Formal Methods of Assurance for CPS

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Formal Assurance of DoD Systems

Assurance Automation for Safe-Critical Cyber-Physical Systems

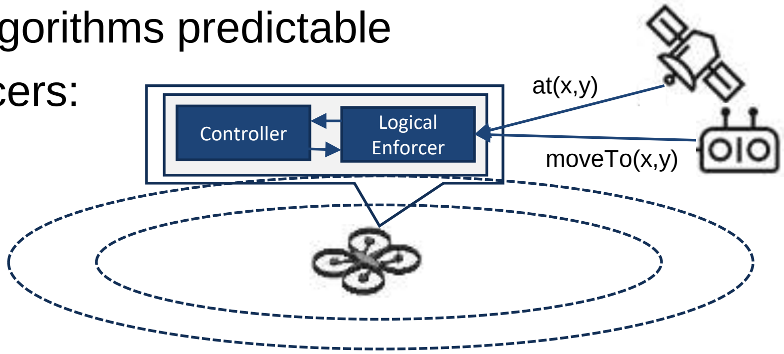
- The DoD requires rapid fielding of critical capabilities to remain competitive with ongoing, urgent and emerging threats.

Challenge:

- Traditional Verification Does Not Scale
- Unpredictable Algorithms like machine learning (Autonomous CPS)
- Timely Interaction with Environment: correct **actions** at correct **time**

Our Solution:

- Add **simpler (verifiable)** runtime enforcer to make algorithms predictable
- Formally: specify, verify, and compose multiple enforcers:
  - Logic: Enforcer **intercepts/replaces** unsafe action
  - Timing: at **right time**
  - In sync with Physics (Control Verification)
- Protect enforcers against failures/attacks



Logical Model

Statespace

- $S = \{s\}$
- $\phi \subseteq S$

Periodic actions

- Transition: $R_P(\alpha) \subseteq S \times S$
- Destination state: $R_P(\alpha, s) = \{s' | (s, s') \in R(\alpha)\}$

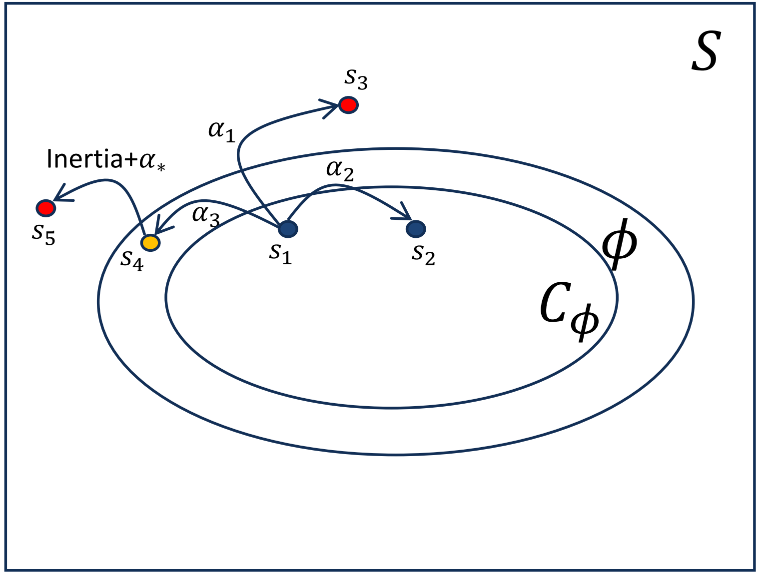
Identify states too close to safety border

- Inertia lead to unsafe state even if enforced
- Enforceable states:

$$C_\phi = \{s | \exists \alpha : R_P(\alpha, s) \in C_\phi\}$$

Safe actions:

- $SafeAct(s) = \{\alpha | R_P(\alpha, s) \in C_\phi\}$



Logical Enforcer

Statespace & actions

- $S = \{s\}, \phi \subseteq S$
- $R_P(\alpha) \subseteq S \times S;\; R_P(\alpha, s) = \{s' | (s, s') \in R(\alpha)\}$

Enforceable states

- $C_\phi = \{s | \exists \alpha : R_P(\alpha, s) \in C_\phi\}$

Safe actions:

- $SafeAct(s) = \{\alpha | R_P(\alpha, s) \in C_\phi\}$

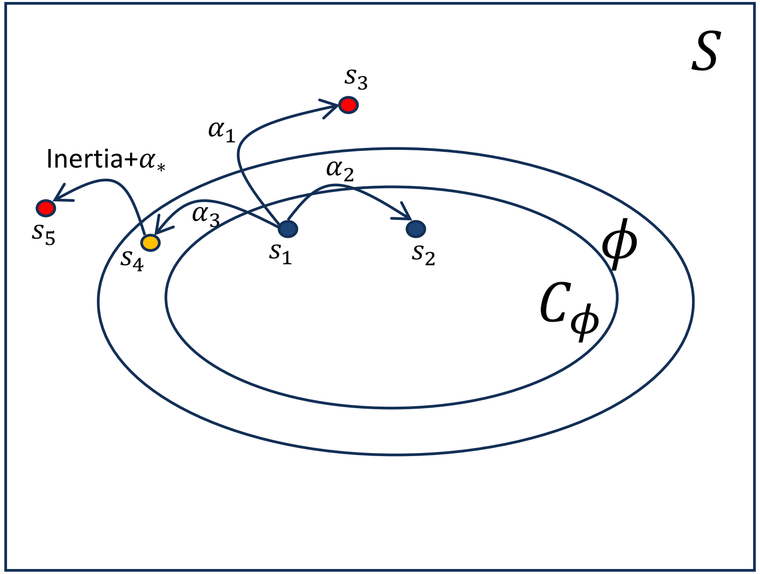
Logical Enforcer: $E = (P, C_\phi, \mu)$

- Set of safe actions:

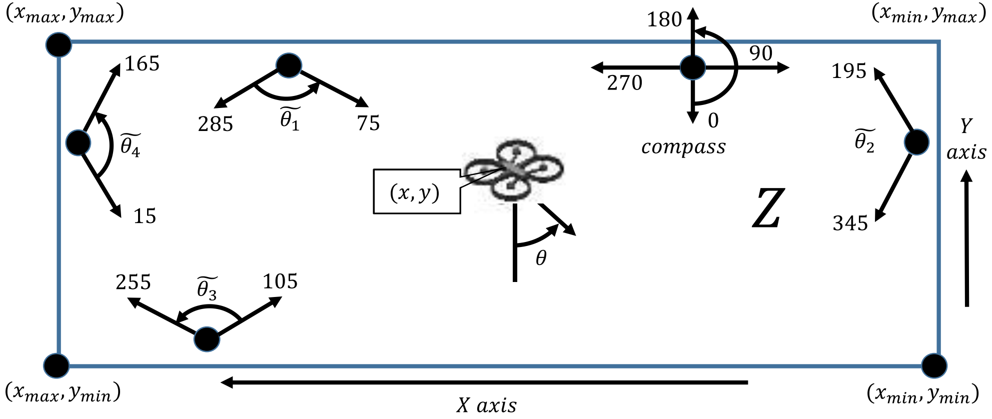
$$\mu(s) \subseteq SafeAct(s)$$

- Monitor and enforce safe action:

$$\tilde{\alpha} = \begin{cases} \alpha, & \alpha \in \mu(s) \\ pick(\mu(s)), & otherwise \end{cases}$$



Drone Example



Statespace

- $S = \{s | s = (x, y, \theta)\}$
- $\phi = \{(x, y, \theta) | \, (x, y) \in Z\}$

Enforceable states

- δ_P: Max distance in one period P
- δ_B: Max distance in opposite direction of enforcement
- $C_\phi = \{(x, y, \theta) | (x + \delta_B, y + \delta_B) \in Z \wedge (x - \delta_B, y - \delta_B) \in Z\}$

Action: constant speed at angle θ

Enforcement: $$\tilde{\theta} = \begin{cases} \tilde{\theta} \in \tilde{\theta}_1, \ if \ Y_{max} - y \leq \delta_B + \delta_P \\ \tilde{\theta} \in \tilde{\theta}_2, \ if \ x - X_{min} \leq \delta_B + \delta_P \\ \tilde{\theta} \in \tilde{\theta}_3, \ if \ y - Y_{min} \leq \delta_B + \delta_P \\ \tilde{\theta} \in \tilde{\theta}_4, if \ X_{max} - x \leq \delta_B \theta + \delta_P \\ \theta, otherwise \end{cases}$$

Composing Enforcers

Enforcer Details: E: (P, C_ϕ, μ, U)

