RHIMES PI Meeting

YOLO Transition to Navy Systems

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IN THE CITY OF NEW YORK

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Cyber-Physical Systems (CPS)

Composed of

- Software Controlling (cyber)
- Physical Phenomena (physical)

Examples:

- Car Airbag
  - Software detects crash and triggers airbag inflation
- Drone
  - Software detects and corrects drone attitude
- Inverted Pendulum
  - Software detects and corrects pendulum inclination

Inertia

- Physical phenomena evolves even w/o software interaction
- Stable control requires continuous cyber-physical interaction at correct timing

Cyber-Physical Systems Security

CPS

- Denial of Service can lead to damage
- Security mechanisms preserve physical process properties (e.g., control stability)
- If software stops physical process continues
- Software state recoverable from sensors

Good News:

- Physical process continues working during software blackouts

Bad News:

- Long software blackout leads to physical damage

IT

- Denial of Service: only temporary interruption
- Security mechanisms focused on information protection
- If software stops service stops
- Software state must be backed up

Cyber-Attacks Resilience in CPS: Software Rejuvenation (YOLO)

YOLO Model: Reset Constantly, and Change Program

Reset processor to safe state (checkpoint)

- Current state is lost

Recover state from:

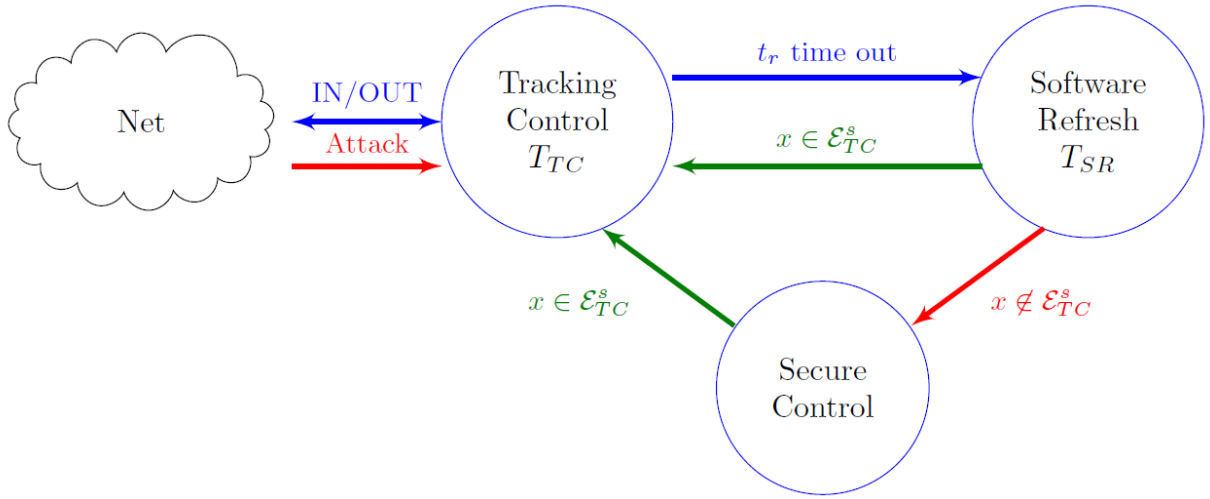
- Physical process
- Protected storage

BUT

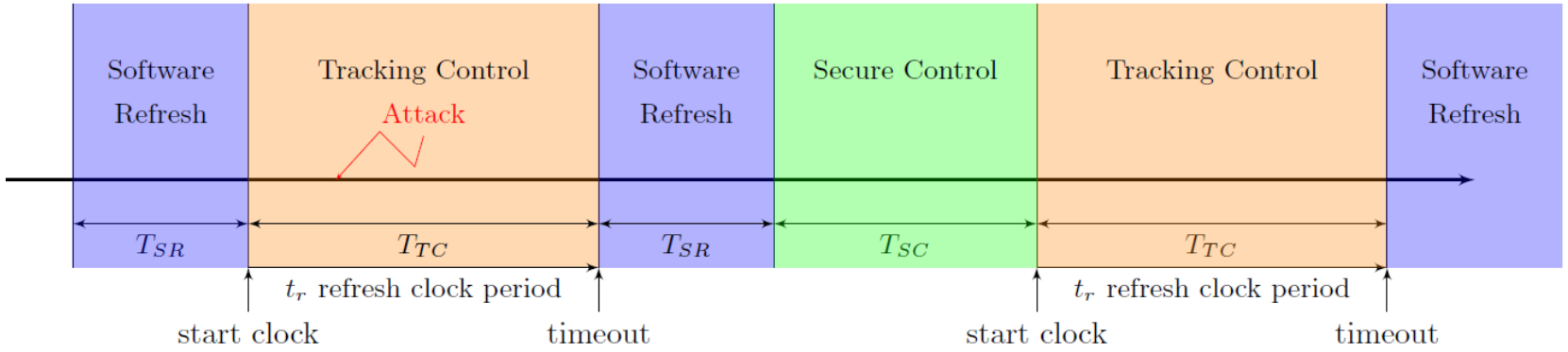
- Ensure: cure not worst than illness
  Verify:
  - Reboot not too frequent
  - Controller blackout not too long
  - State is recoverable or protected (including checkpoint)

Software Rejuvenation Operating Modes

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



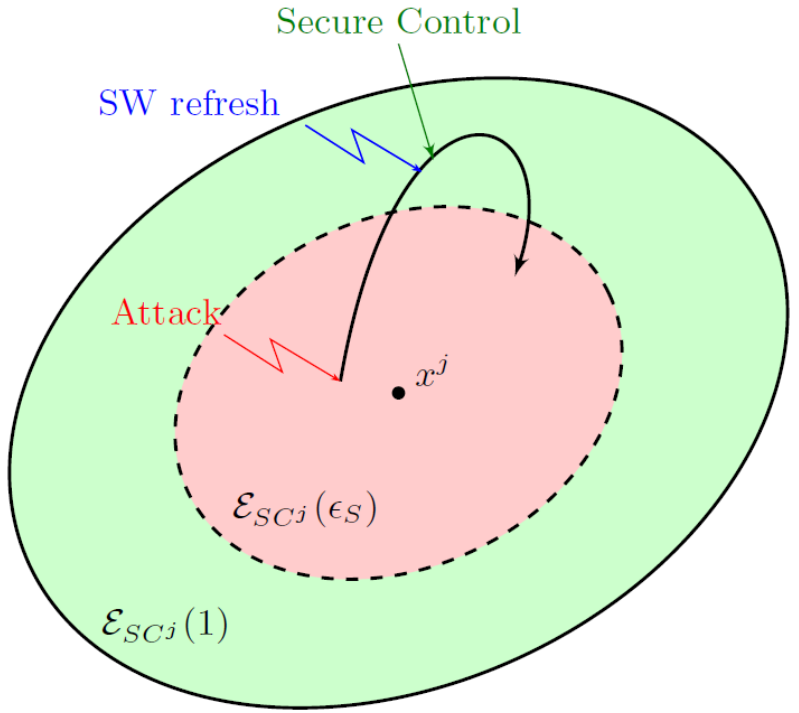
- The switch from TC to SR is triggered by a timer (unsecure information)
- From SR to TC or SC there is a condition to be satified (secure information)



Software Rejuvenation Secure Control

Defining

- Safety Set $\mathcal{E}_{SC^j}(1)$ (green)
- $\mathcal{E}_{SC^j}(\epsilon_s) \triangleq \epsilon_s \mathcal{E}_{SC^j}(1)$ (light red)
- $T_{UC} = T_{TC} + T_{SR}$

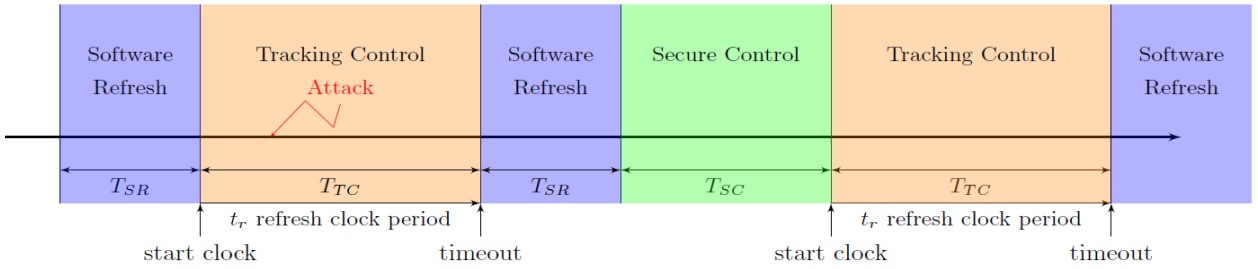


Goal

- Find ϵ_s and T_{UC} such that

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

$$T_{UC} > T_{SR}$$



Reachability set computed from the inner set under the action of uncertain control input for the time interval T_{UC}

