Software Rejuvenation for Safe Operation of Cyber-Physical Systems in the Presence of Run-time Cyber Attacks

Carnegie Mellon University
Software Engineering Institute

AUGUST 16, 2023

Raffaele Romagnoli, Bruce Krogh, **Dionisio de Niz**, Anton Hristozov, Bruno Sinopoli

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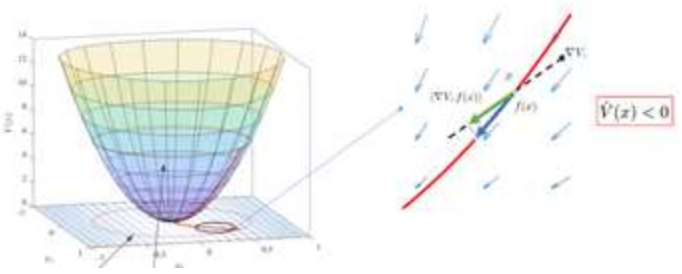
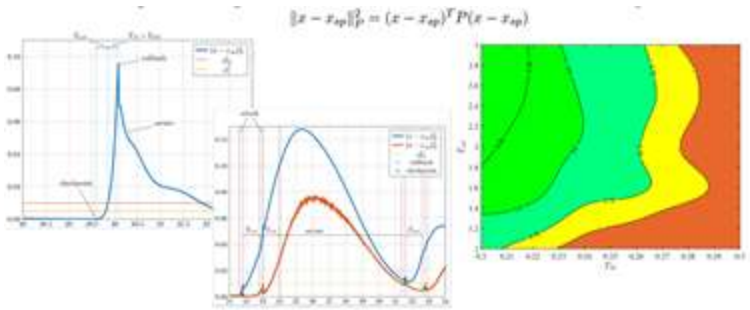
DM23-0803

Outline

1. **Introduction to Software Rejuvenation**
   a. Flight Control Software Architecture
   b. Cyber Attack Exposure
   c. Software Refresh\Rollback
   d. Periodic vs Aperiodic SR
2. **Proposed Software Rejuvenation Solution**
   a. Ensuring Safety and Safe Tracking
   b. Software Rejuvenation Scheme
3. **Safety and Quadratic Boundedness**
   a. Empirical method for SR design
   b. Results
4. **Conclusions**

crazyflie





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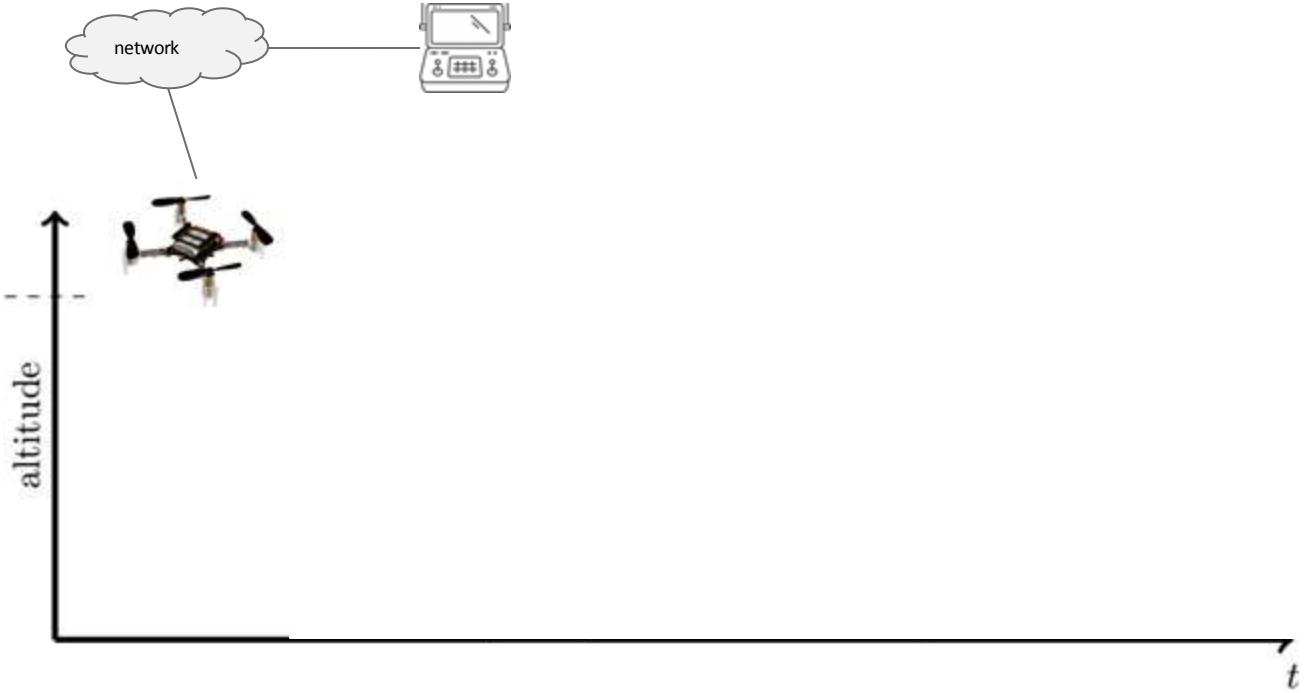
1 - Introduction to Software Rejuvenation



Mission

- Hovering

Communication

- Connected to the network

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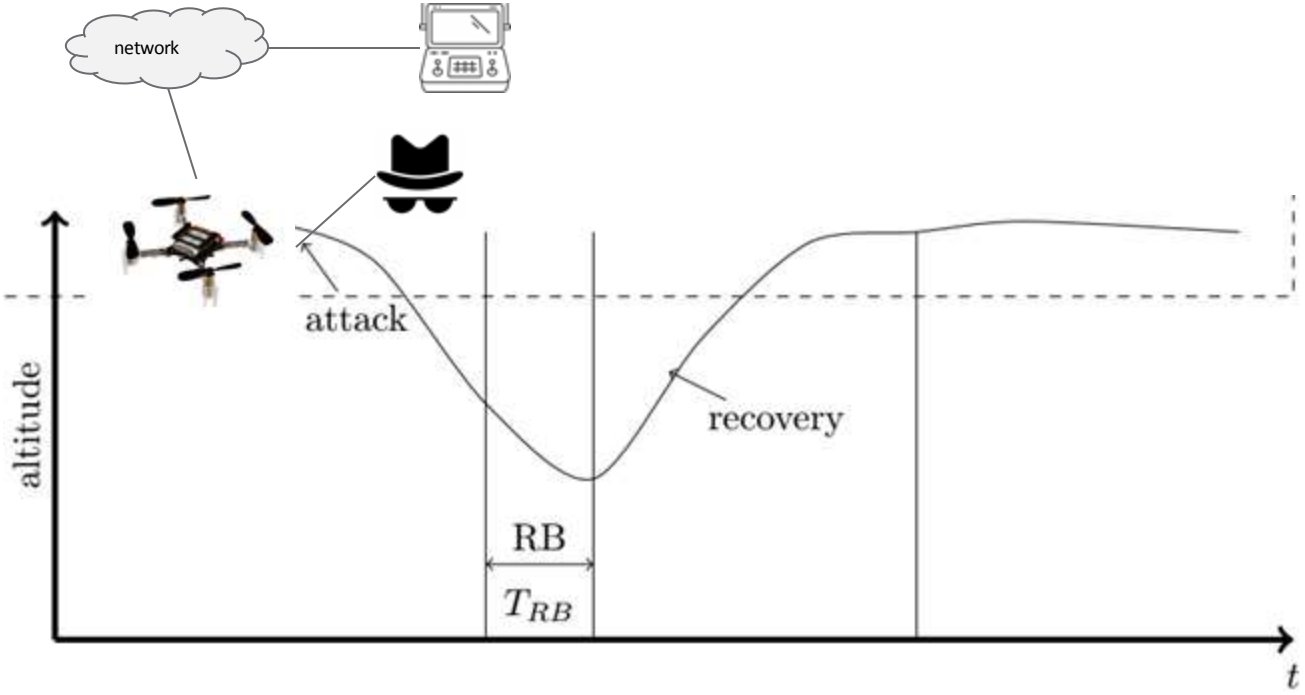
1.c - Software Refresh/Rollback



