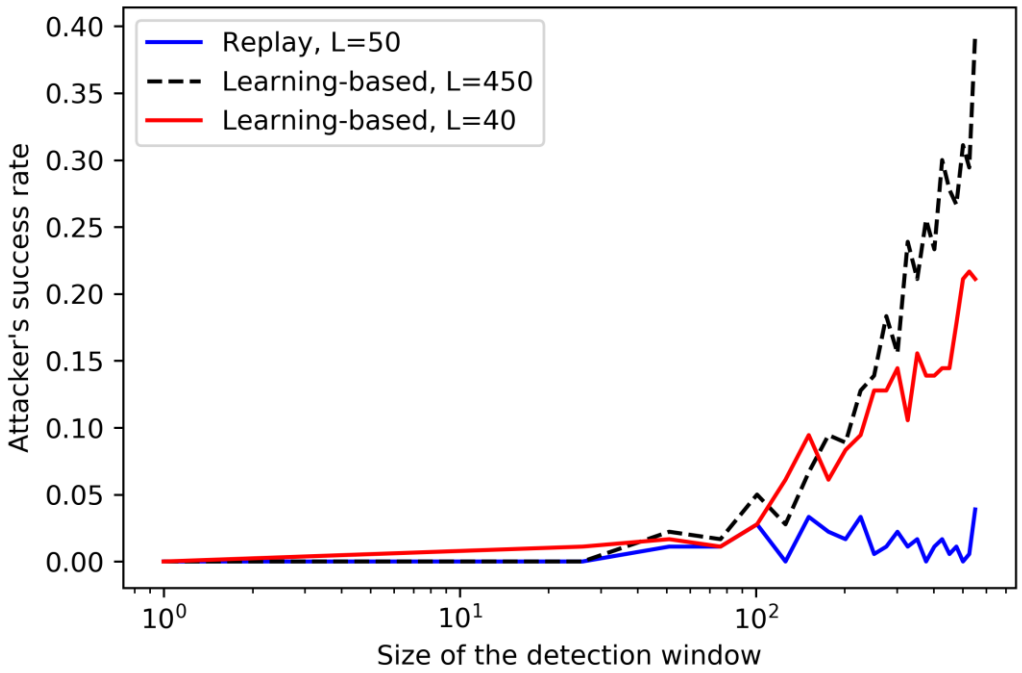


MJ Khojasteh et al. (2020)

Learning-based attack: vector systems

$$A \longrightarrow \mathbf{A} = \begin{bmatrix} ? \end{bmatrix}$$

$$\mathrm{Var} \longrightarrow \mathrm{Cov}$$



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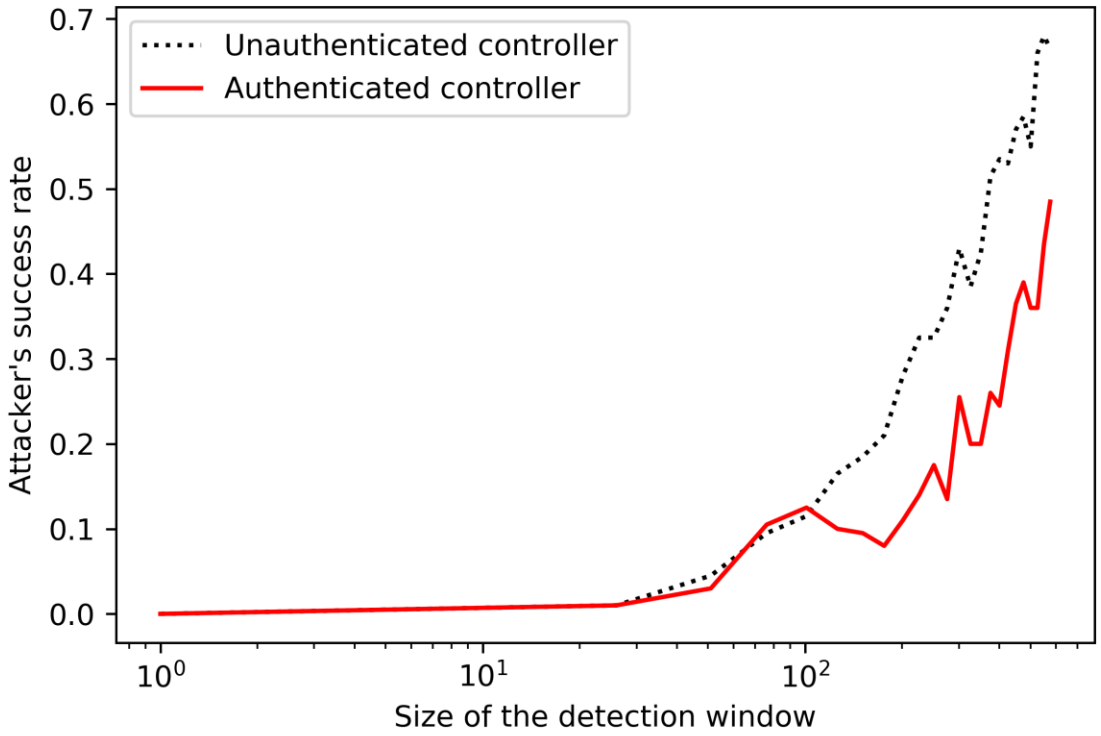
Stuxnet