- $\forall s \in C_\phi: \mu(s) \subseteq SafeAct(s)$
- U: utility

Composition without conflict

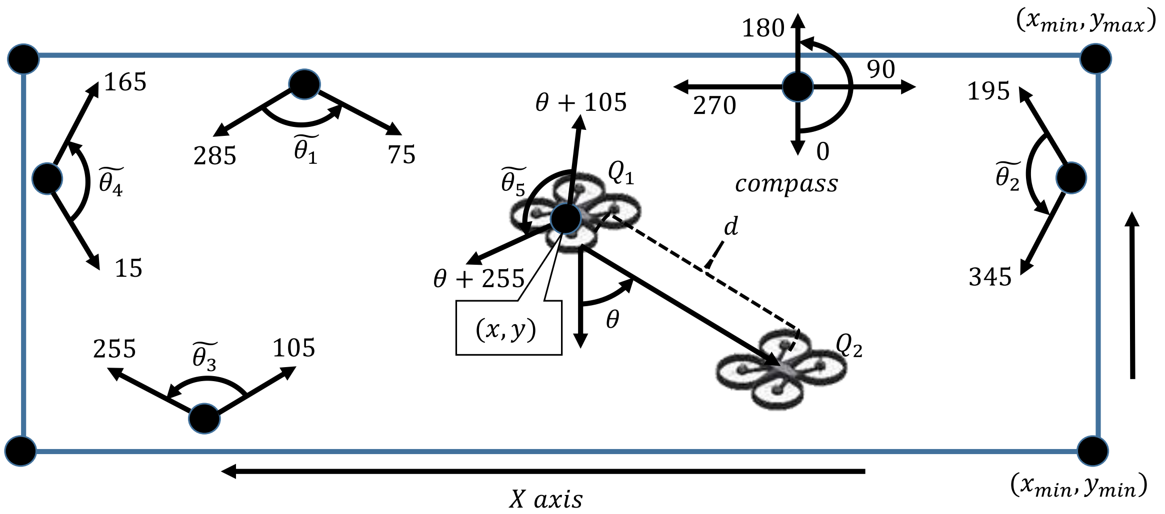
- $E_1: (P_1, C_{\phi_1}, \mu_1, U_1)$
- $E_2: (P_2, C_{\phi_2}, \mu_2, U_2)$
- $\mu_{1,2}:\ \mu_1 \cap \mu_2$

Conflicting: Priority:

- $\mu_{1,2}: \mu_1 \cap \mu_2 \neq \emptyset\ ?\ \mu_1 \cap \mu_2\ :\ \mu_1$

Conflicting: Utility

- $\mu_{1,2}: \mu_1 \cap \mu_2 \neq \emptyset\ ?\ argmax_{\alpha \in \mu_1 \cap \mu_2} \sum U_i(s, \alpha')\ :\ argmax_{\alpha \in \mu_1} \sum U_i(s, \alpha')$




Drone piloted by human
Virtual Fence Marked by Black Posts
-- No Enforcers Active --

Are We Done Yet?

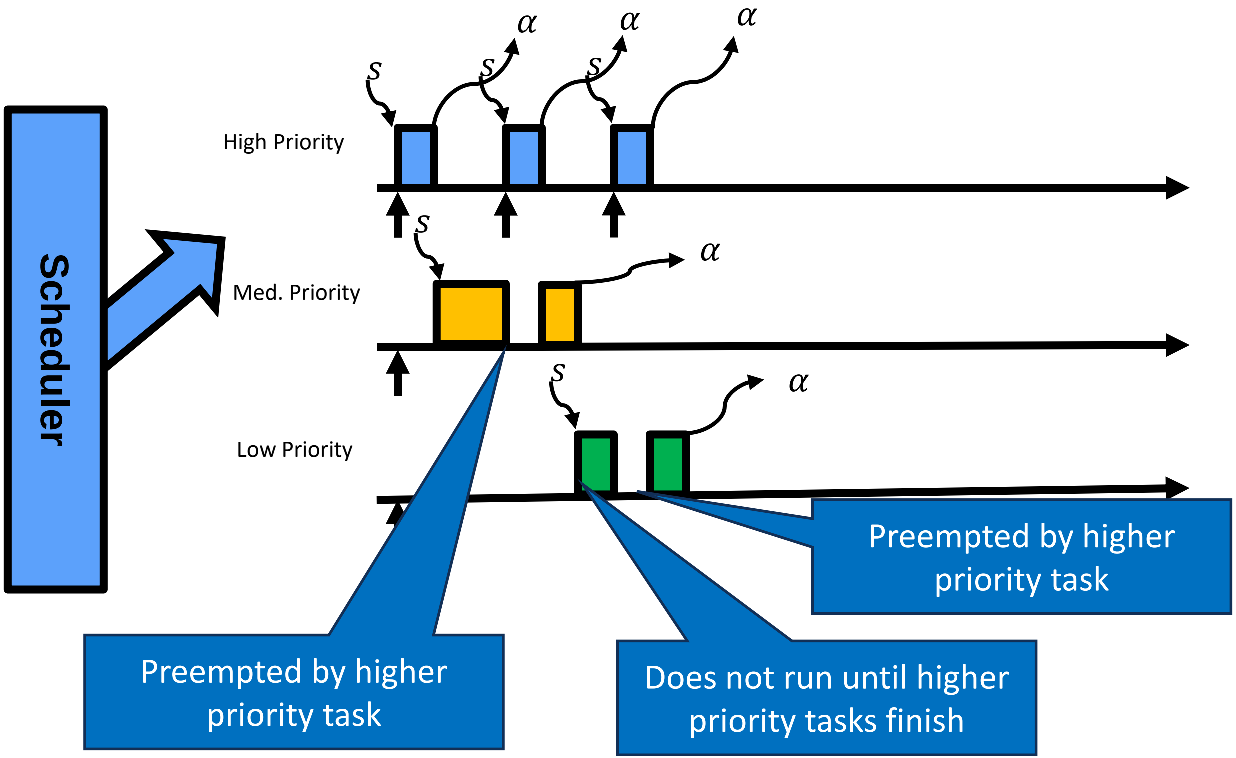
Timing Assumption:

- Unverified software + enforcer finish before end of every P period.
  - Unverified software executes for less than its Worst-Case Execution Time (WCET)
  - Other software running executes for less than its WCET
  - Schedulability analysis successful

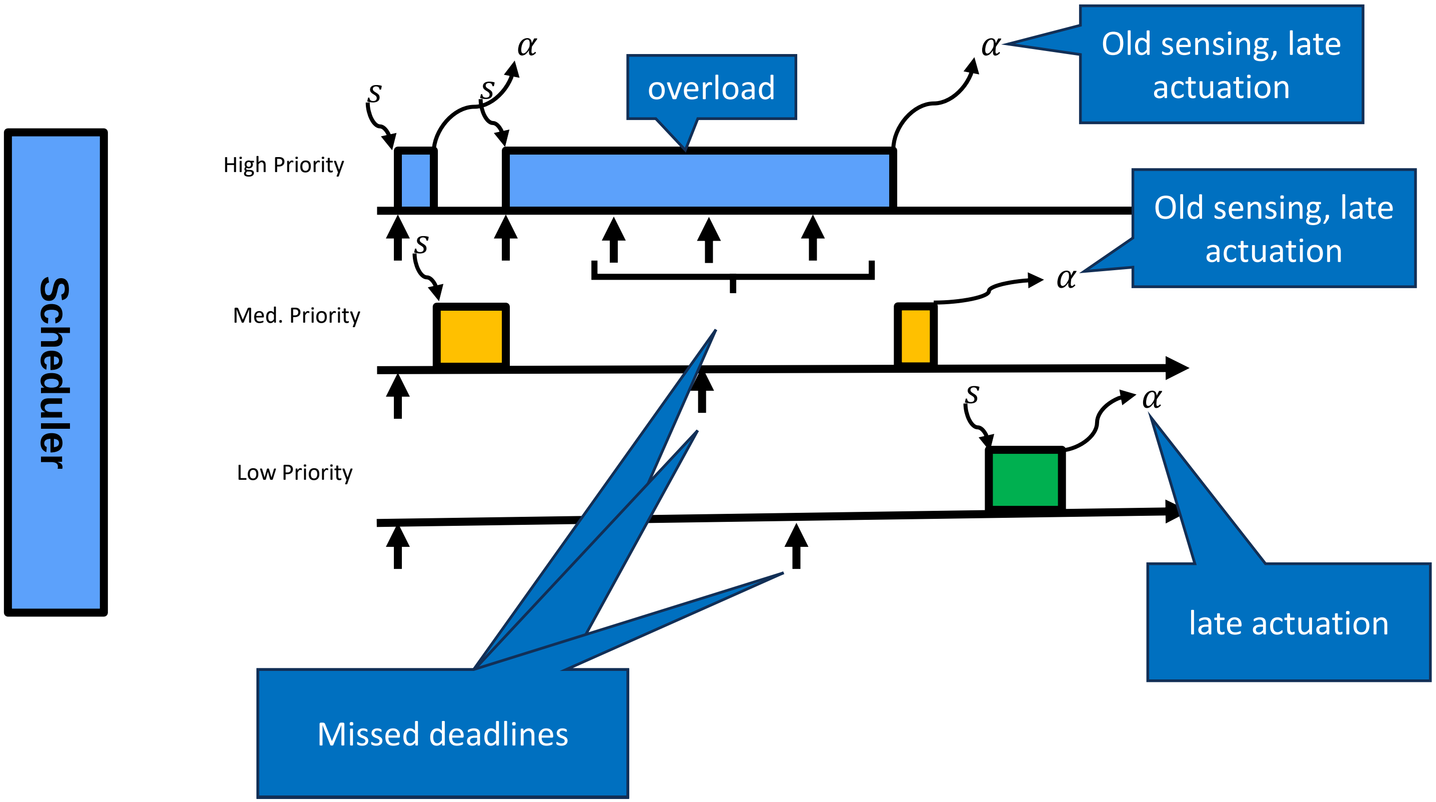
What can go wrong?