Mission

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Communication

- Connected to the network
  - PX4 : Mavlink

Cyber attacks

- On the run-time code

Idea

- **Software Reset/Rollback**

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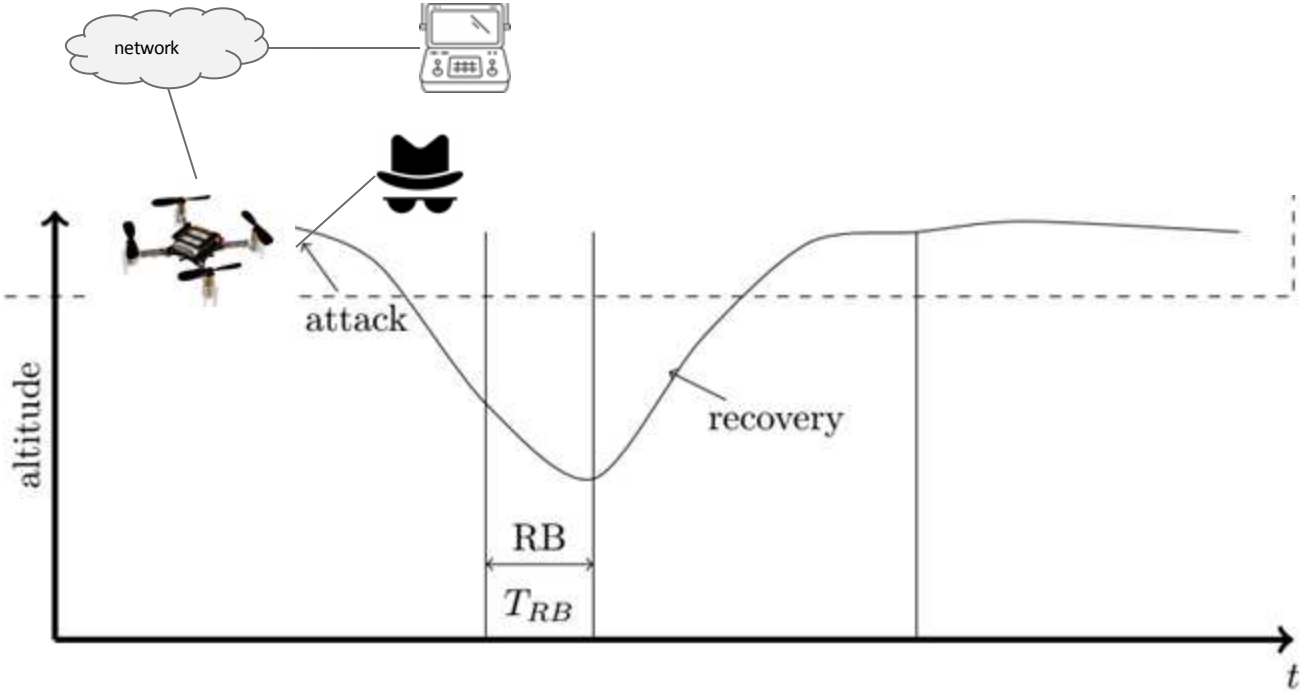
1.d - Periodic vs Aperiodic Rollback



Mission
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Cyber attacks
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Idea
- **Software Reset/Rollback**

★ Periodic Reboot - (Focus on the Security) [Arroyo et al 2017]
★ On-line Reach set analysis - (Focus on the Performance) [Abdi et al 2019]

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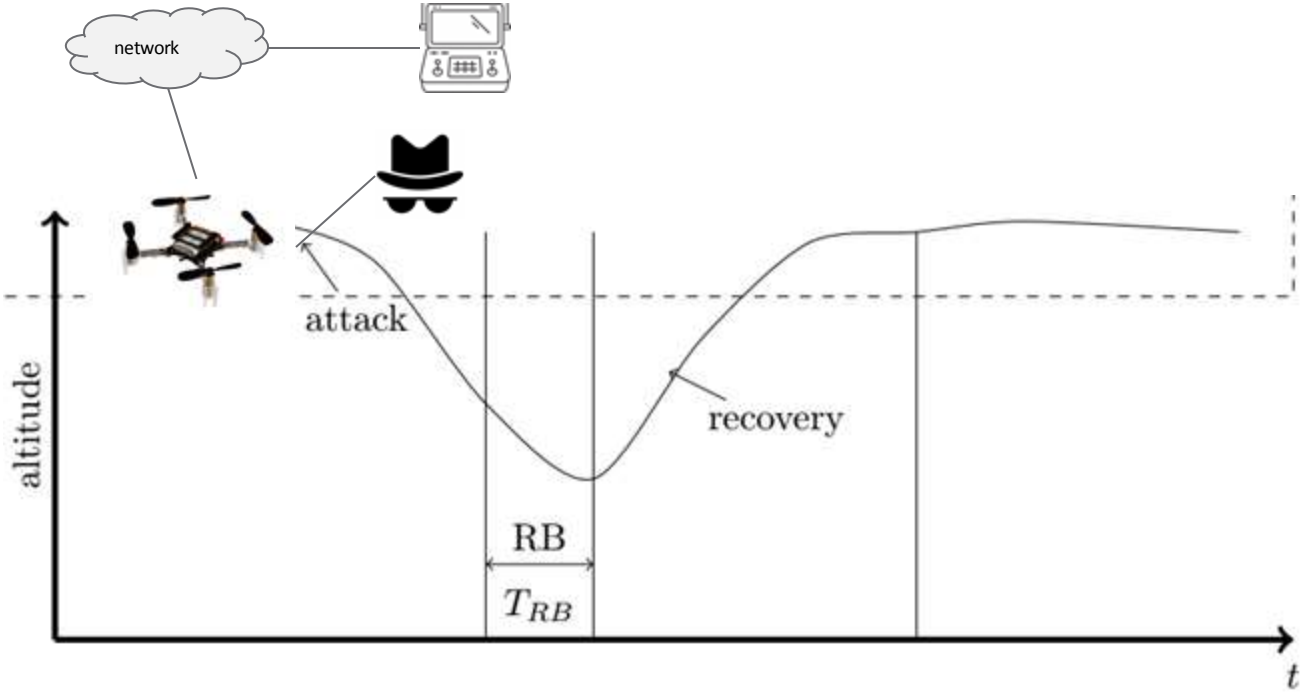
1.d - Periodic vs Aperiodic Rollback



★ Periodic Reboot - (Focus on the Security) [Arroyo et al 2017]

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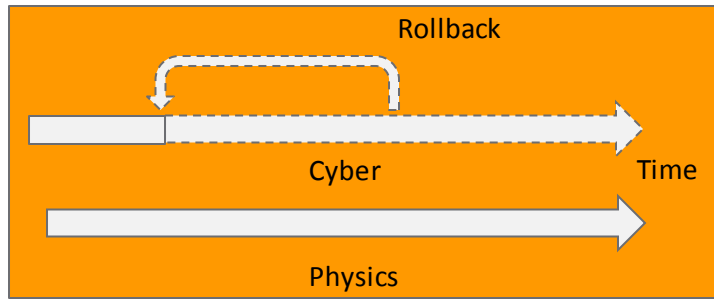