Defense against vector learning-based attack

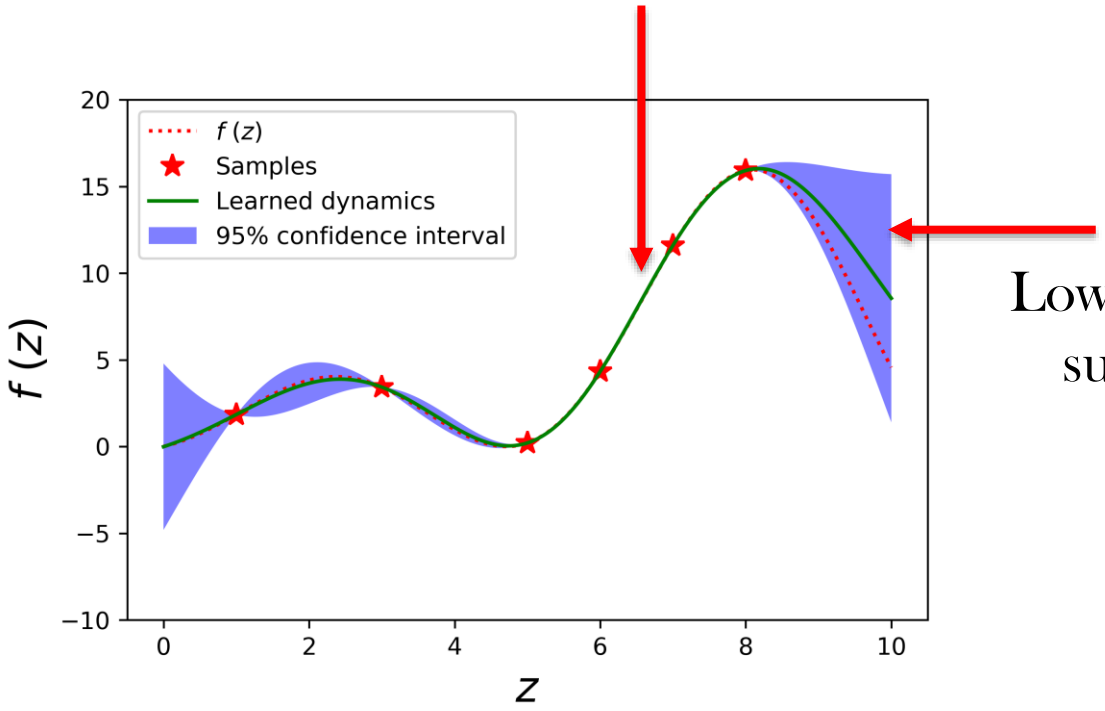


Nonlinear learning-based attack

$A \rightarrow f(X,U) \in$ Reproducing Kernel Hilbert Space (RKHS)

Linear regression → Bayesian learning: Gaussian processes (GP)

Vulnerable region



Lower attacker's success rate

References

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  IFAC-PapersOnLine. 2019 Jan 1; 52(20): 369-74.

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