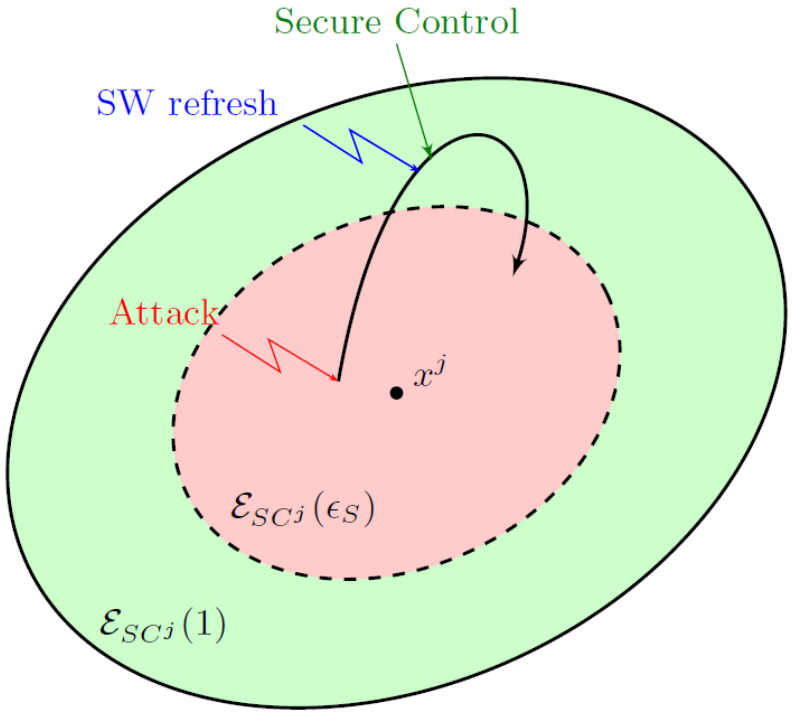
Software Rejuvenation Secure Control

Given ϵ_s and T_{UC} such that

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

How can we guarantee stability and recoverability?

$\mathcal{E}_{SC^j}(1)$ has to be a Positively Invariant Set



Software Rejuvenation
Secure Control

Controlled System: $\dot{x} = f_\phi(x) \triangleq f(x, \phi(x))$

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

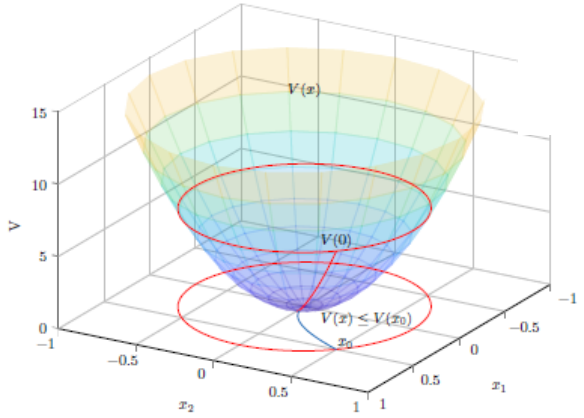
$$\dot{V}_\varphi(x) = \frac{\partial V}{\partial x} \cdot f_\varphi(x) < 0$$

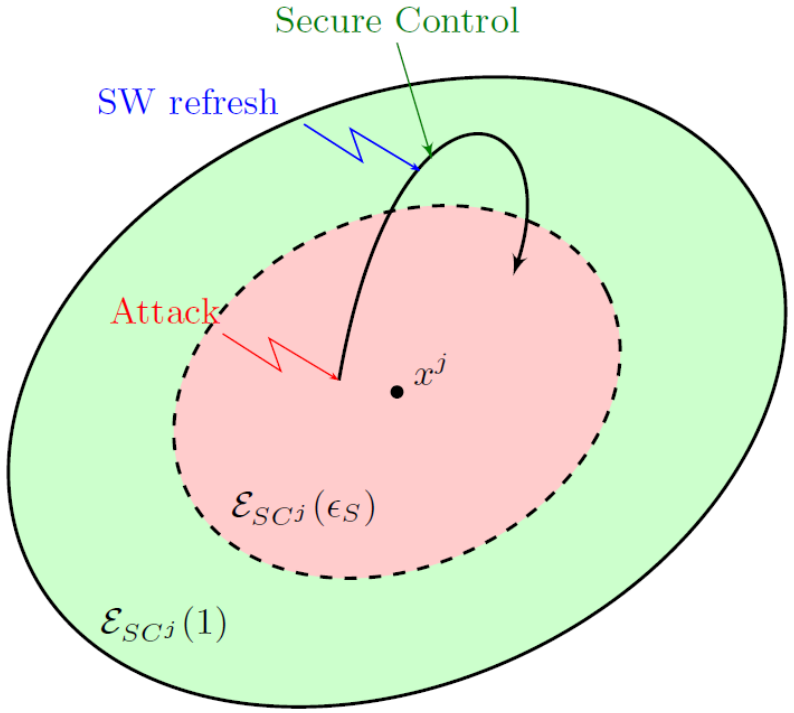
Lyapunov level set:For $\epsilon > 0$,

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

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

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



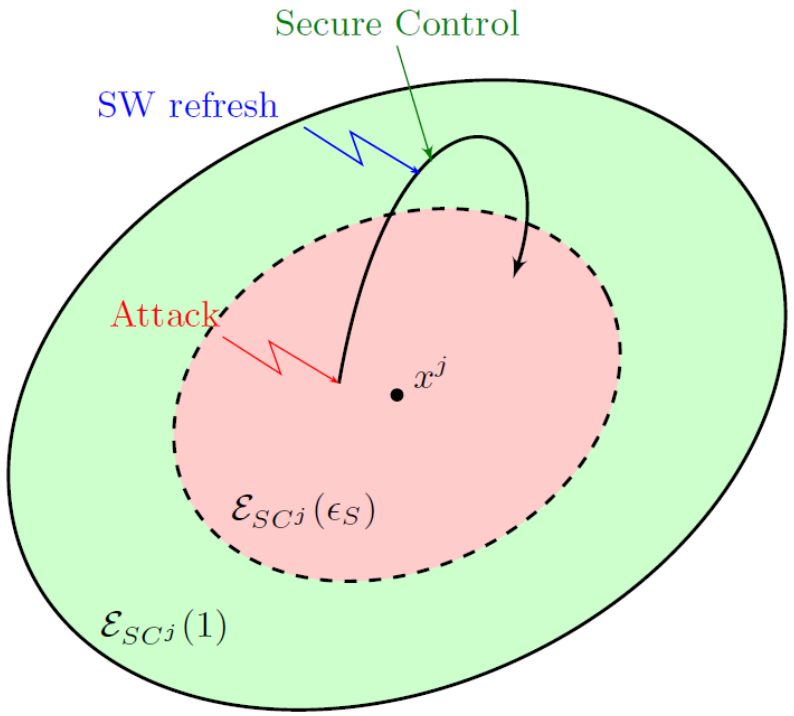


Software Rejuvenation
Secure Control

Prop.1. Given $\dot{x} = f_\phi(x) \triangleq f(x, \phi(x))$ 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 $0 < \epsilon < \epsilon' \leq 1$, $\exists \; T_U > 0 \;\ni\; \mathcal{R}(t; \mathcal{E}_\varphi(\epsilon), U) \subseteq \mathcal{E}_\varphi(\epsilon') \; \forall \; t < T_U$.

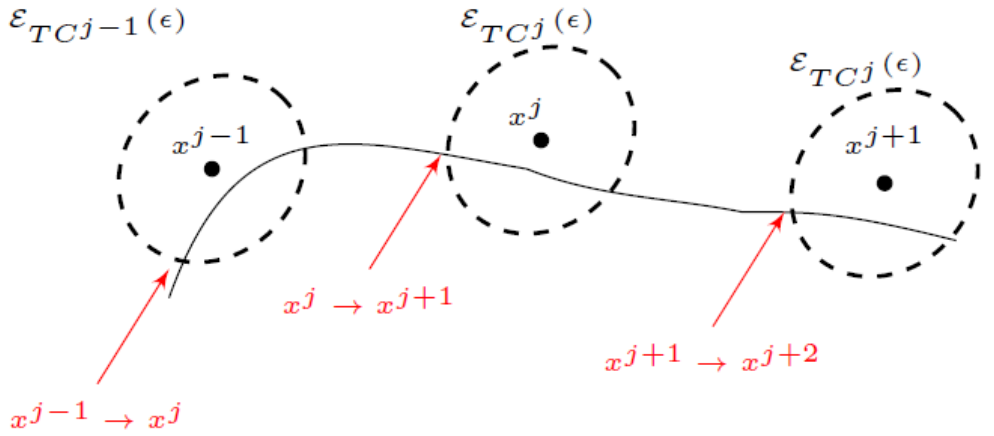


- We can always recover in a finite time
- Given a reduced version of the Safety Set we can always find a period of time where is allowed uncertain control.