- Unbounded preemption
  - High priority software executes longer than WCET
  - Can make other software miss deadlines: late actions with old sensing
- Unbounded execution
  - Software executes longer than WCET
  - Misses its own deadline: Does **NOT** produce output on time: late action + old sensing
    - **Inertia** takes it to **unsafe state**

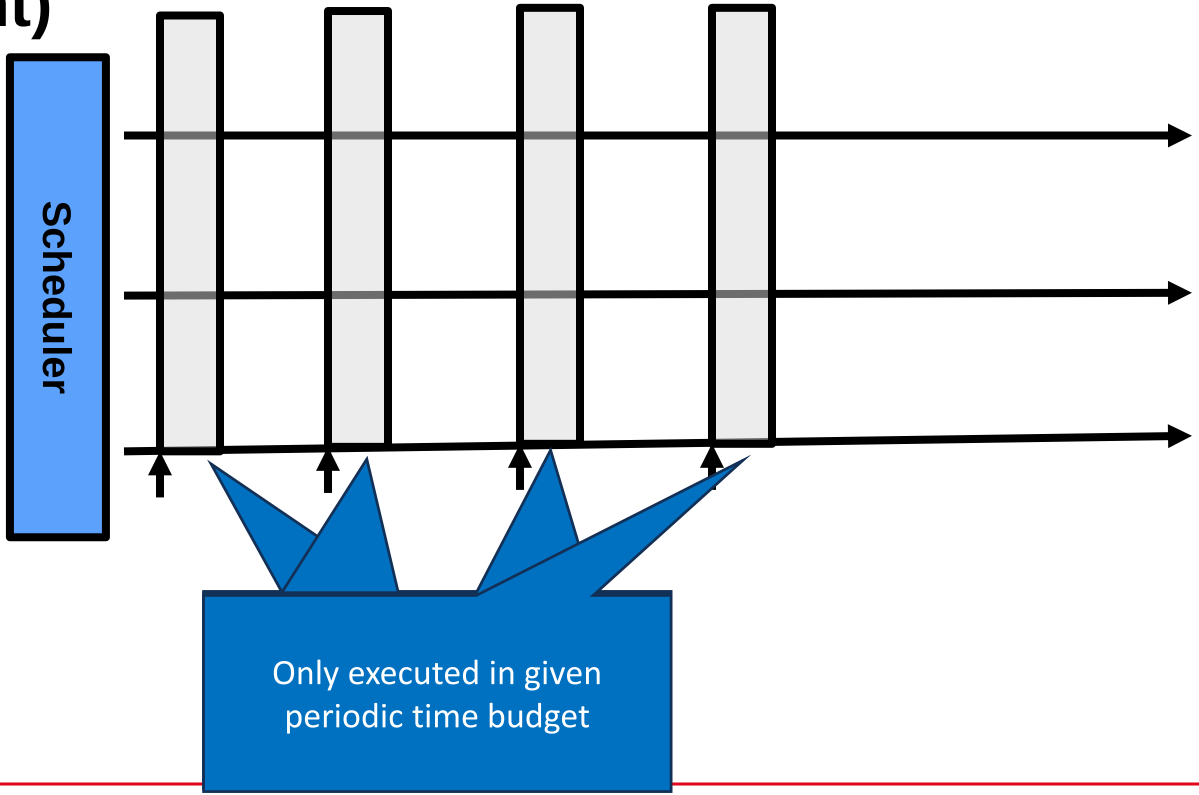
Fixed-Priority Scheduling + Rate Monotonic



Overload -> old sensed data + late actuation



Unbounded preemption
Solution: Enforce timing budgets (timing enforcement)



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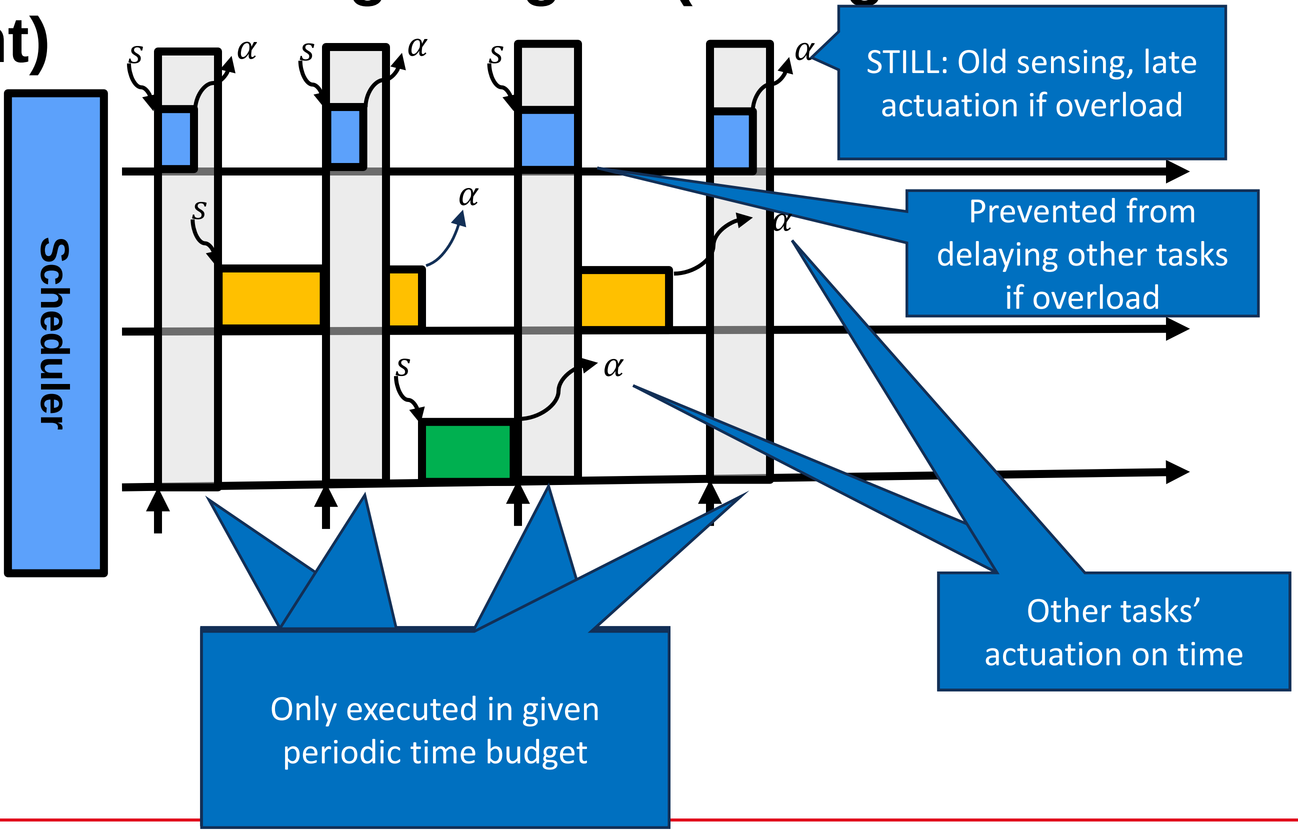
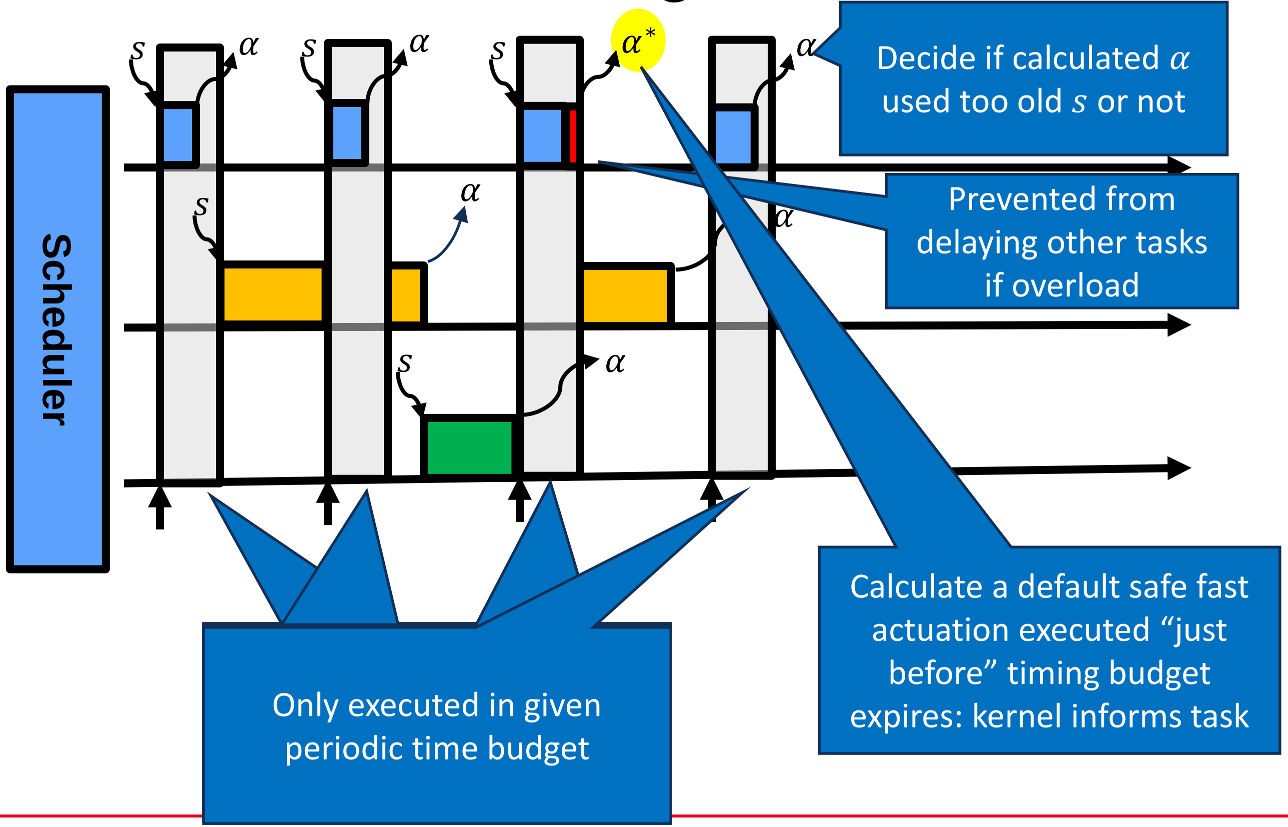