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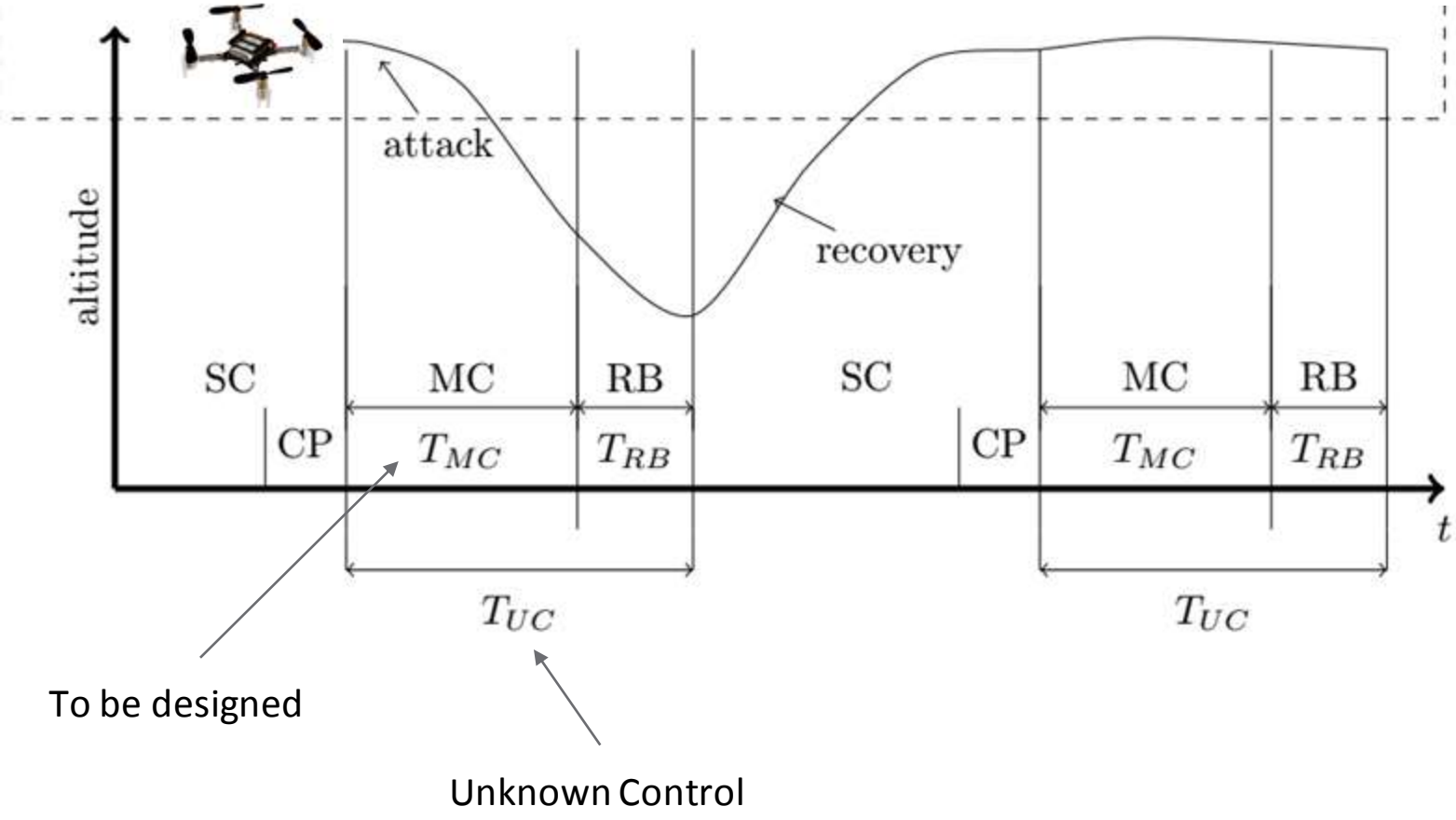
2 - Proposed Software Rejuvenation Solution



- SC - Secure Control
- CP - Checkpoint
- MC - Mission Control
- RB - Rollback

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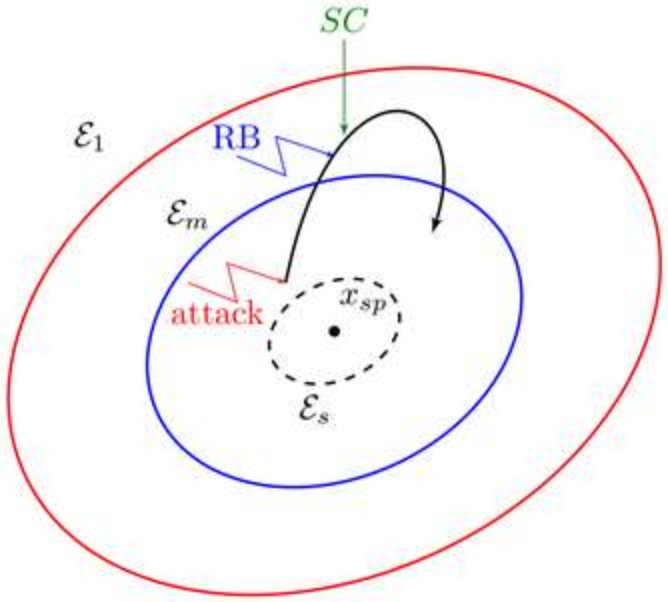
2.a - Ensuring Safety and Safe Tracking



$$\|x - x_{sp}\|_P^2 = (x - x_{sp})^T P (x - x_{sp})$$

$$\mathcal{E}_c = \left\{ x \in \mathbb{R}^n : \|x - x_{sp}\|_P^2 \leq c \right\}$$

$$s < m < 1 \Rightarrow \mathcal{E}_s \subset \mathcal{E}_m \subset \mathcal{E}_1$$

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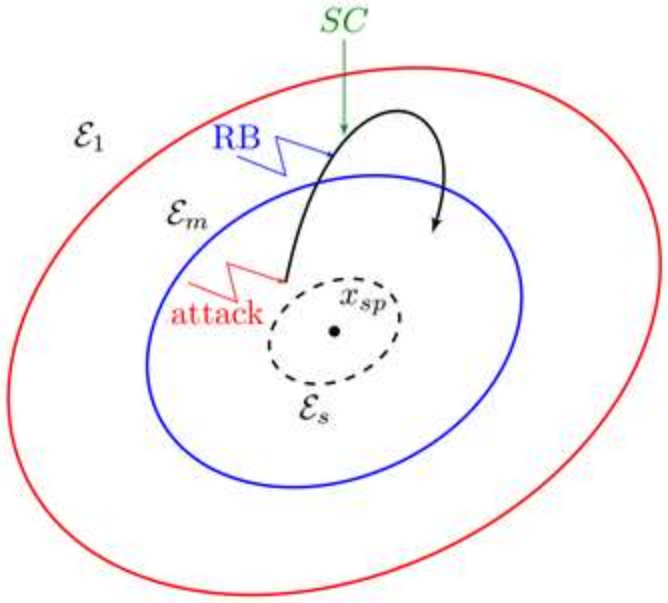

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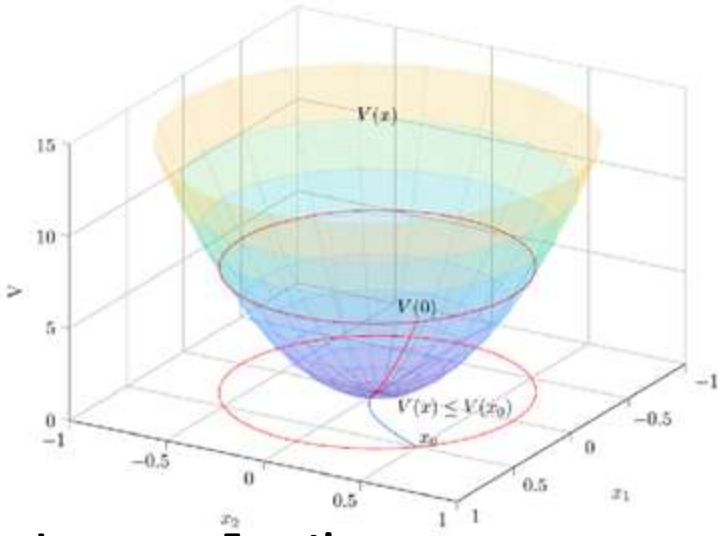
Lyapunov Theory