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.

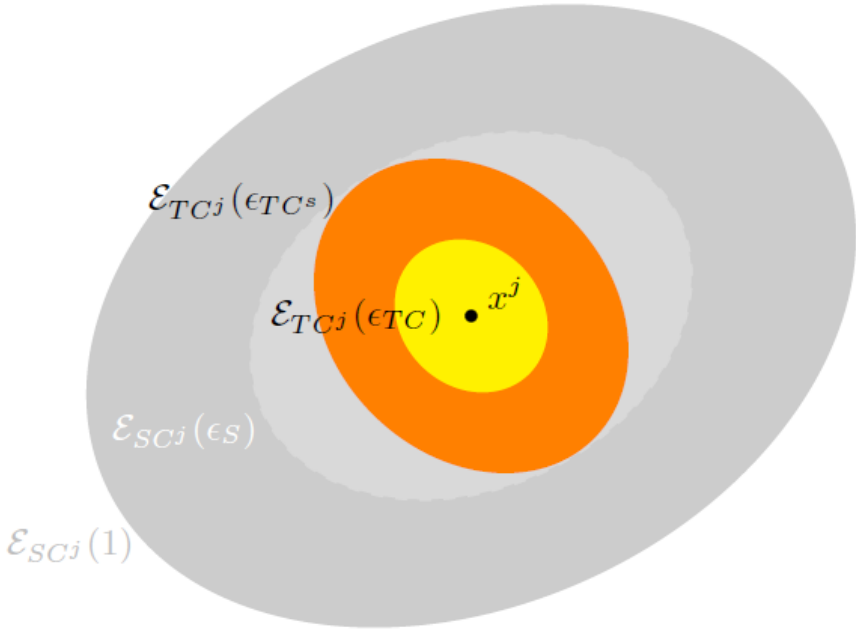


Goal:

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

Software Rejuvenation
Analysis of mission progress

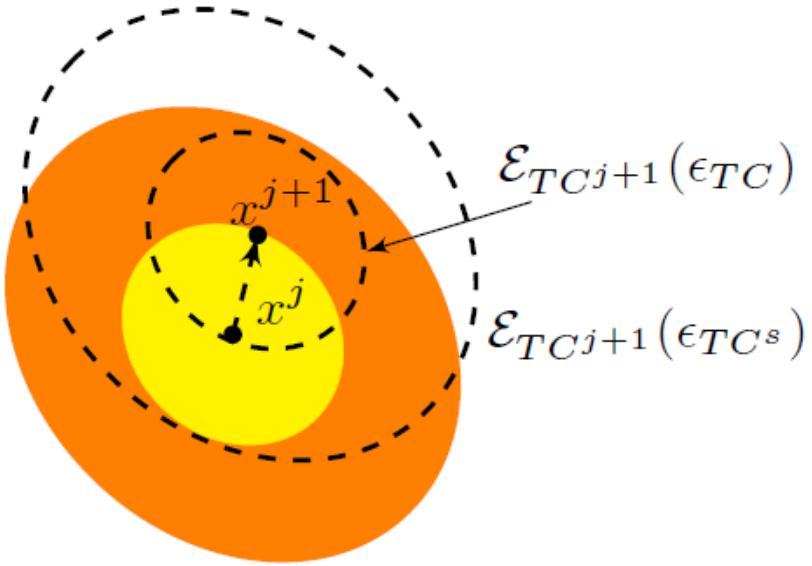
- The new sets generalize the fact that a different controller may be used during TC.
- Those sets are contained in the Safety Set



$$\mathcal{E}_{TCj}(\epsilon_{TCs}) \subseteq \mathcal{E}_{SCj}(\epsilon_s)$$
$$\mathcal{E}_{TCj}(\epsilon_{TC}) \subseteq \mathcal{E}_{TCj}(\epsilon_{TCs})$$

Software Rejuvenation
Analysis of mission progress

Safety Transition

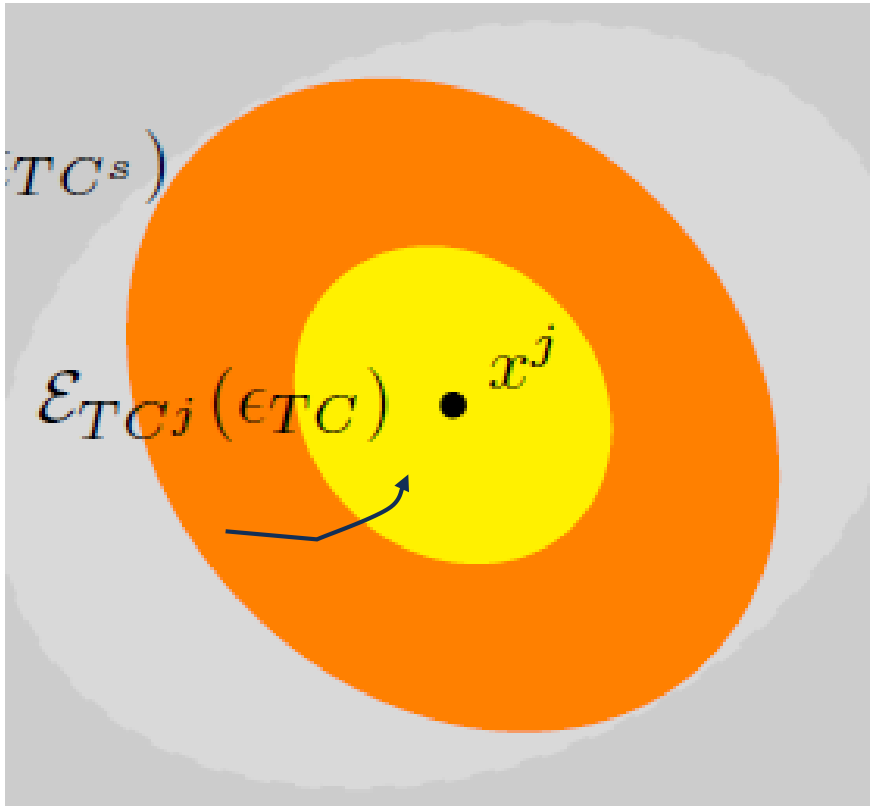


Theorem. Let $\bar{t}$ be the time instant associated to the transition between two consecutive equilibrium points x^j and x^{j+1}, then $x(\bar{t}; x_0, U) \in \mathcal{E}_{TC^{j+1}}(\epsilon^s_{TC})$ with $x_0 \in \mathcal{E}_{SC}(1)$ if and only if

$$\mathcal{E}_{TC^j}(\epsilon_{TC}) \subseteq \mathcal{E}_{TC^{j+1}}(\epsilon^s_{TC})$$

Software Rejuvenation
Analysis of mission progress

Liveness: in presence of software refresh the state of the system has to converge in to $\mathcal{E}_{TCj}(\epsilon_{TC})$



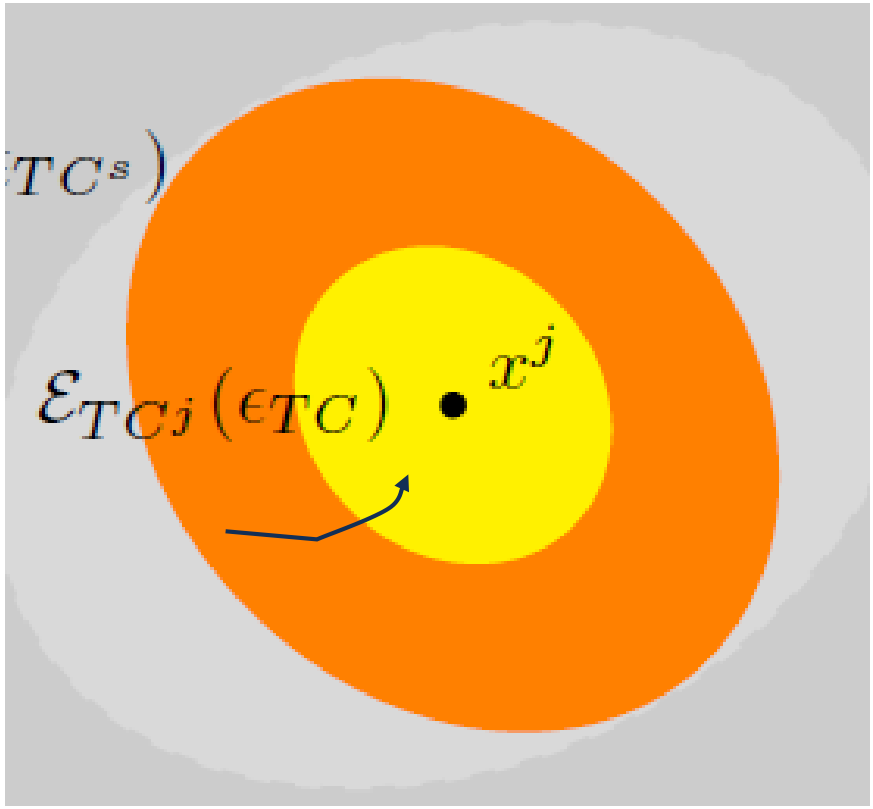
Assumptions

- No attack
- During SR the control inputs are constant and equal to the last value provided by the controller before the reboot.