Unbounded Execution:
Solution: safe actuation on timing enforcement



Are we done yet?

Unverified software may corrupt Logical Enforcer

- It can even be malicious

Unverified software uses

- Unverified OS/kernel
- Unverified libraries

Temporal Enforcer relies on

- Unverified kernel / scheduler

Mixed-Trust Computing

System composed of trusted (verified) and untrusted (unverified) components

- Trusted : Verified Enforcers
- Untrusted: Unverified software

Untrusted should not corrupt trusted

Trusted should not depend on untrusted

- Cannot depend on unverified kernel / scheduler

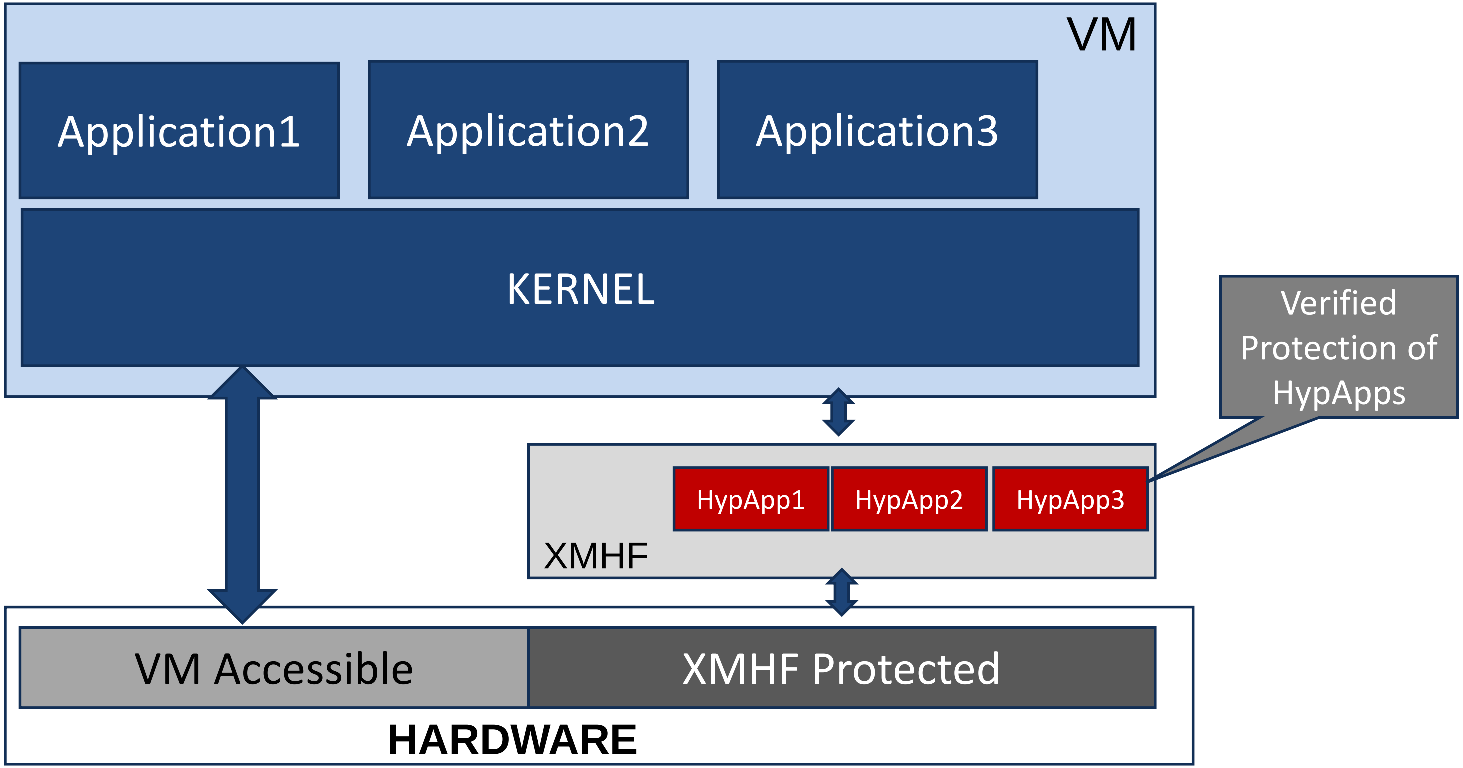
Trusted components

- Preserve safety

Untrusted components

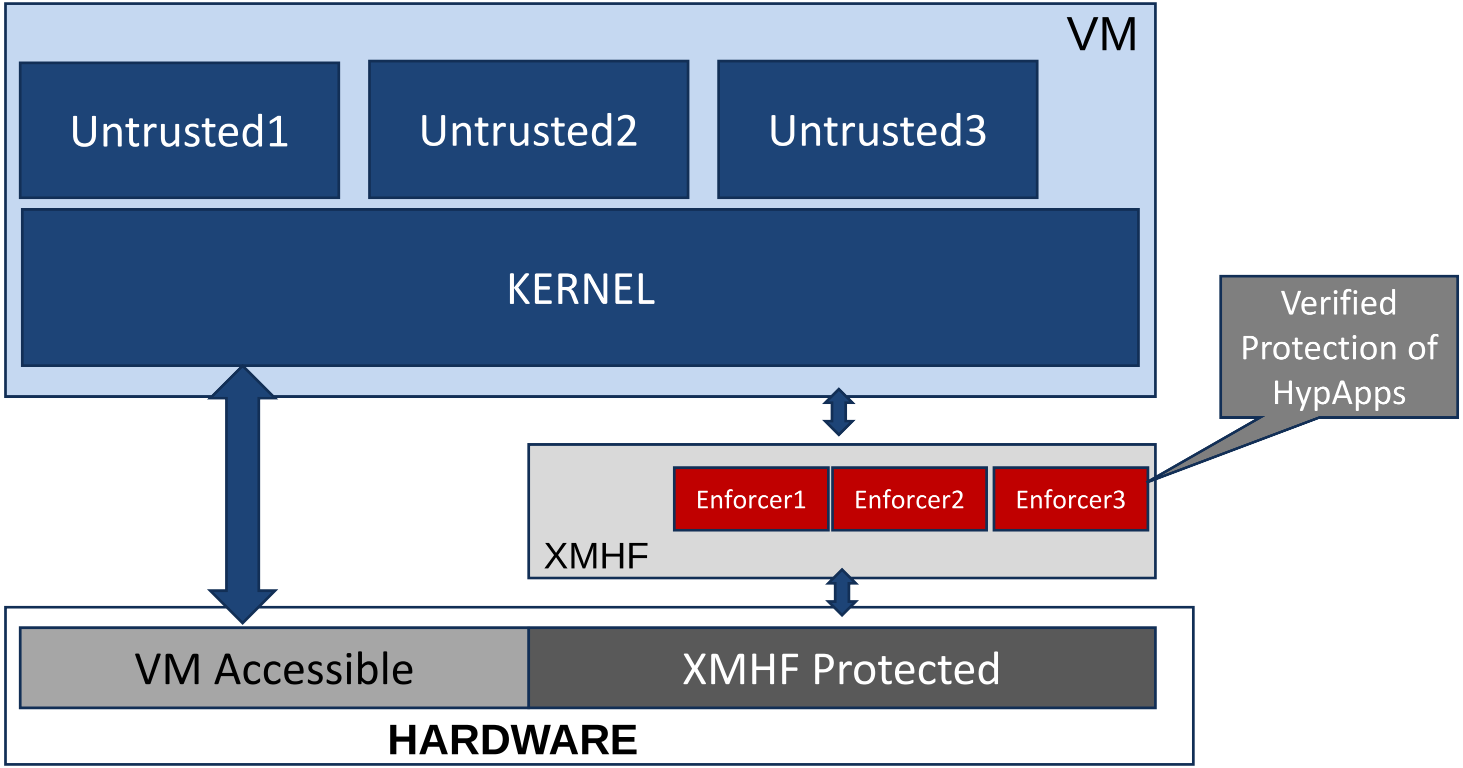
- Provide mission capability / performance
- Potential spurious failures