$$\dot{x} = f(x) = Ax$$



Lyapunov Function

$$V(x) = \|x - x_{sp}\|_P^2 \qquad \dot{V}(x) < 0$$

- $\mathcal{E}_c$ is **positively invariant**

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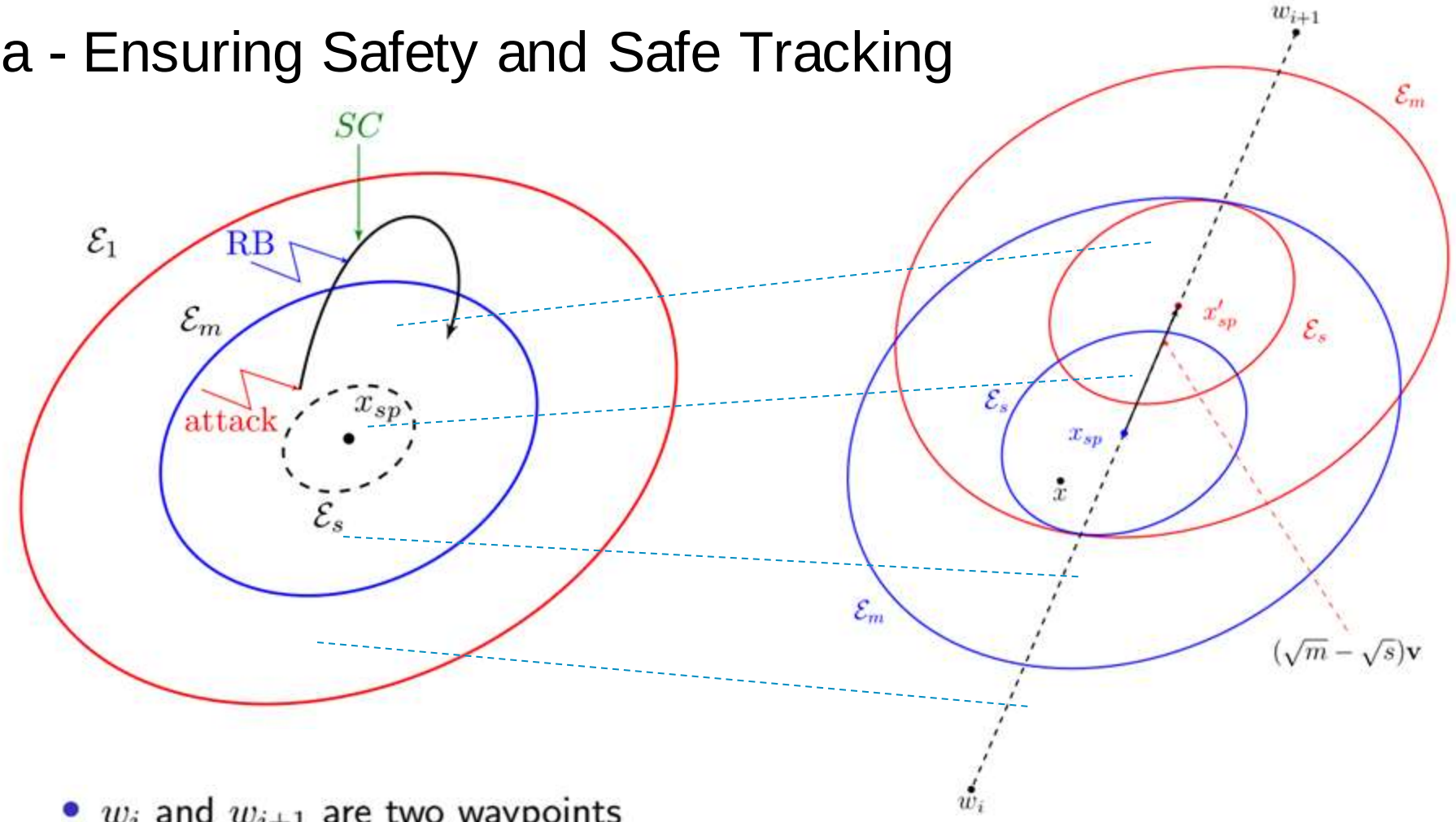
2.a - Ensuring Safety and Safe Tracking



- w_i and w_{i+1} are two waypoints

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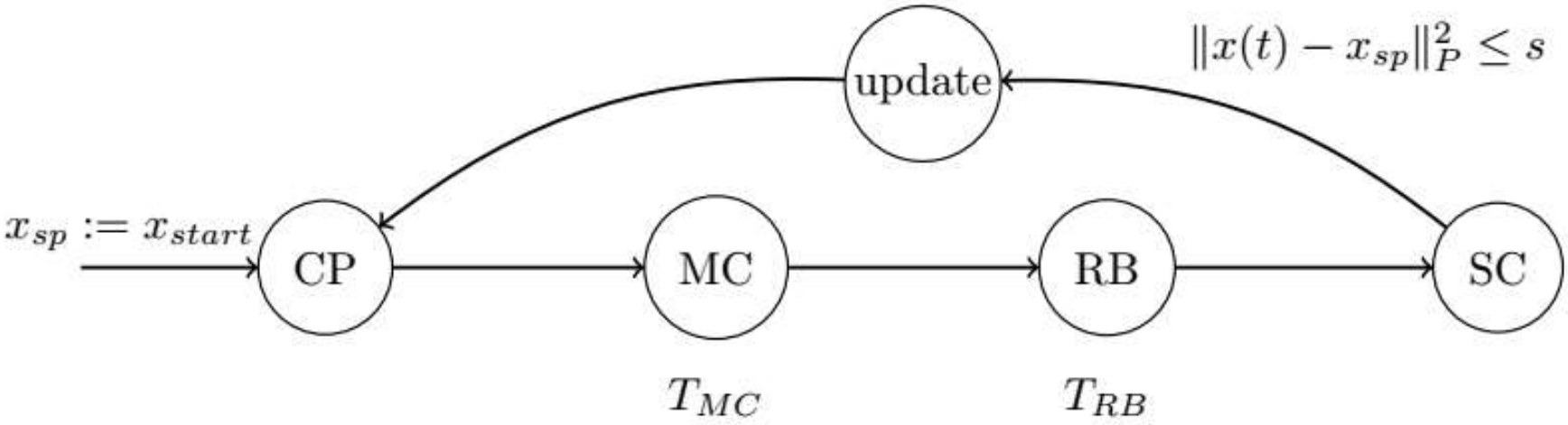
2.b - Software Rejuvenation Scheme



$$x(t) \longrightarrow \hat{x}(t)$$

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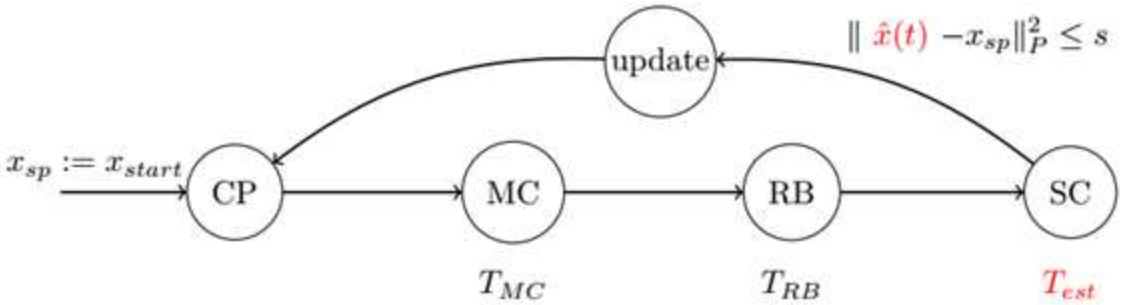
3 - Safety and Quadratic Boundedness

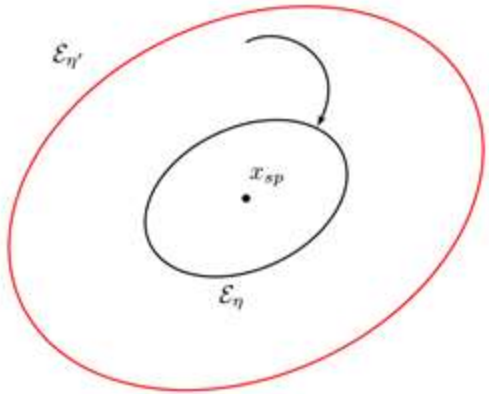


Quadratic Boundedness

$$\dot{x} = Ax + Dd, \quad \|d\| \leq \delta$$

$$V(x) = \|x - x_{sp}\|_P^2$$

$$V(x) > \eta \rightarrow \dot{V}(x) < 0$$



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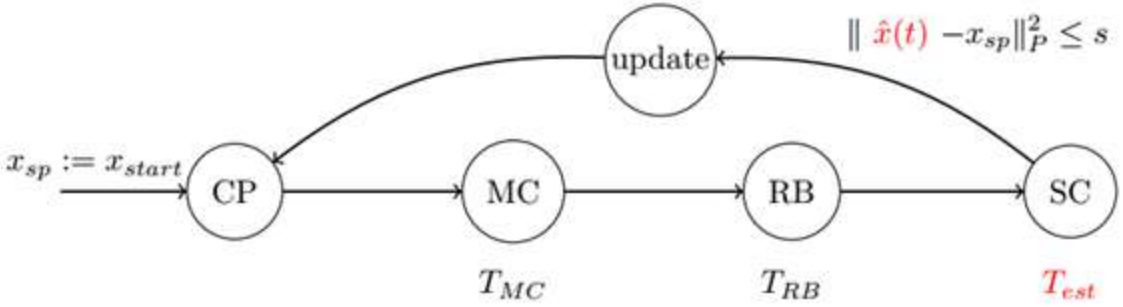