PS: If the attack is persistent the liveness cannot be guaranteed in this case. But the system is always safe.

Software Rejuvenation
Analysis of mission progress

Liveness: in presence of software refresh the state of the system has to converge in to $\mathcal{E}_{TCj}(\epsilon_{TC})$



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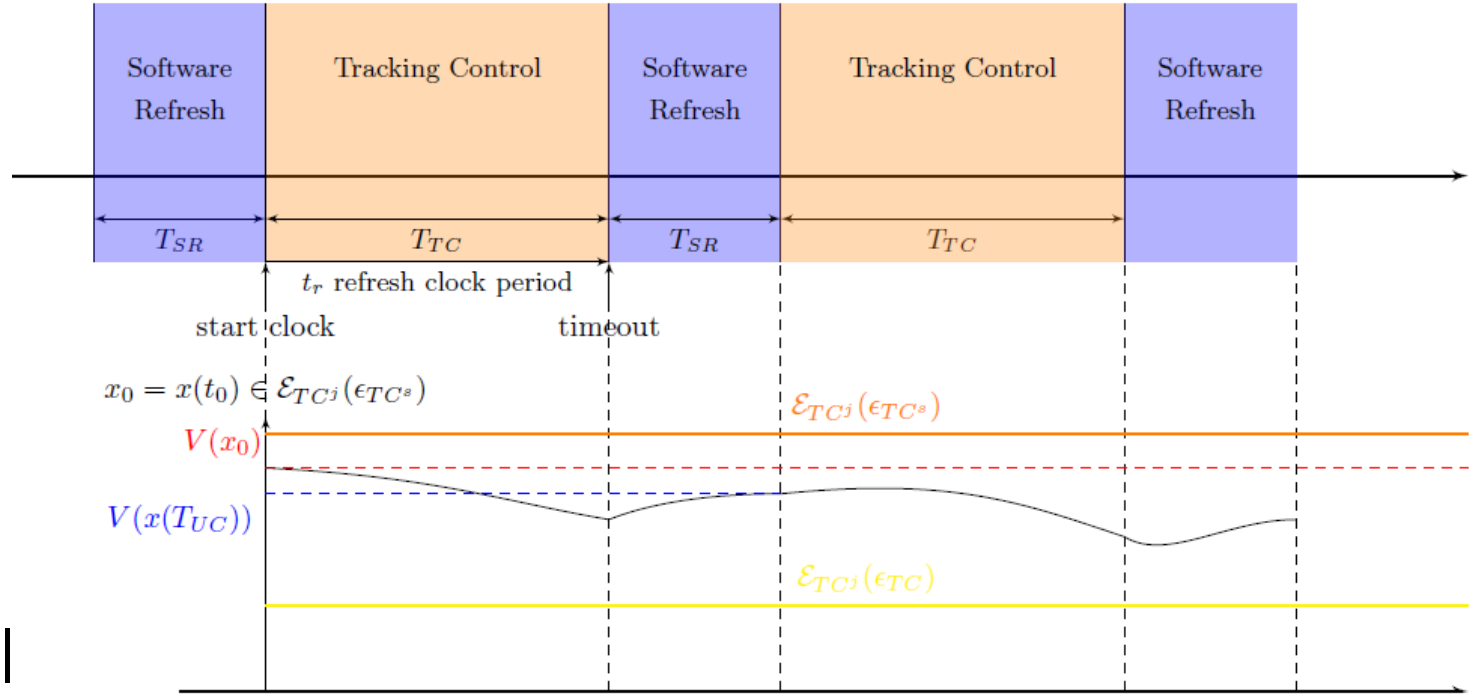
Software Rejuvenation
Analysis of mission progress

- From $V(x_0)$ the Lyapunov function decreases up to $V(x(T_{TC}))$
- At the end of SR, the function V may increase



$$V(x_0) - V(x(T_{TC})) > |\, V(x(T_{TC})) - V(x(T_{TC} + T_{SR}))\,|$$

Theorem 2. For all $x_0 \in [\mathcal{E}_{TC^j}(\epsilon^s_{TC}) - \mathcal{E}_{TC^j}(\epsilon_{TC})]$, $\exists \bar{T} > 0 \ni \forall t > \bar{T}\ x(t; x_0, u_{[0,t]}) \in \mathcal{E}_{TC^j}(\epsilon_{TC})$, if

$$V_{TC^j}(x_0) - V_{TC^j}(x(T_{TC}; x_0, TC) >$$

$$|V_{TC^j}(x(T_{UC}; x_0, \bar{u}_{[0,T_{SR}]})) - V_{TC^j}(x(T_{TC}; x_0, TC^j))|.$$

Software Rejuvenation
Analysis of mission progress

6 DOF $\Rightarrow$ 12 state variables

$$\ddot{p}_x = -\cos\phi \sin\theta \frac{F}{m}$$

$$\ddot{p}_y = \sin\phi \frac{F}{m}$$

$$\ddot{p}_z = g - \cos\phi \cos\theta \frac{F}{m}$$

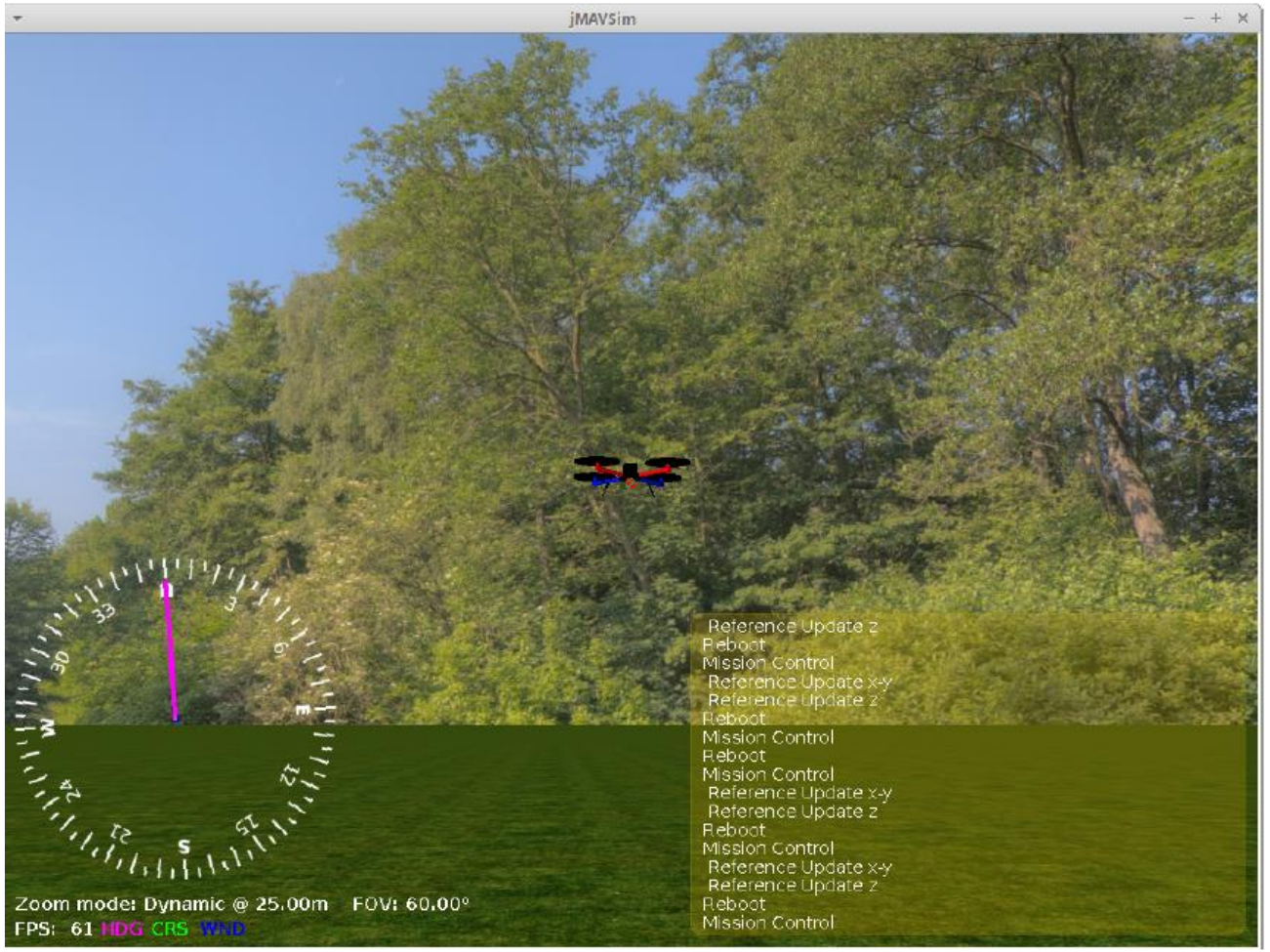
$$\ddot{\phi} = \frac{1}{J_x}\tau_\phi$$