Uber XMHF: Verified Micro-Hypervisor Protection



Uber XMHF: Verified Micro-Hypervisor Protection

Only temporal enforcer can be protected if untrusted does not finish



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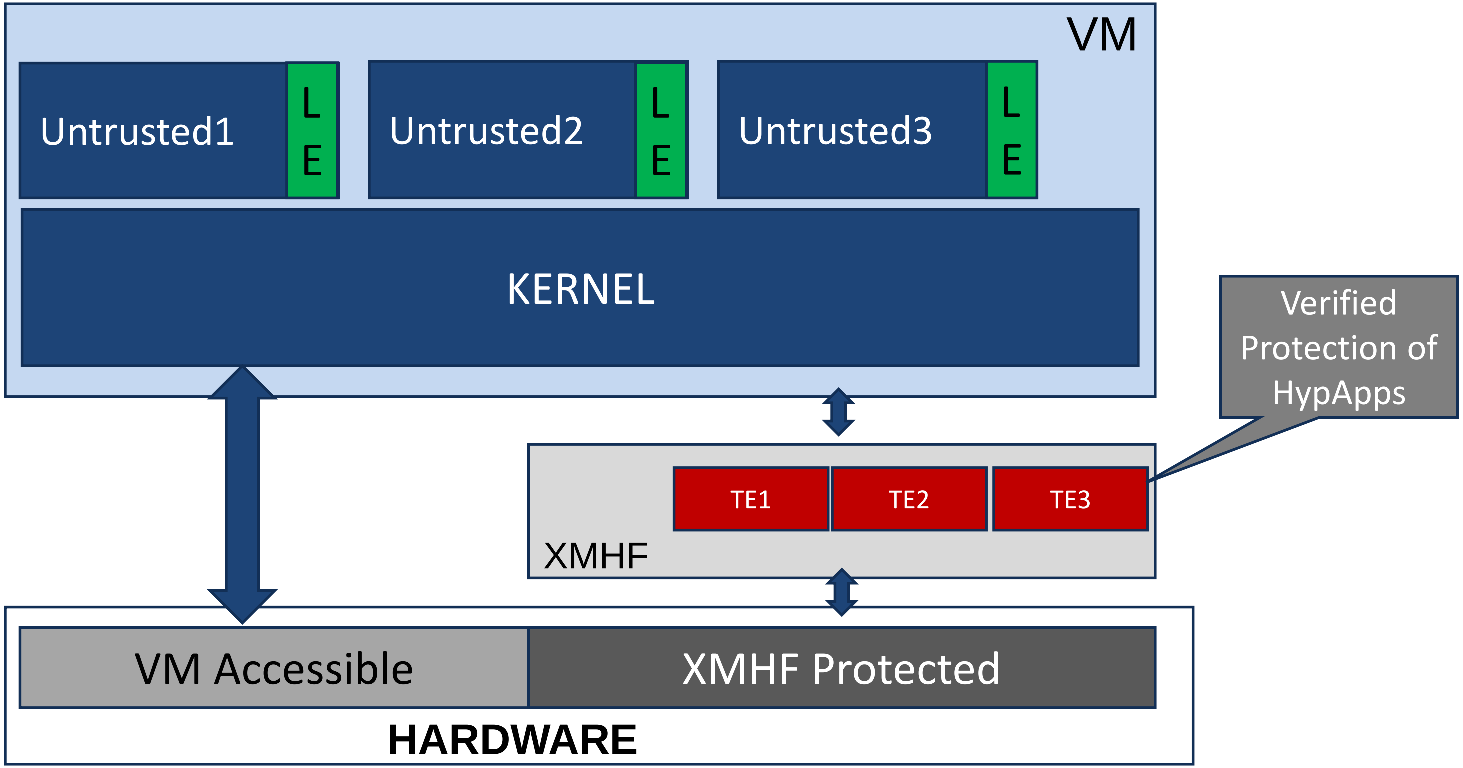
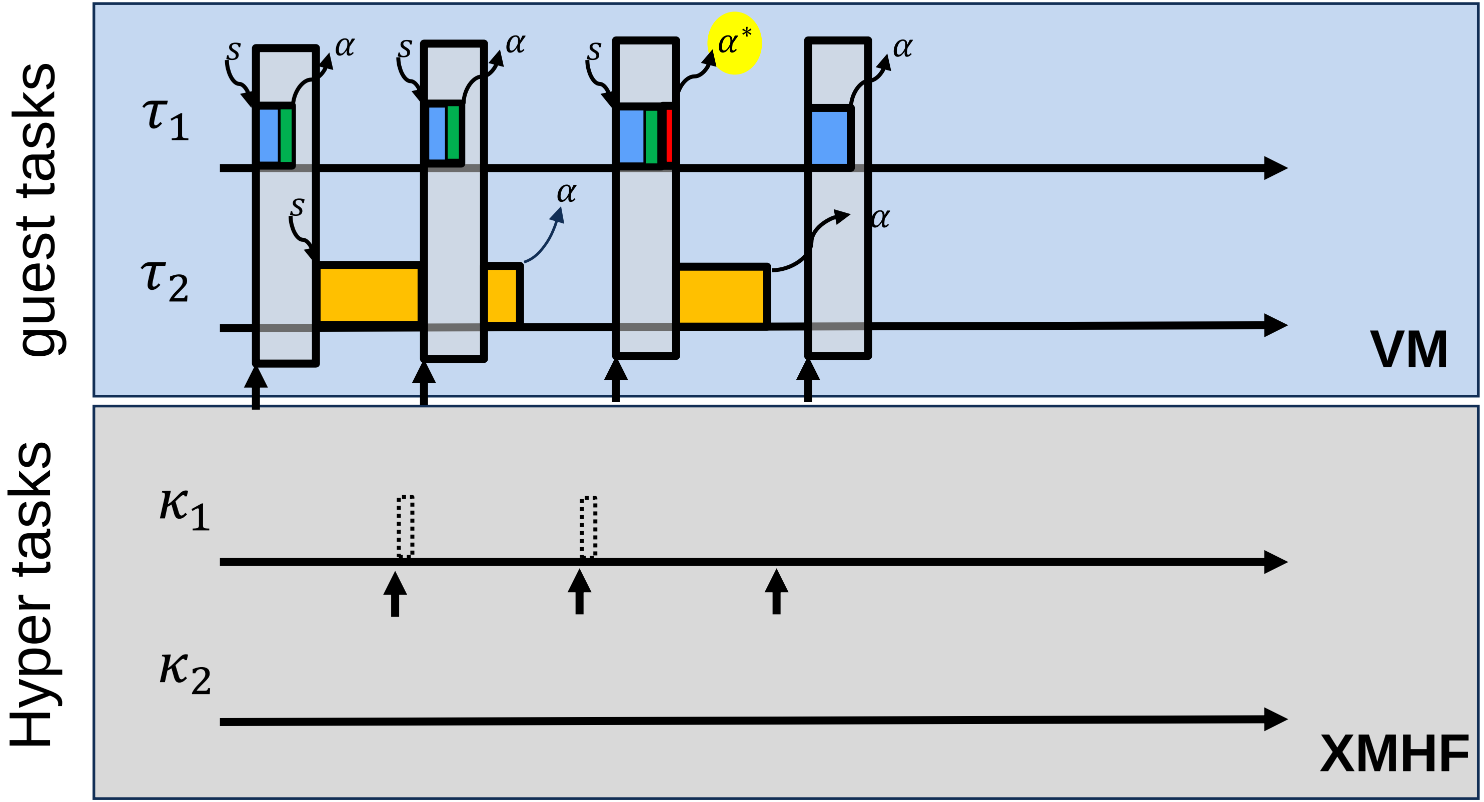