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$$\dot{x} = Ax + Dd, \quad \|d\| \leq \delta$$

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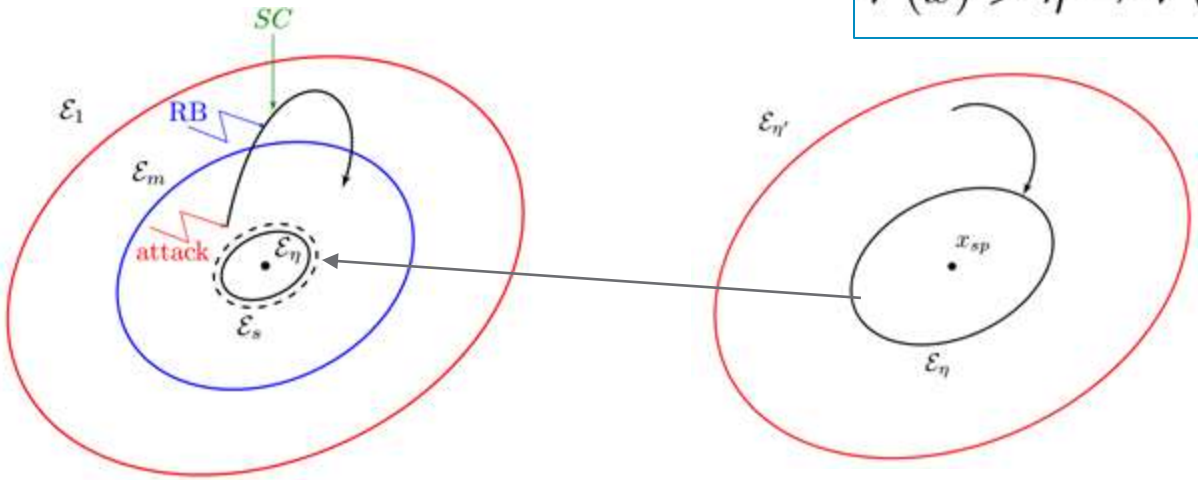
$$V(x) > \eta \rightarrow \dot{V}(x) < 0$$

- Estimation error due to SR.
- Model approximations



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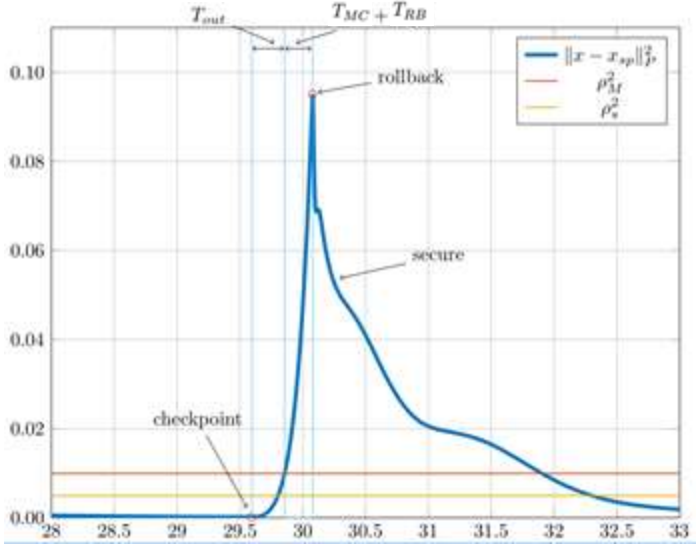
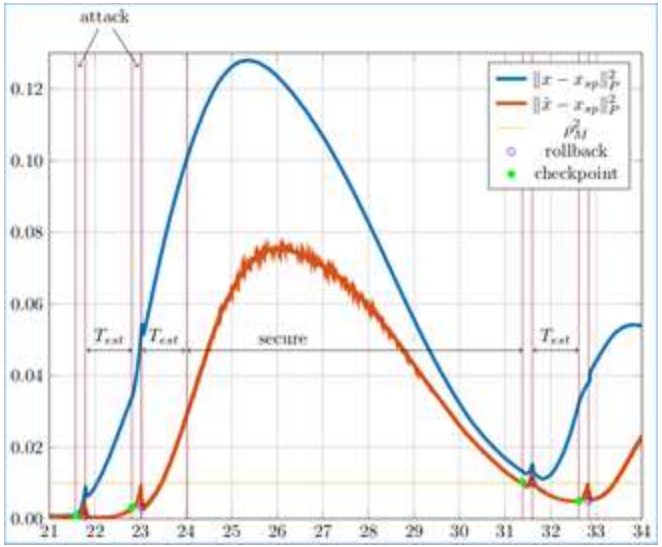
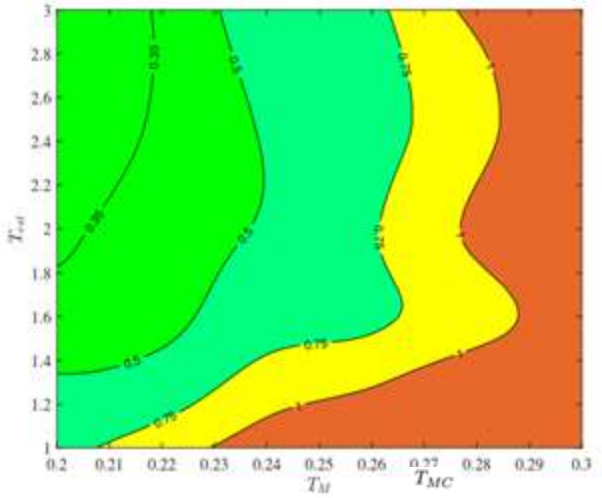
3.a - Empirical Method for SR Design



$$\|x - x_{sp}\|_P^2 = (x - x_{sp})^T P (x - x_{sp})$$





R. Romagnoli, B.H. Krogh, D. de Niz, A. Hristozov, B. Sinopoli. "Software Rejuvenation for Safe Operation of Cyber-Physical Systems in the Presence of Run-time Cyber Attacks". IEEE Transactions on Control System Technology. 2023.