$$\ddot{\theta} = \frac{1}{J_y}\tau_\theta$$

$$\ddot{\psi} = \frac{1}{J_z}\tau_\psi.$$

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

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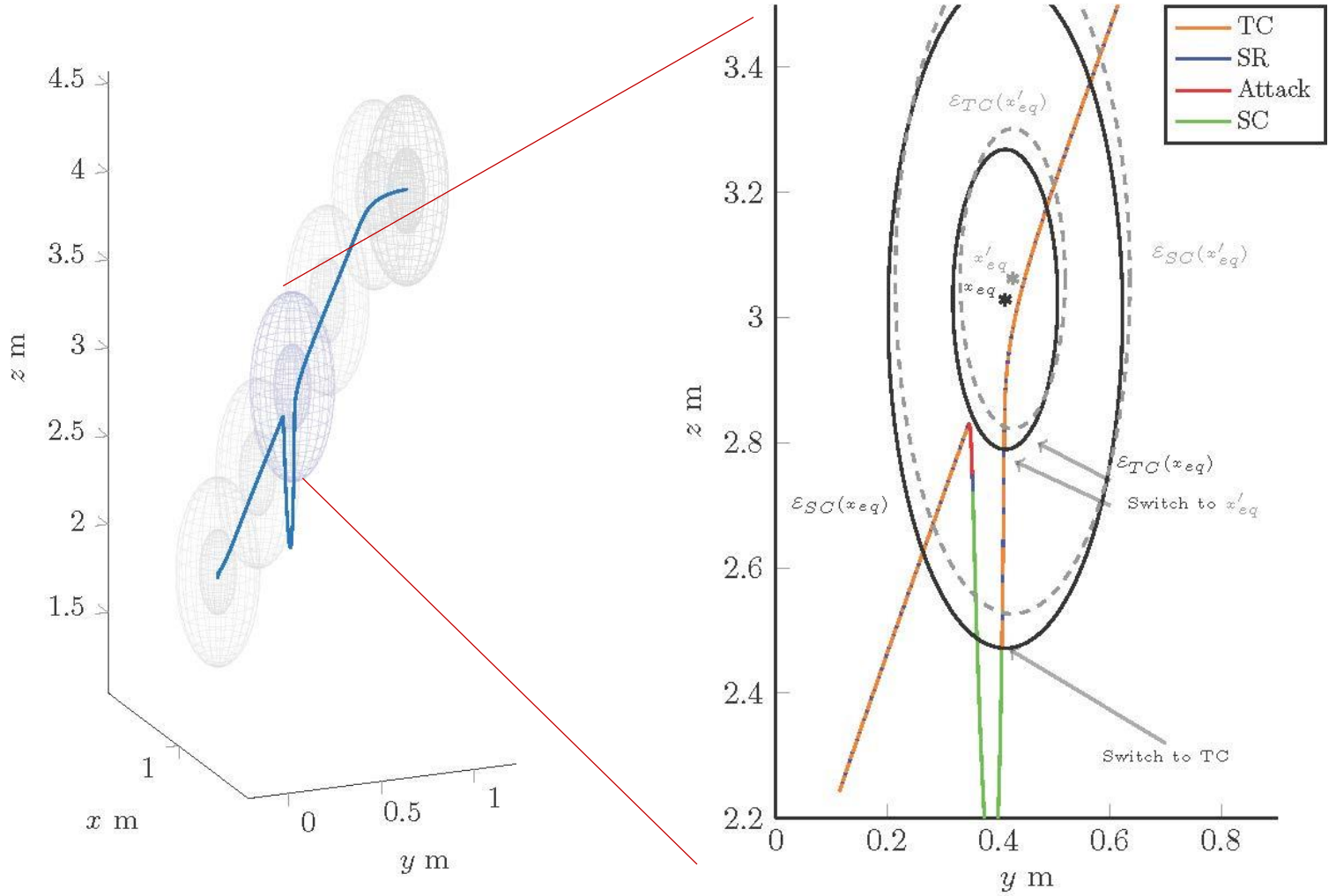
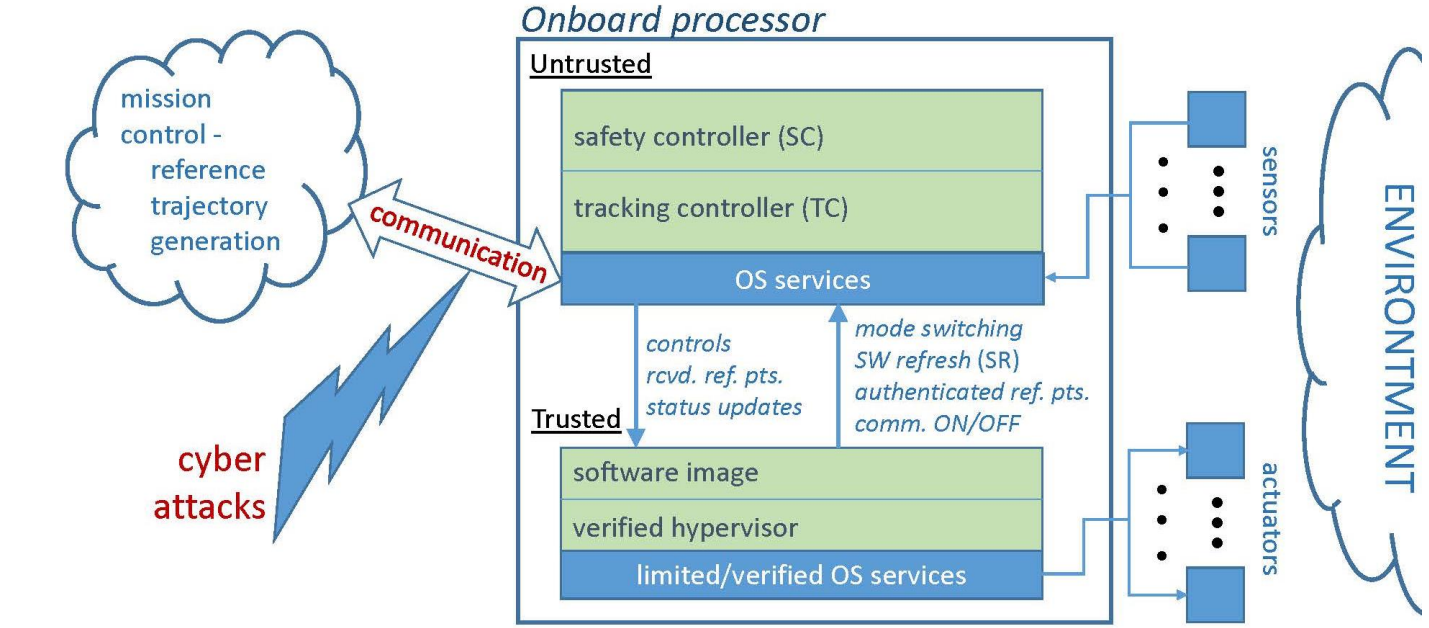
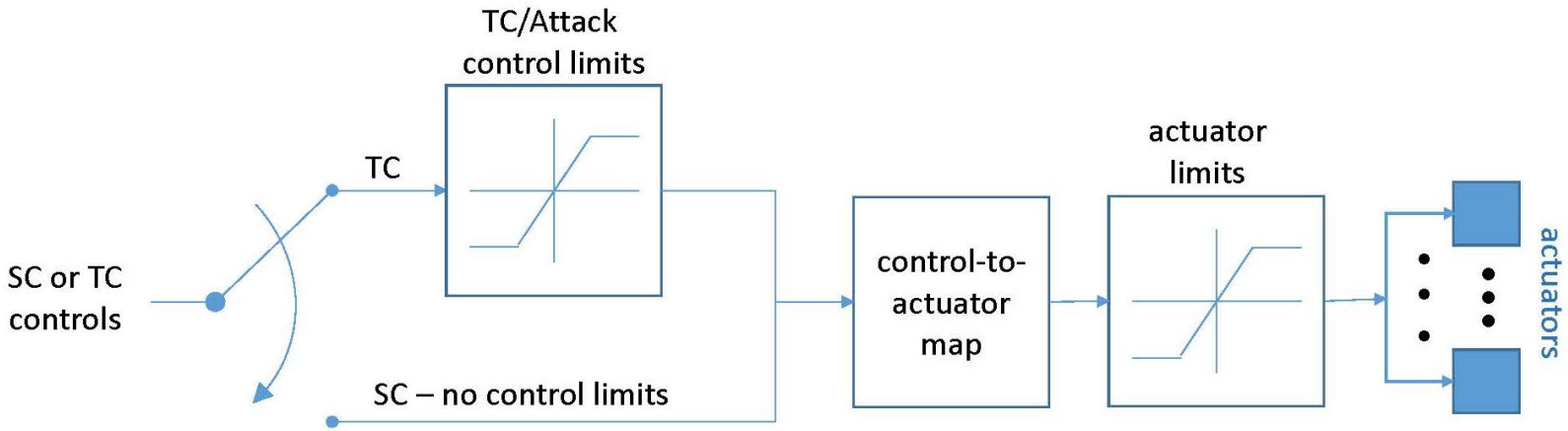