Two schedulers: VM scheduler + XHMF Scheduler

Mixed-trust task: $\mu_i = (\tau_i, \kappa_i)$



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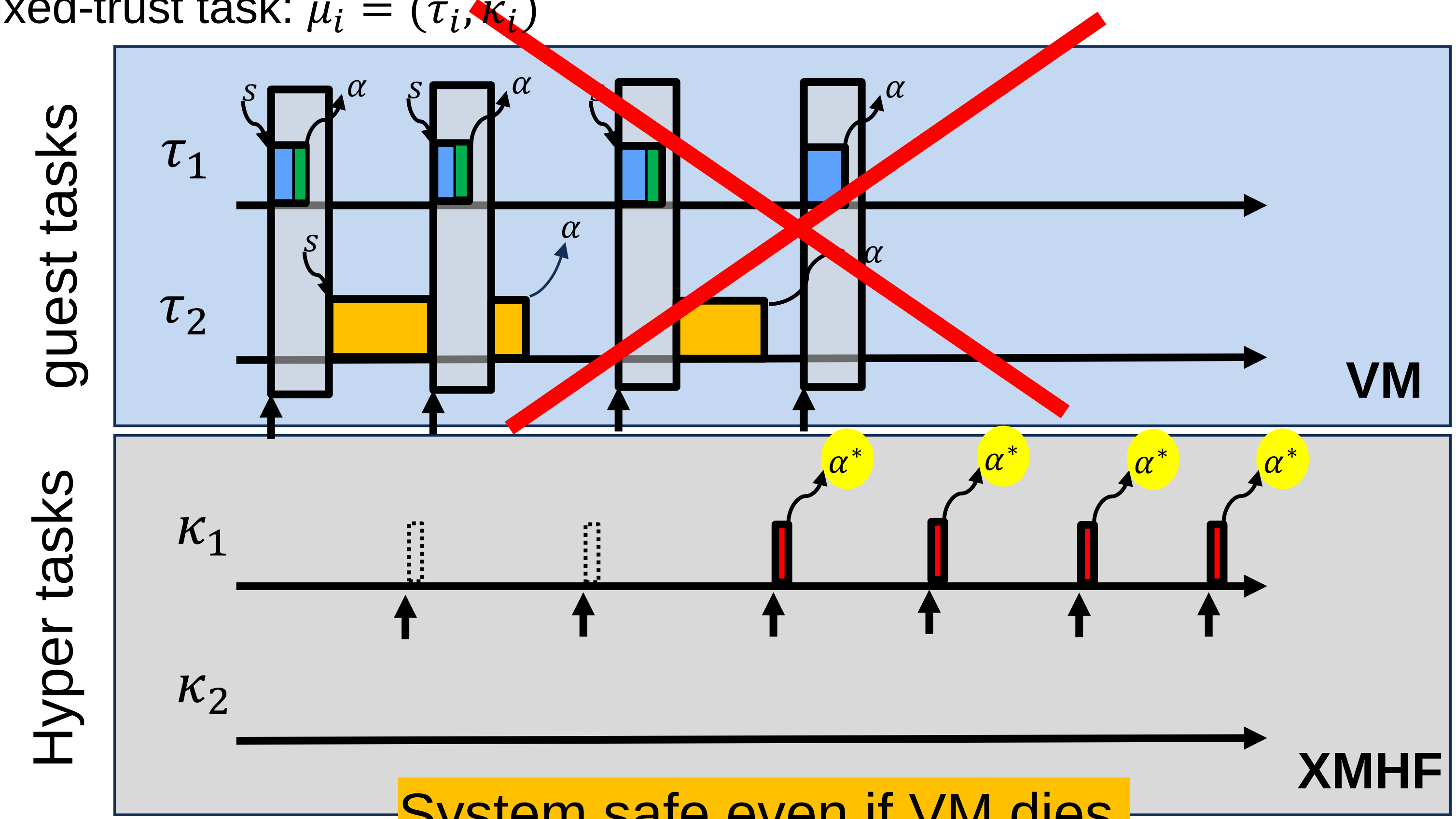
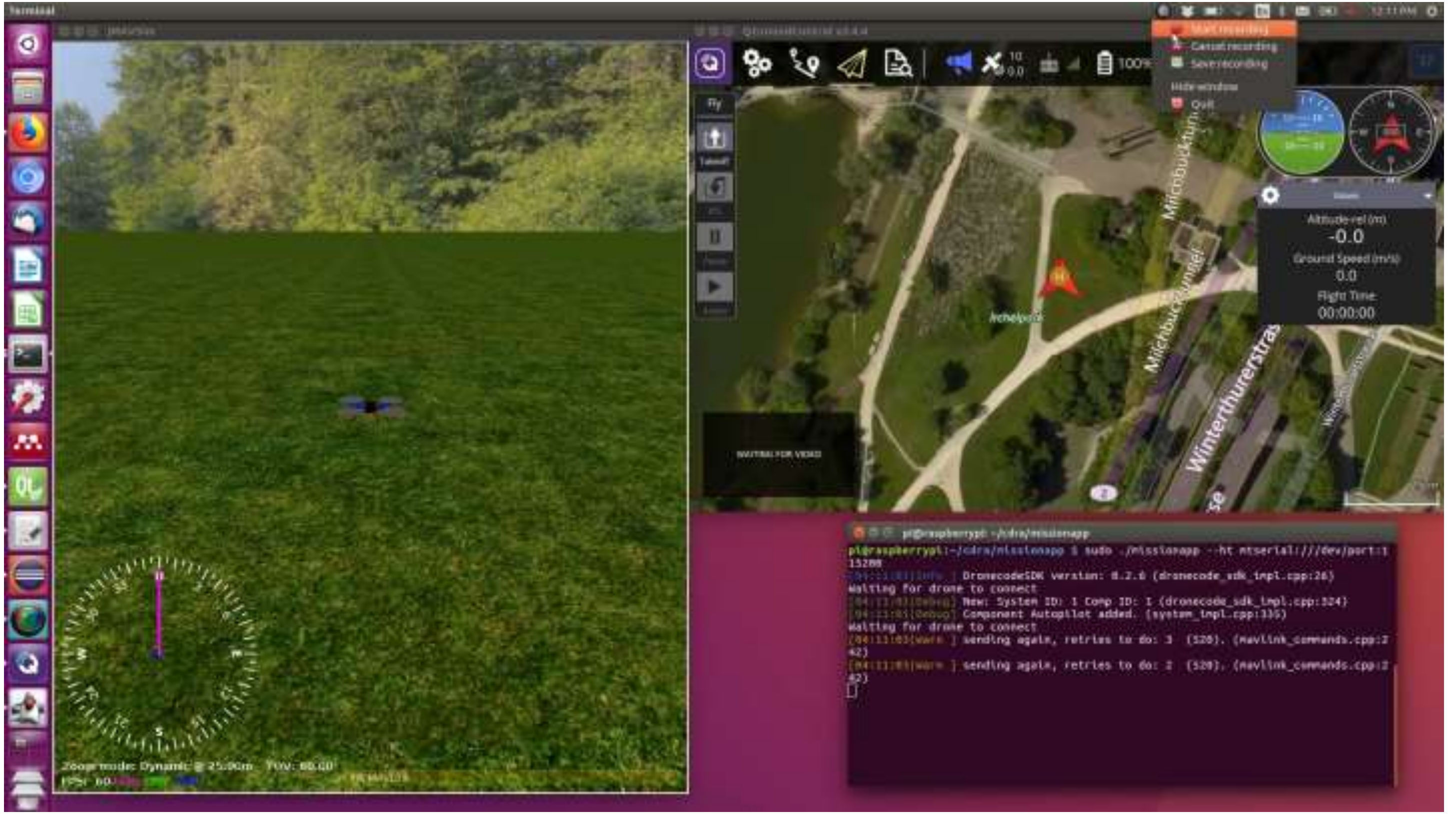


System safe even if VM dies

Simulation Demo

Drone Protection (VM Crash) – Hardware in the loop



Application to Security Intrusion: Controller Rejuvenation ONR Project

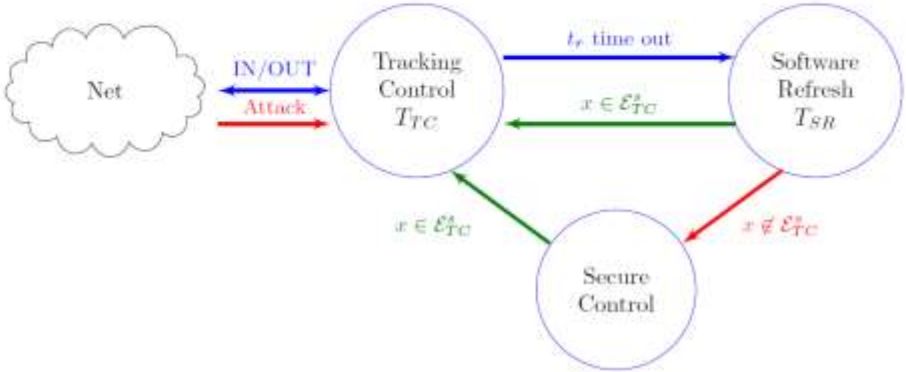
Problem:

- Controller compromised by security attack
- Difficult to detect

Solution:

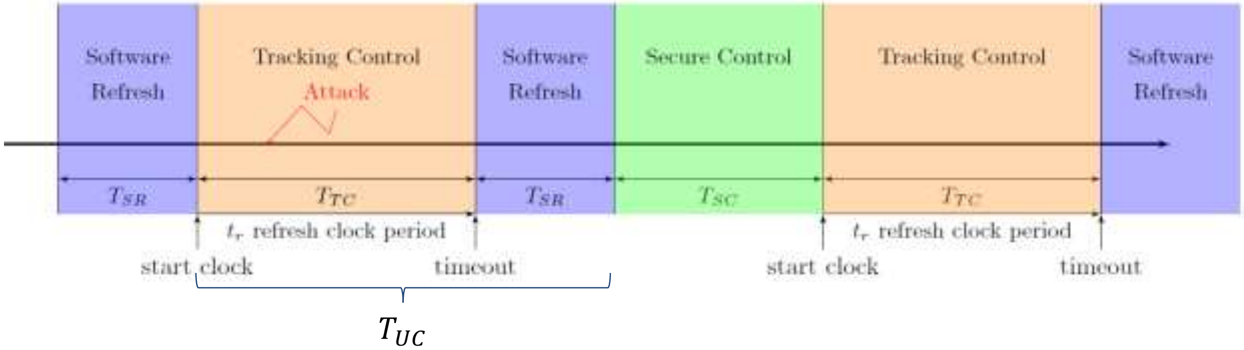
- Reboot (rollback to previous safe state)
- Re-establish stability of system
- Track mission progress