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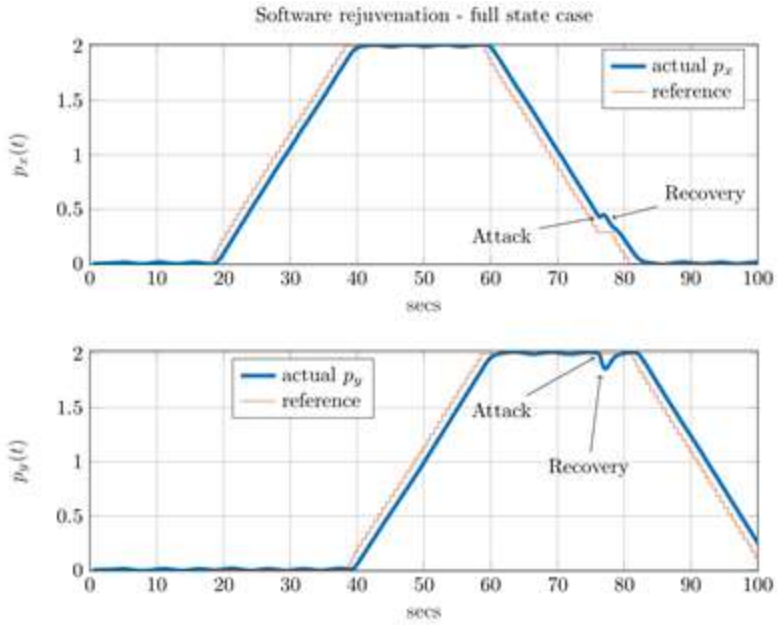
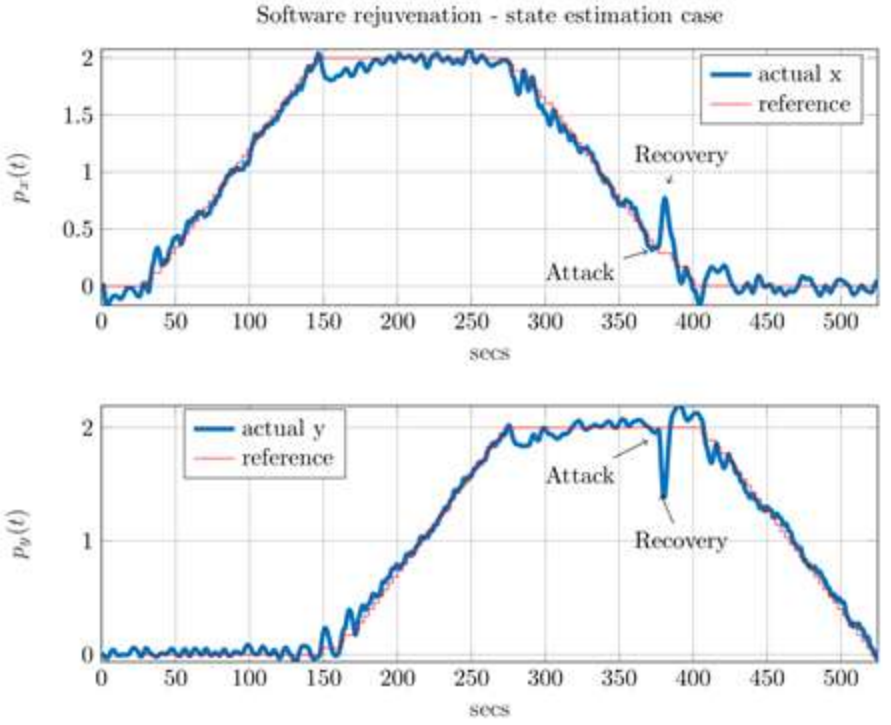
3.b - Results





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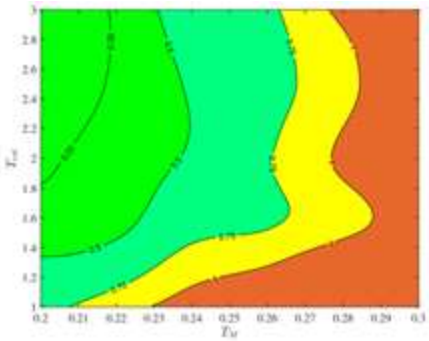
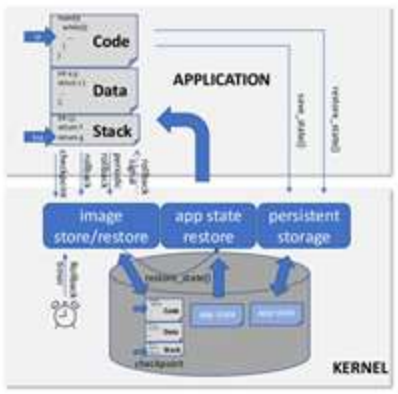
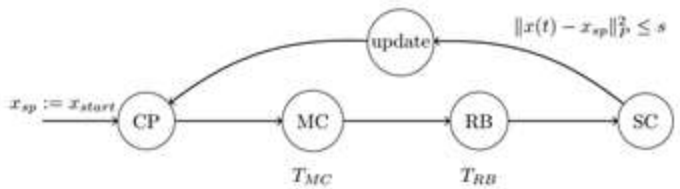
4 - Conclusions



Cyber

Physics





Romagnoli R, Krogh B.H, DeNiz D, Hristozov A.D, Sinopoli B. (2023). Runtime System Support for CPS Software Rejuvenation. IEEE TRANSACTIONS ON EMERGING TOPICS IN COMPUTING, ISSN: 2168-6750, doi: 10.1109/TETC.2023.3267899

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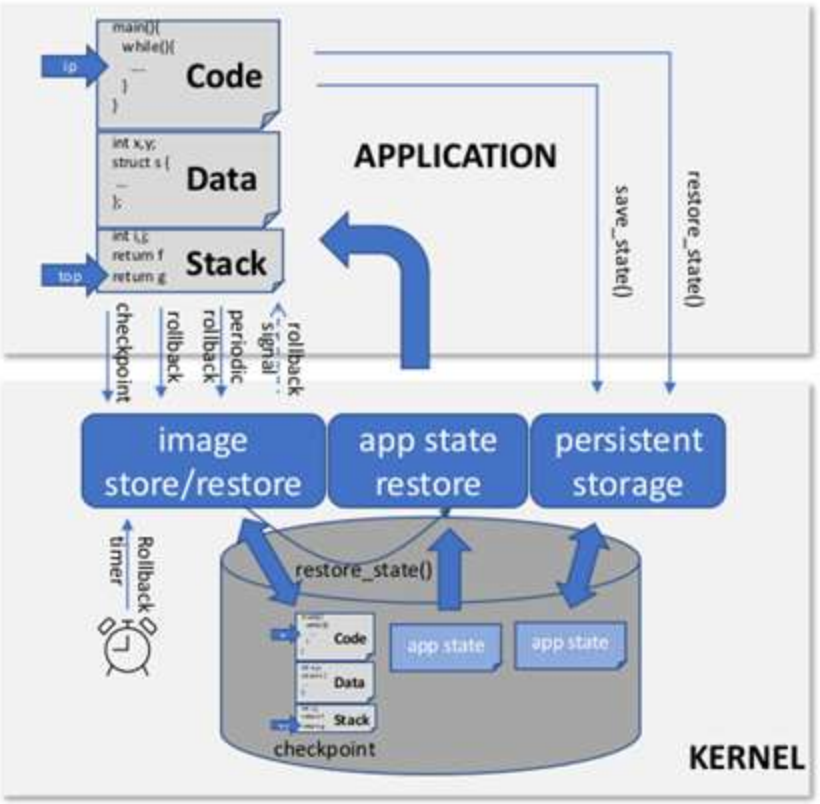
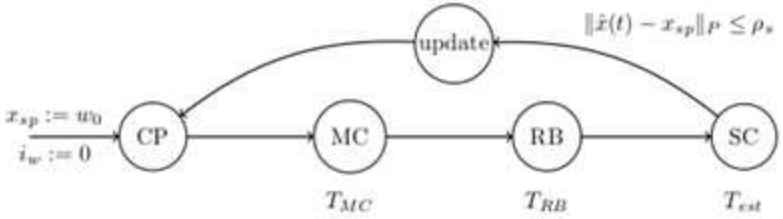
4 - Implementation