Software Rejuvenation Protection Requirements





Requirements

- Authenticate reference points
- Protect checkpoint integrity
- Protect refresh mechanism
- Set actuator limits

Software Rejuvenation Protections (1)

Space (Memory) Protection

- Cheap implementation (low/no overhead)

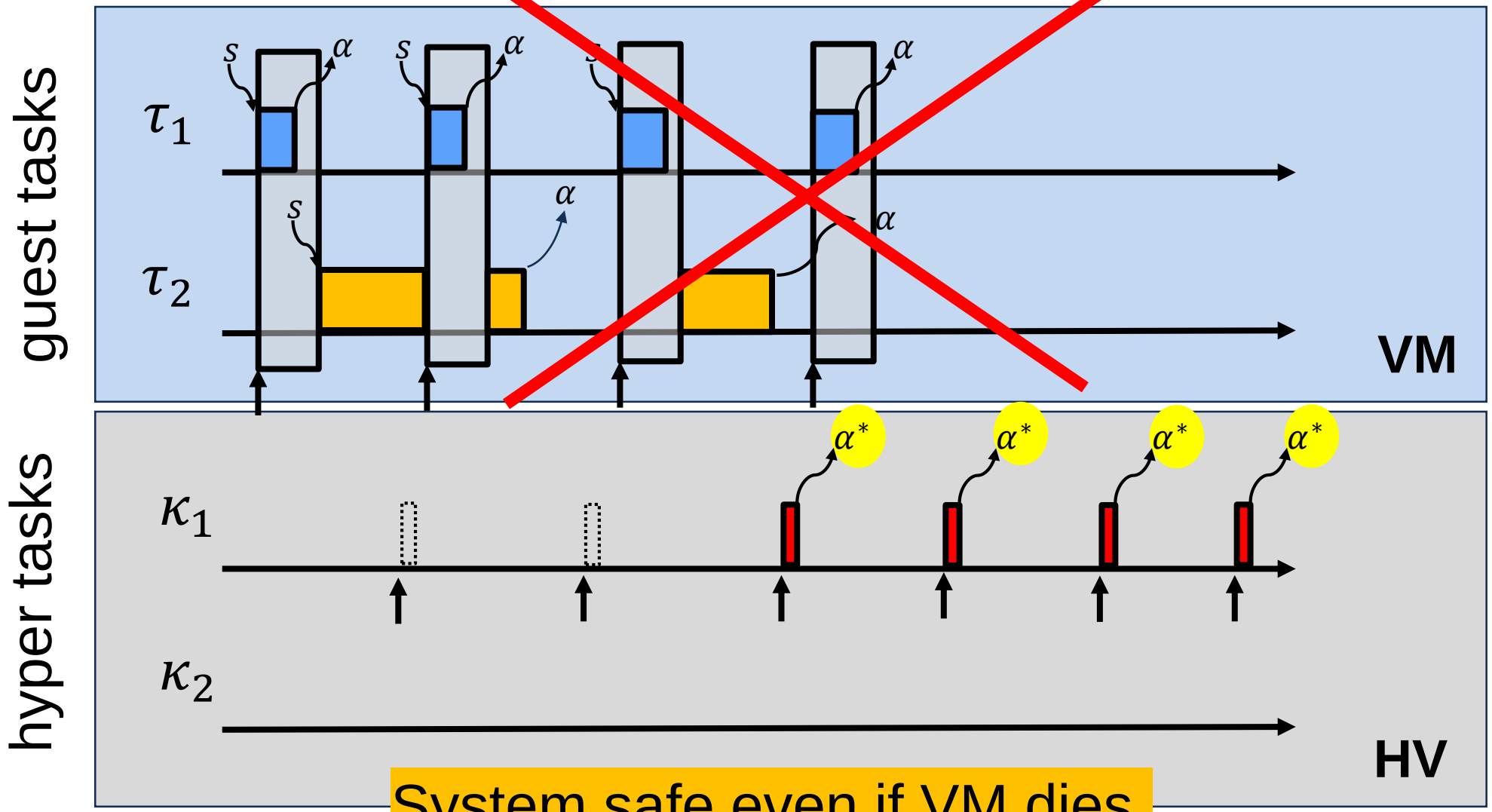
Drone Experiment

- Take advantage of Micro-Hypervisor :
  - Only memory protection: (nested page tables – hardware translation)
    - Data
    - Code
  - No other virtualization
  - Verified code implementing memory protection
  - Separate serial port for communication

Time Protection

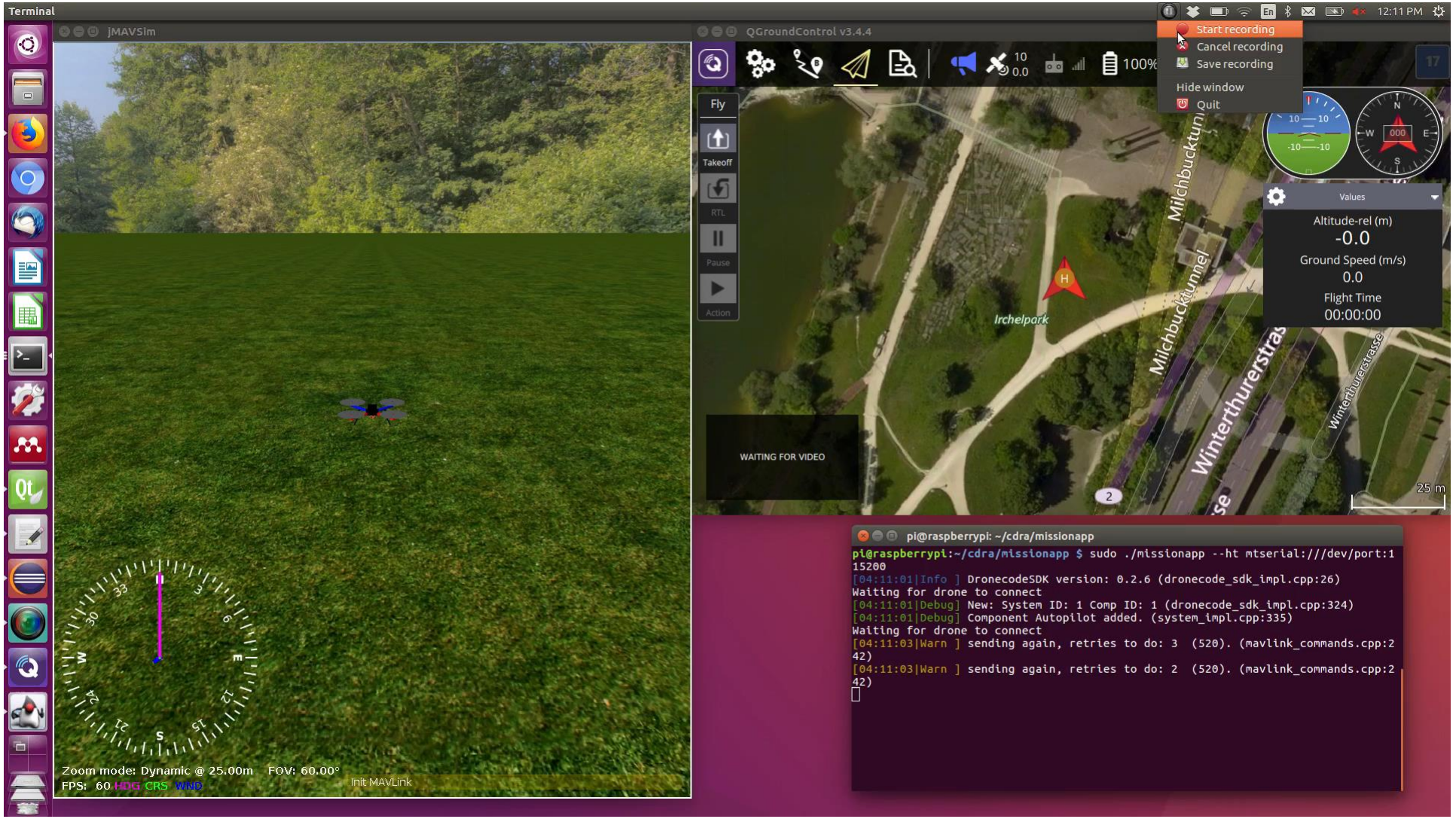
- Separate timer for hypervisor (no virtualization)
- Execute protected code in hypervisor (hyperapp)