Software Rejuvenation Operating Modes



1. Tracking Control (TC)
2. Software Refresh (SR)
3. Secure Control (SC)

- The switch from TC to SR is triggered by a timer (unsecure information)
- From SR to TC or SC there is a condition to be satified (secure information)



Software Rejuvenation
Secure Control

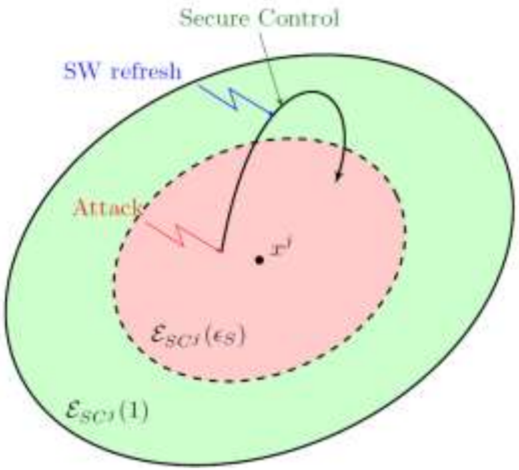
- Recoverable Set

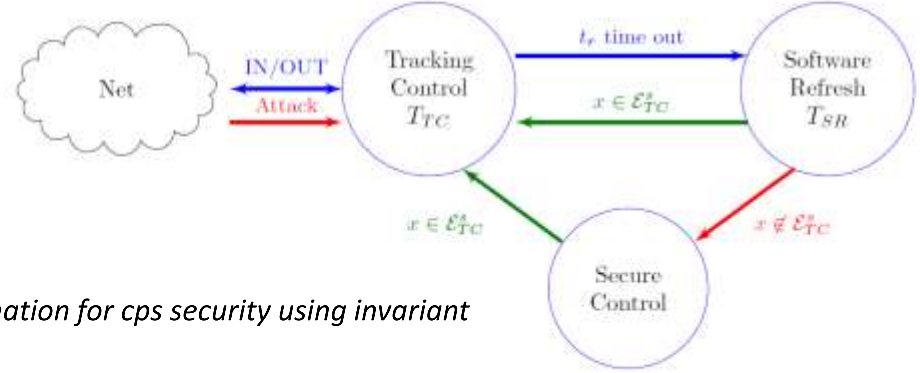
$\mathcal{E}_{SCj}(1)$ Lyapunov Theory and Positively Invariant Sets

- Safety Set $\mathcal{E}_{SCj}(\epsilon_s) \triangleq \epsilon_s \mathcal{E}_{SCj}(1)$

ϵ_s T_{UC}

$$\mathcal{R}(T_{UC}; \mathcal{E}_{SCj}(\epsilon_s), U) \subseteq \mathcal{E}_{SCj}(1)$$





R. Romagnoli, B.H. Krogh, and B. Sinopoli, *Design of software rejuvenation for cps security using invariant sets*, accepted to 2019 American Control Conference (ACC).

Software Rejuvenation
Secure Control

Controlled System: $\dot{x} = f_\varphi(x) \triangleq f(x, \varphi(x))$
Lyapunov Function: $V_\varphi : \mathbb{R}^n \to \mathbb{R}$, $\mathcal{N}_{V_\varphi}(x_{eq}) \subseteq \mathcal{N}_\varphi(x_{eq})$,
$V_\phi(x_{eq}) = 0$ and $\forall x \in \mathcal{N}_{V_\varphi}(x_{eq}) - \{x_{eq}\}$: (i) $V_\varphi(x) > 0$,

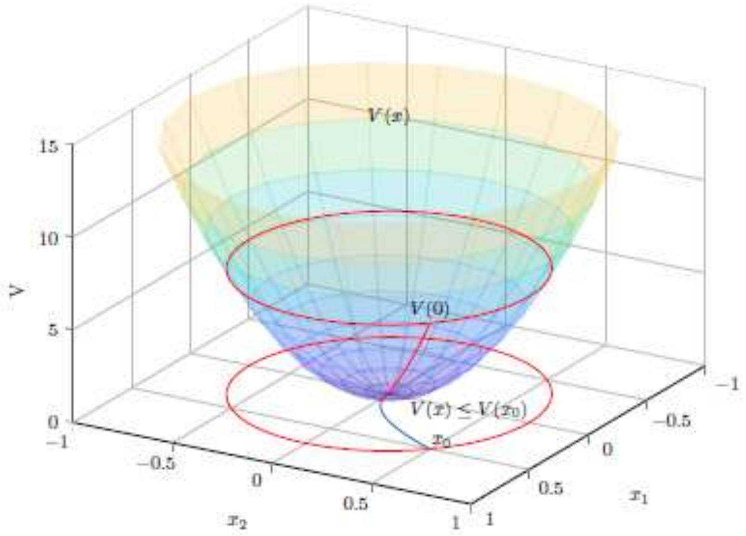
$$\dot{V}_\varphi(x) = \frac{\partial V}{\partial x} \cdot f_\varphi(x) < 0$$

Lyapunov level set: For $\epsilon > 0$,

$$\mathcal{E}_\varphi(\epsilon) = \{x \in \mathcal{N}_{V_\varphi}(x_{eq}) | V_\varphi(x) \leq \epsilon\}. \qquad \epsilon \leq 1$$

Positively Invariant Set. For any $0 < \epsilon \leq 1$, $\mathcal{E}_\varphi(\epsilon)$ is an *invariant set*.

$$\forall\, t > 0,\ \mathcal{R}(t; \mathcal{E}_\varphi(\epsilon), \varphi) \subseteq \mathcal{E}_\varphi(\epsilon)$$

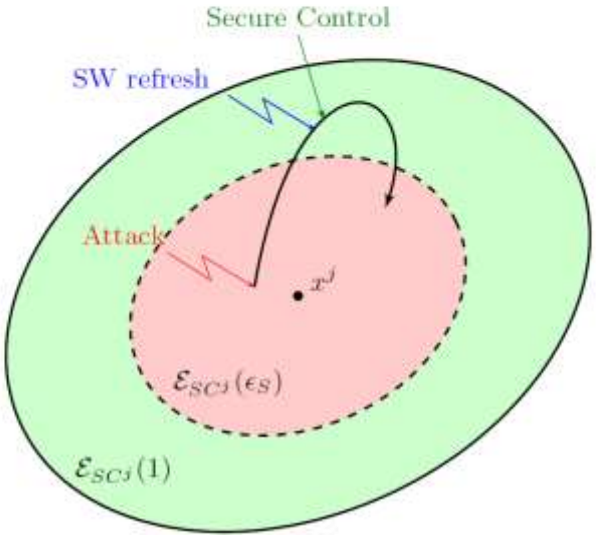


Software Rejuvenation Secure Control

Prop.1. Given $\dot{x} = f_\varphi(x) \triangleq f(x, \varphi(x))$ with stabilizing controller φ for equilibrium state $(x_{eq}, \varphi(x_{eq}))$ and Lyapunov function $V_\varphi(x)$ as defined above, given $\epsilon > 0$ for any $\epsilon < \epsilon' \leq 1 \; \exists \, \gamma > 0 \; \ni \forall \, t \geq (\epsilon' - \epsilon)\gamma^{-1}$,

$$\mathcal{R}(t; \mathcal{E}_\varphi(\epsilon'), \varphi) \subseteq \mathcal{E}_\varphi(\epsilon).$$

Prop.2. For any $U \subseteq \mathcal{U}$ and any $0 < \epsilon < \epsilon' \leq 1$, $\exists \, T_U > 0 \; \ni \; \mathcal{R}(t; \mathcal{E}_\varphi(\epsilon), U) \subseteq \mathcal{E}_\varphi(\epsilon') \; \forall \, t < T_U$.

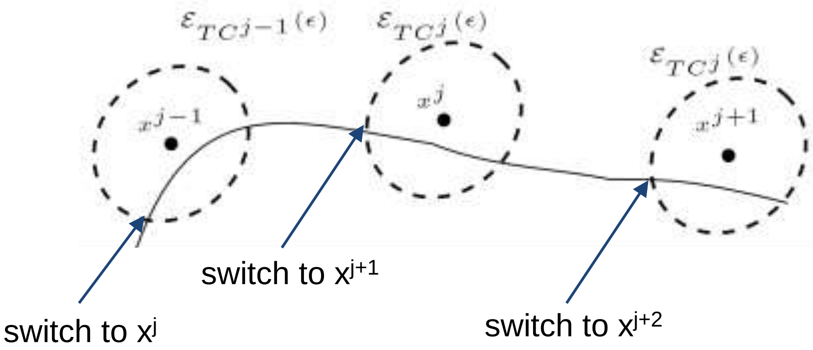


- Prop1. We can always recover in a finite time
- Prop2. Given a reduced version of the Safety Set we can always find a period of time where is allowed uncertain control.