- Application vs Kernel level



- `rollback_handler()`

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Safety Analysis

- State of the system

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

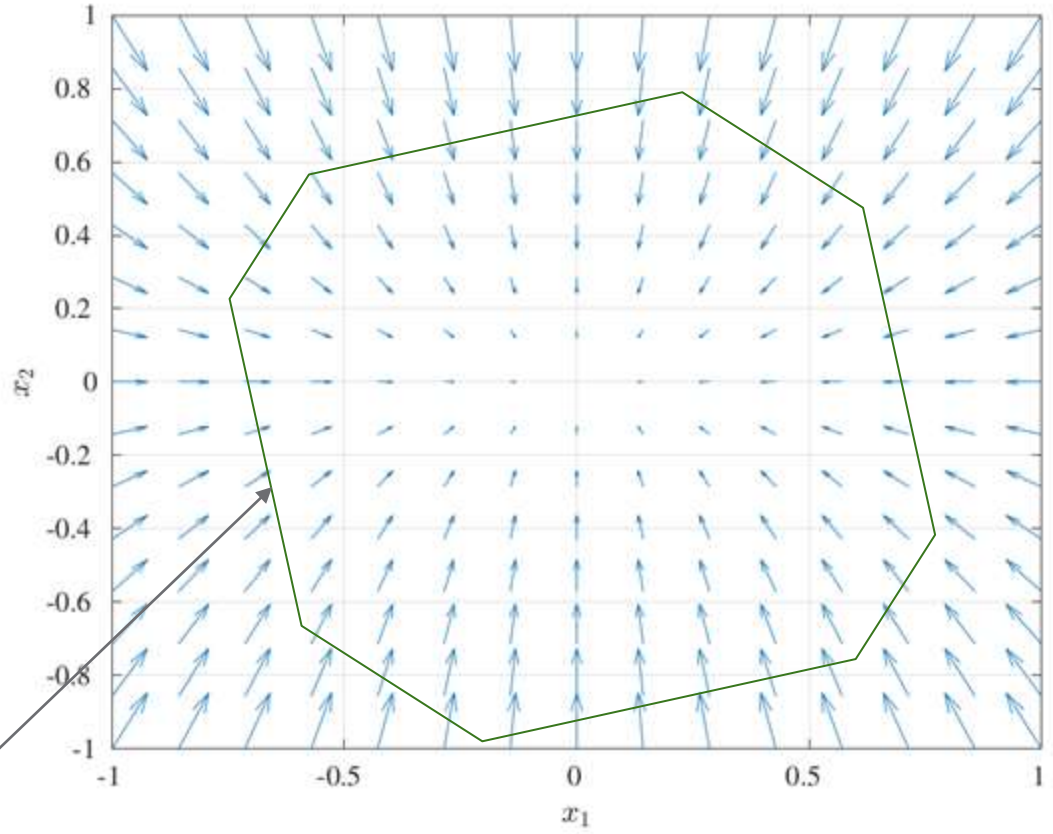
- Vector field

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix}$$

- Dynamical system

$$\dot{x} = f(x)$$

Positively Invariant



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Safety Analysis

6 DOF drone, the state has 12 components

- State of the system

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

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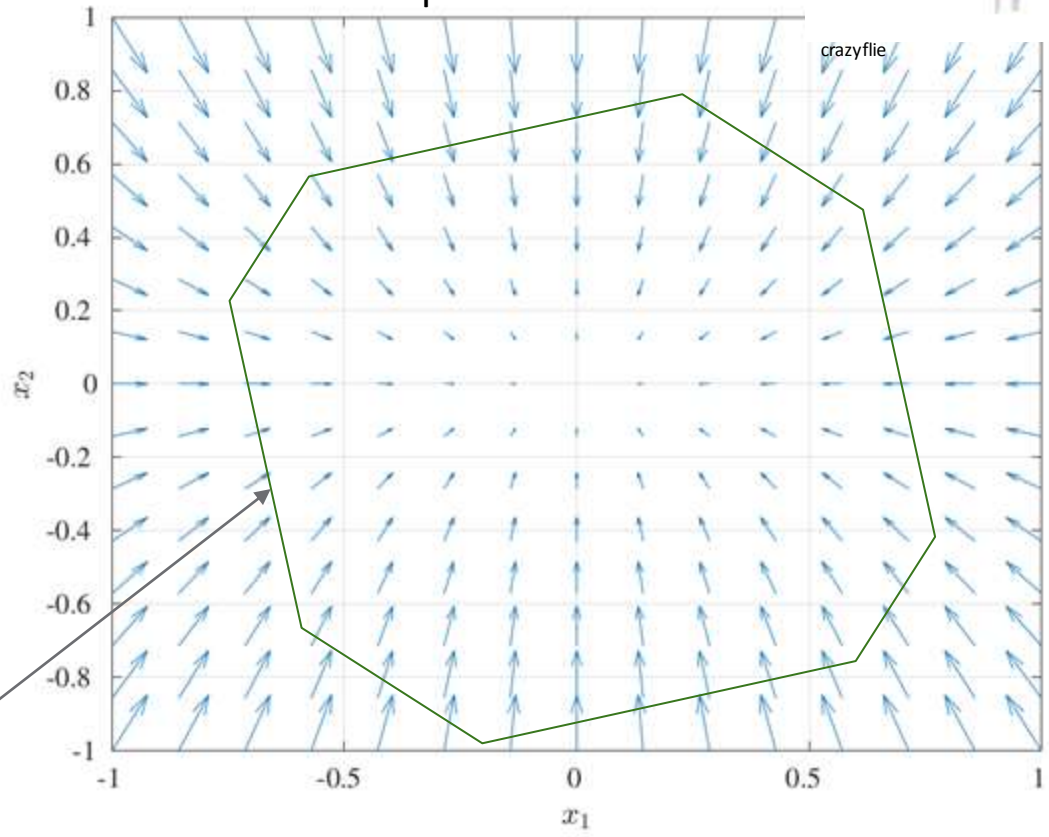

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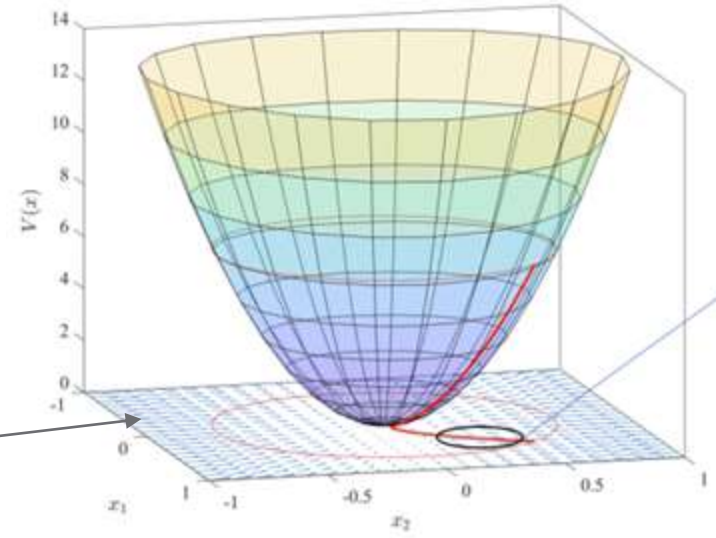
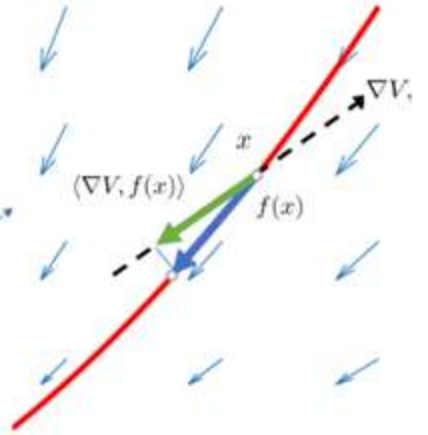
Software Rejuvenation Safety