Software Rejuvenation Protection (2)
Two Execution Environments: Two schedulers: VM+HV

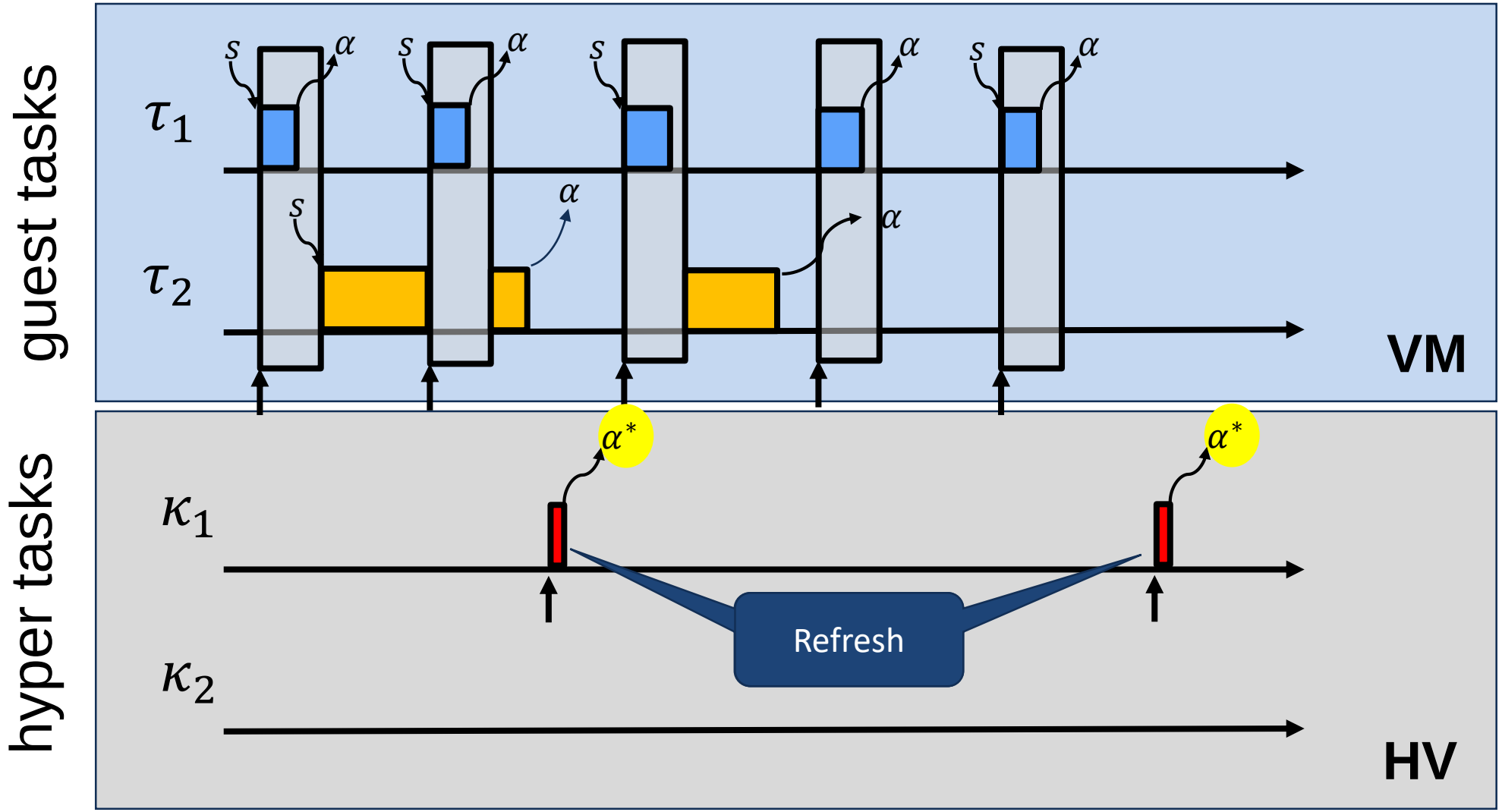


System safe even if VM dies

Current Experiments (1)
Drone Protection (VM Crash)



Software Rejuvenation Protection (3)
Two Execution Environments: Two schedulers: VM+HV



Experiment to put it all together (ongoing)

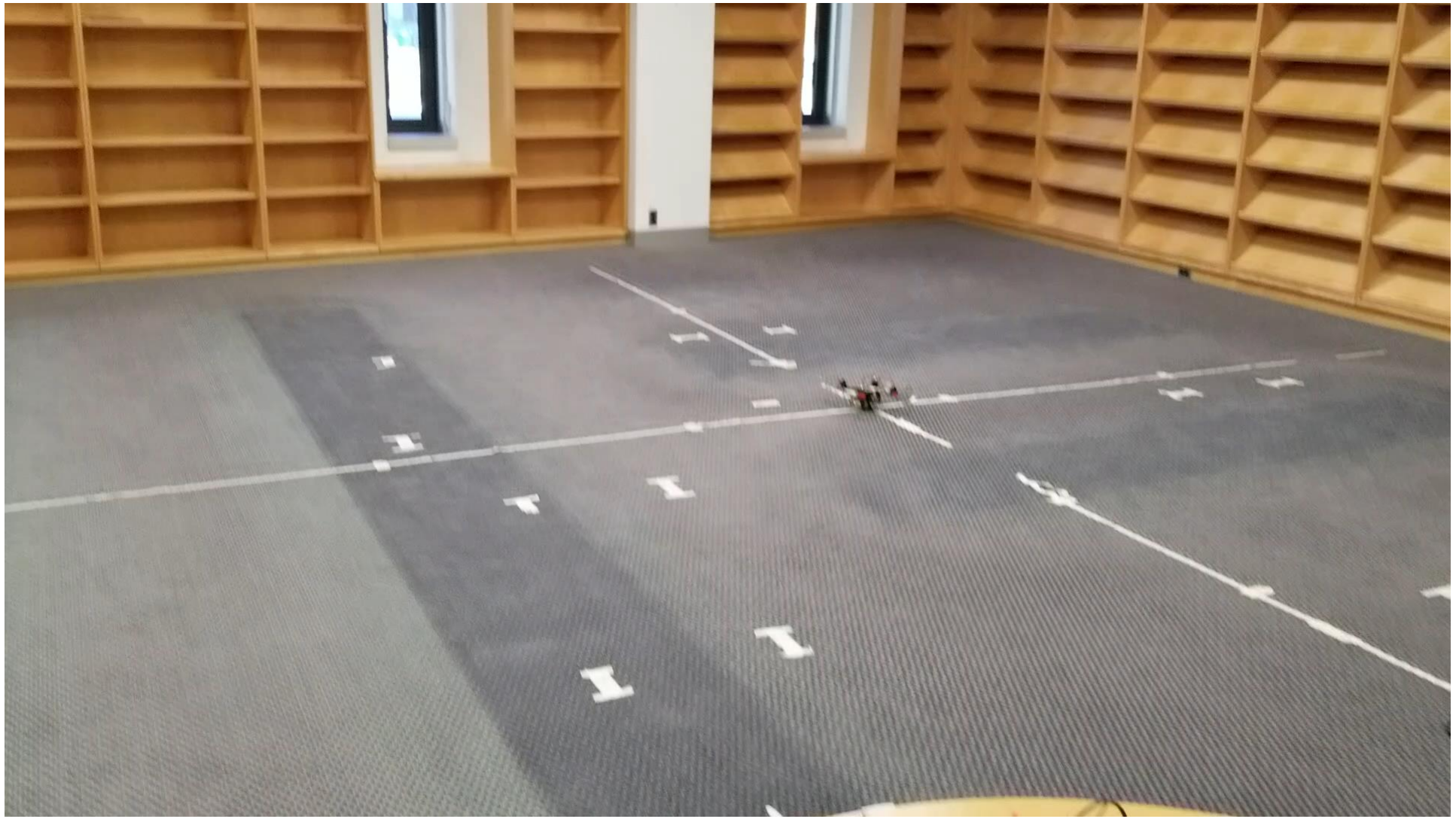
Implement a YOLOized System

- Verified Refreshing Controller
- Verified Refreshing Trajectory Tracker
- Timing Verification
- Space and Timing Protection
- YVT Tool Verification Model (more in a moment)

Indoor Drone

- PX4 Controller Implementation
- Process-based refresh (micro-reboots)

Current Experiments (2)
Micro-reboot in indoor drone



Yoloized-system Verification Tool (YVT)

Integrate verification tools into architectural model

- AADL Model
- OSATE (AADL modeling tool)