Software Rejuvenation
Analysis of mission progress

Idea:

Provide a sequence of way points that represent a sequence of equilibrium points around which we define the Safe Set.



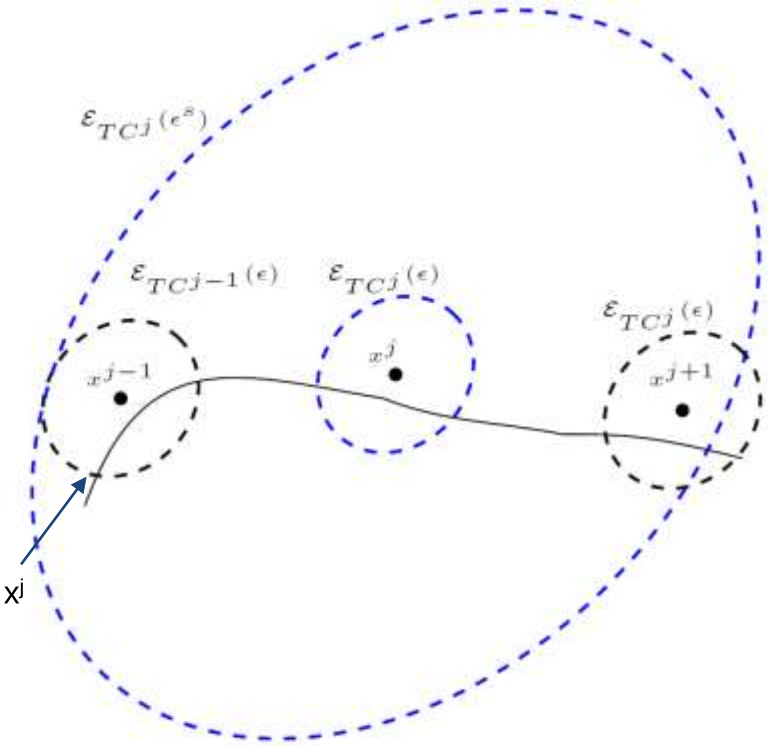
Goal:

- Safety transition from one way point to the next one.
- Liveness (in the case of no attack)

Software Rejuvenation
Analysis of mission progress

- Safety
- Liveness

R. Romagnoli, B.H. Krogh, and B. Sinopoli. Safety and liveness of software rejuvenation for secure tracking control, accepted to 2019 European Control Conference (ECC).

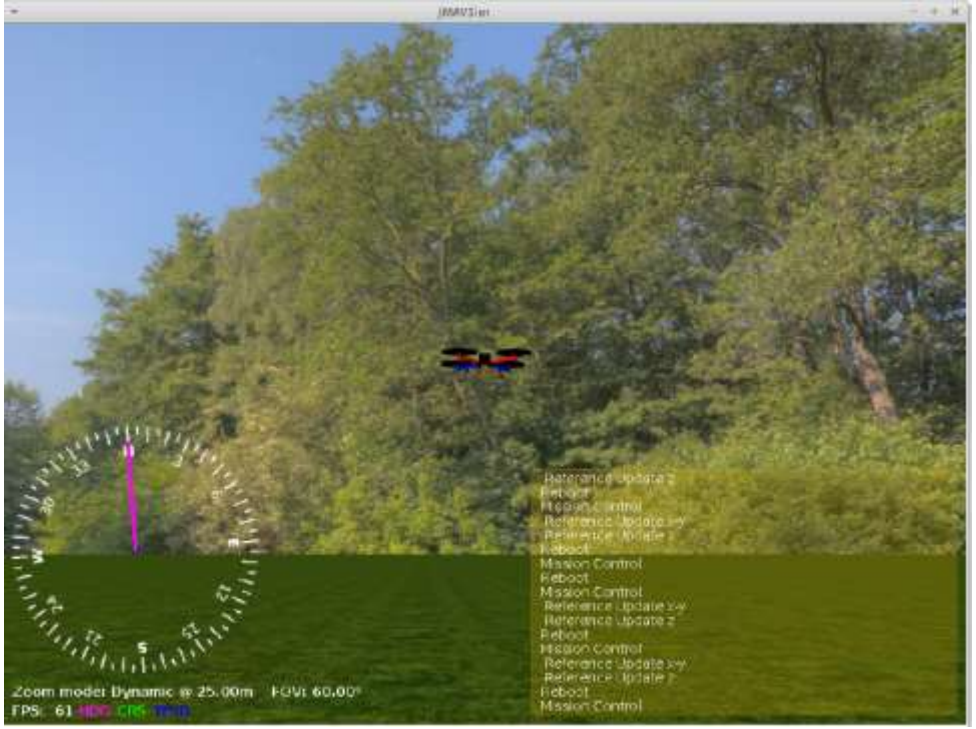


switch to x^j

Software Rejuvenation
Drone experiment

6 DOF $\Rightarrow$ 12 state variables

$$\ddot{p}_x = -\cos\phi \sin\theta \frac{F}{m}$$
$$\ddot{p}_y = \sin\phi \frac{F}{m}$$
$$\ddot{p}_z = g - \cos\phi \cos\theta \frac{F}{m}$$
$$\ddot{\phi} = \frac{1}{J_x}\tau_\phi$$
$$\ddot{\theta} = \frac{1}{J_y}\tau_\theta$$
$$\ddot{\psi} = \frac{1}{J_z}\tau_\psi.$$



Linear design:

- linearize at equilibrium
- assume full state available
- LQ state feedback design
- reference points = equilibrium states

Software Rejuvenation: Drone experiment

Software Rejuvenation
Analysis of mission progress

6 DOF ⇒ 12 state variables

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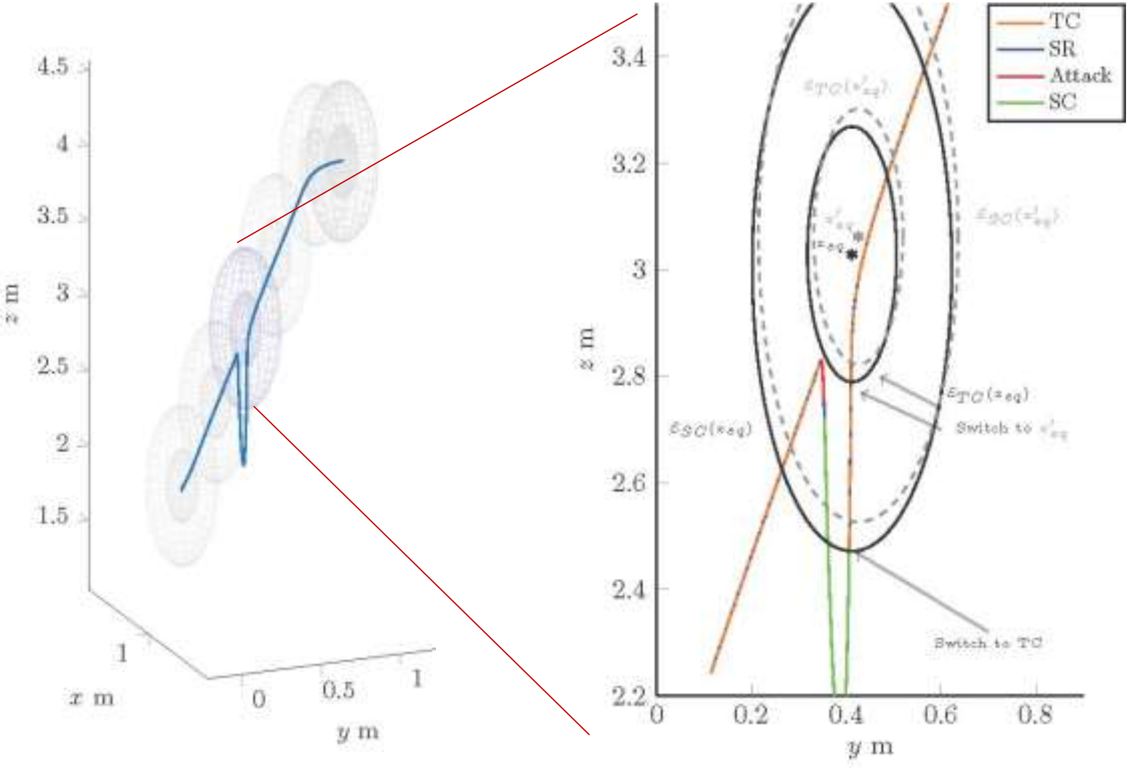

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Current Experiments
Micro-reboot in indoor drone

Summary

Scalable formal verification

- Using enforcers
- Untrusted components guarded by trusted (verified) ones

Full verification of CPS

- Control
- Logical
- Time

Protected verification

- Enables building trusted system with untrusted components
- Protection verified down to the metal