$\dot{x} = f(x)$



Lyapunov level set

$$\Omega_c = \{x \in D \mid V(x) \leq c\}$$

Positively Invariant

Linear Systems $\dot{x} = f(x) = Ax$

$$V(x) = x^T P x$$

$$\mathcal{E}_c = \{x \in D \mid x^T P x \leq c\}$$ Ellipsoid

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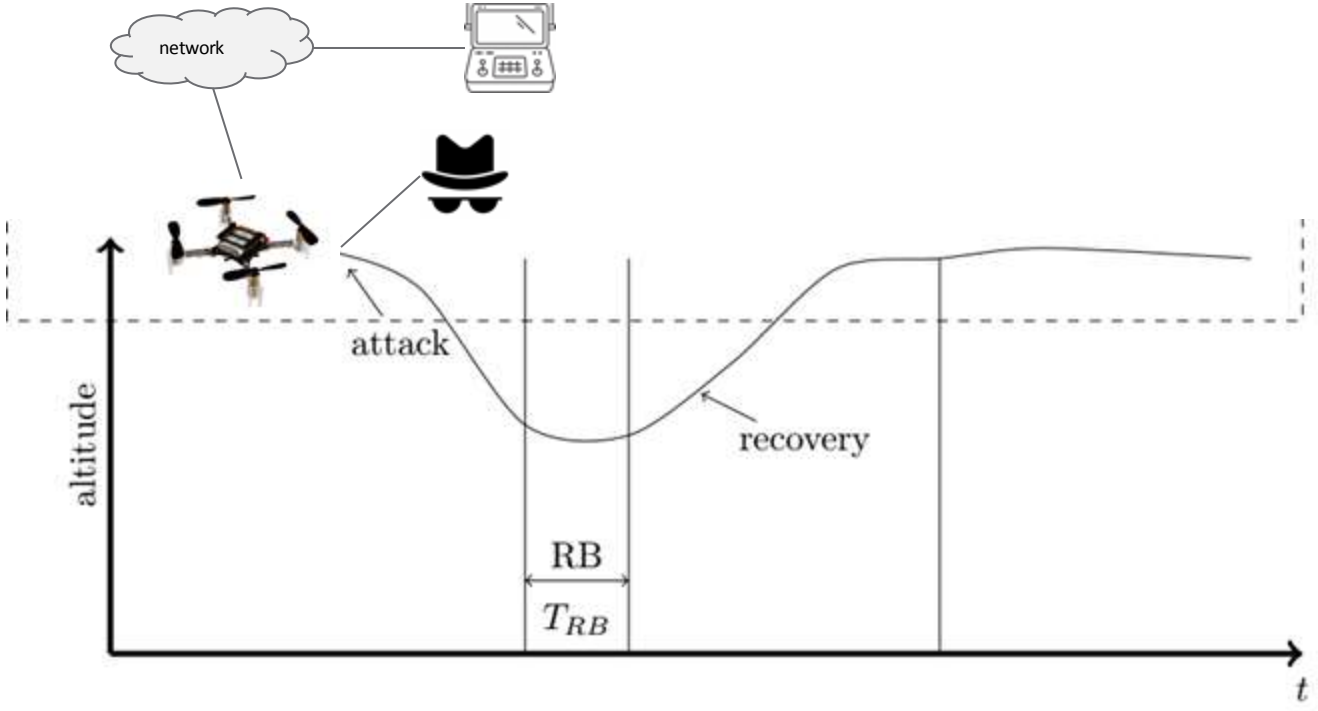
Example: Drone Hovering



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- **Software Reset/ Rollback**

★ Periodic Reboot
★ On-line Reach set analysis

➔ Trajectory Tracking
➔ Full information (state) is not available

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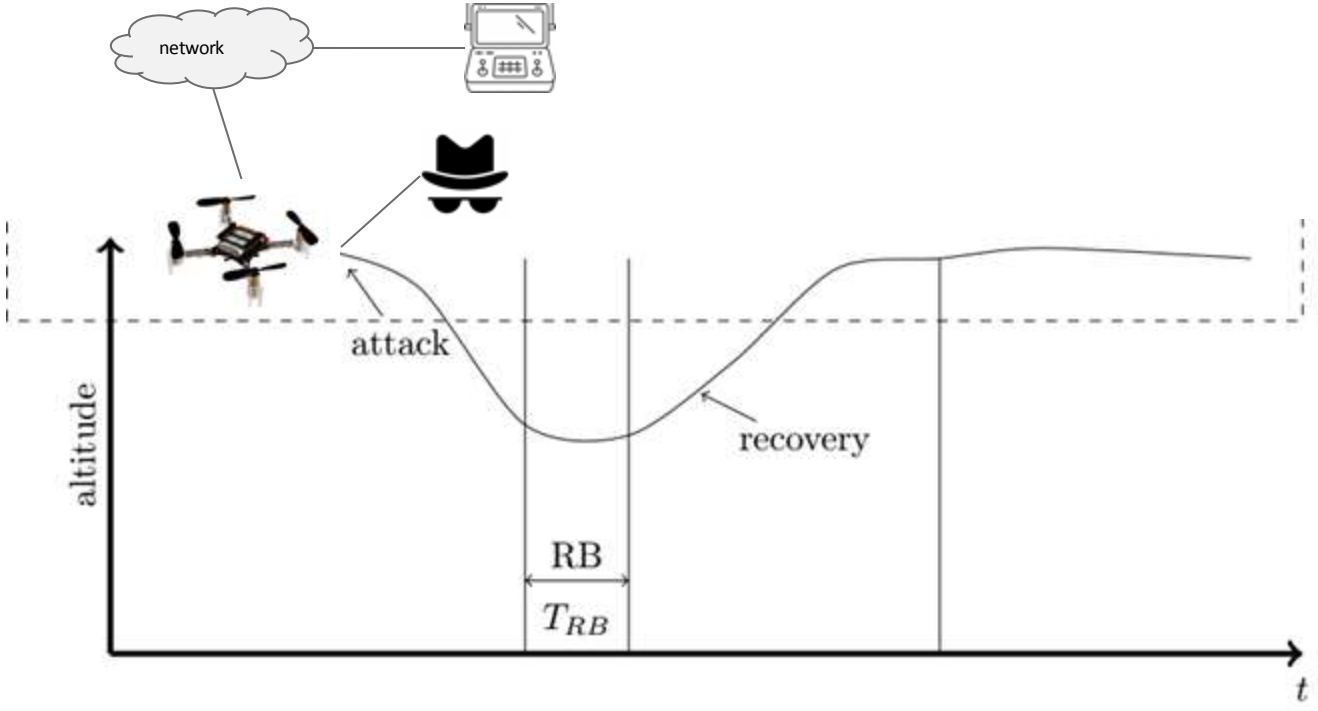

- Hovering
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- Cyber attacks on the run-time code
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Software Rejuvenation

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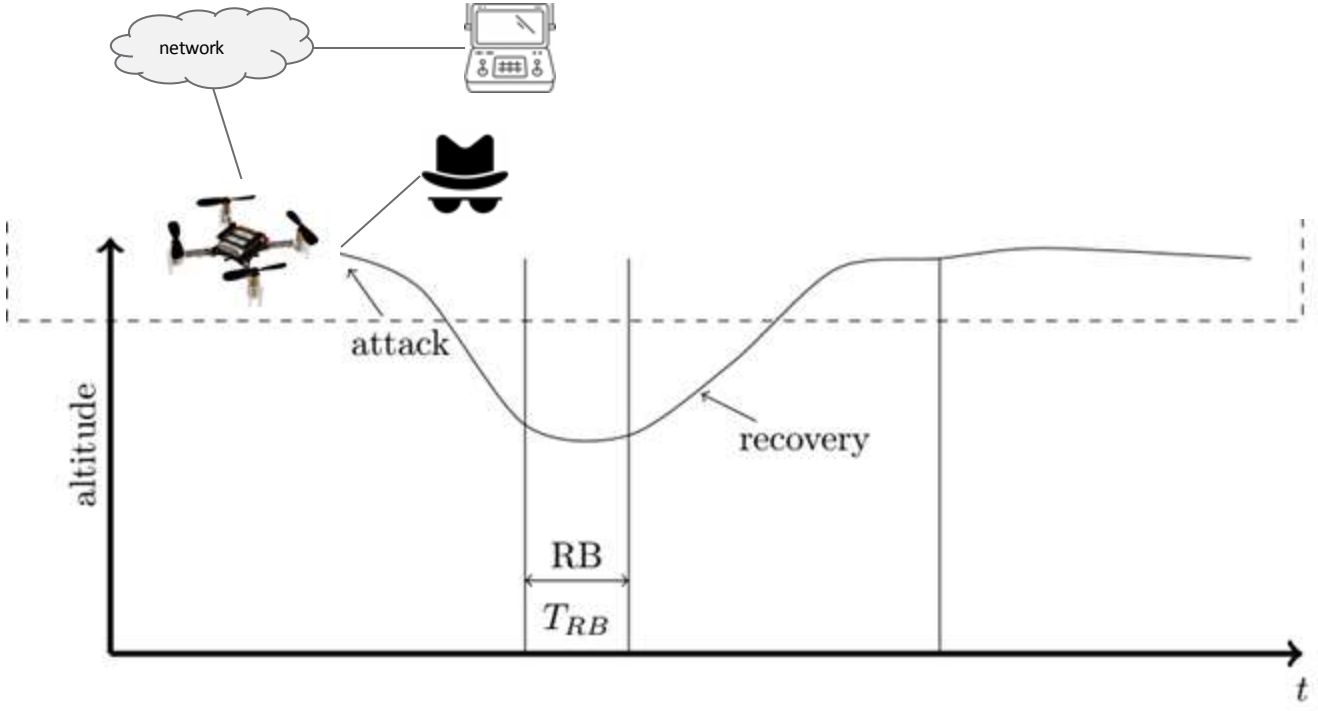
Proposed Software Rejuvenation Scheme



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