Physics Verification

- Matlab Annex (sublanguage)
  - Model of Plant and Controller
- Java interface with Matlab
- Display safe ellipsoids
- Prove properties

Scheduling tool

- Generates SMT models (calling Z3)
- Generates counter-example timeline

AADL Model

Top Level Model

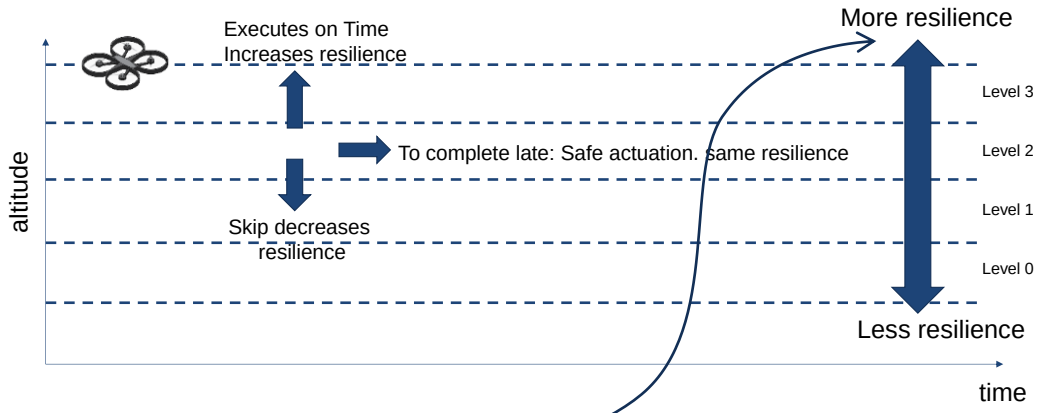
```
system implementation test1.i
        subcomponents
                p1: process controllers.i;
                quadrotor: system quadrotor.i;
                cpu: processor generic_processor;
        connections
                c1:port quadrotor.transfer->p1.transfer;
        connections
                Actual_Processor_Binding => (reference (cpu)) applies to p1;
end test1.i;
```

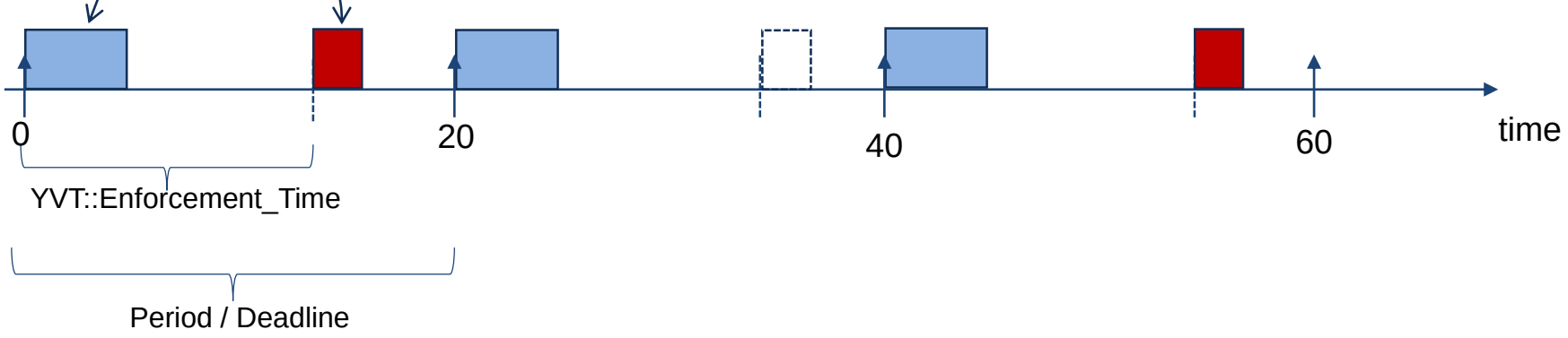
Controllers component

```
process implementation controllers.i
        subcomponents
                t1:thread controller_thread.quadrotor_controller2;
                t2:thread controller_thread.i;
        connections
                c1: port transfer->t1.transfer;
end controllers.i;
```

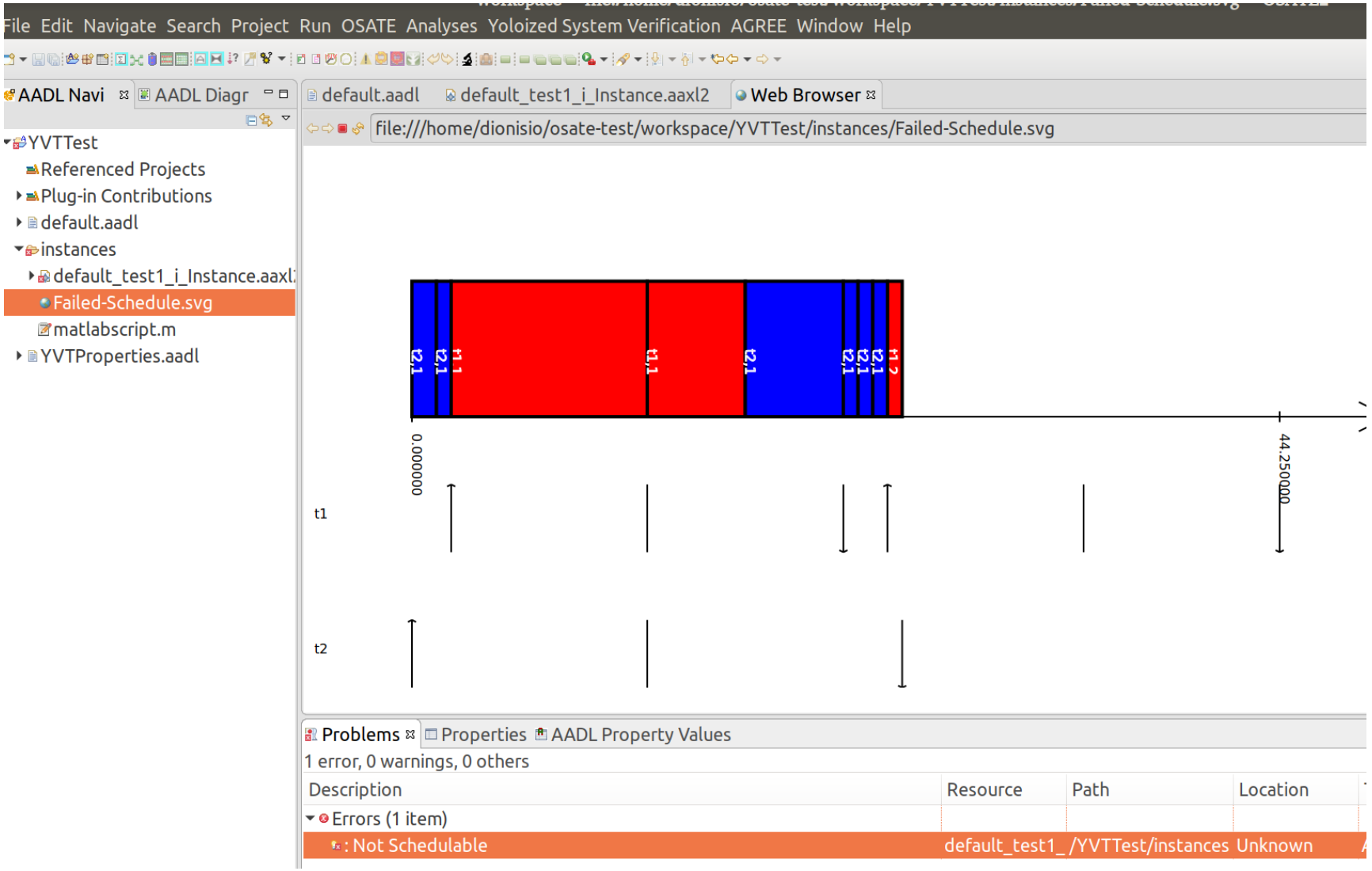
Scheduling Parameters

```
process implementation myproc.i
        subcomponents
                t1:thread controller_thread.quadrotor_controller2;
                t2:thread controller_thread.i;
        connections
                c1: port transfer->t1.transfer;
        properties
                -- Unschedulable parameters
                Priority => 2 applies to t1;
                Period => 20 ms applies to t1;
                Deadline => 20 ms applies to t1;
                YVTProperties::Enforcement_Time => 10 ms applies to t1;
                Compute_Execution_Time => 8 ms .. 8 ms applies to t1;
                YVTProperties::Enforcement_Execution_Time => 8 ms applies to t1;
                YVTProperties::Max_Resilience_Level => 2 applies to t1;
                YVTProperties::Max_Jobs_Per_Valid_Exec_Time => 2 applies to t1;
                ...
```





Schedulability feedback (counter-example timeline)



Physics Verification (1)

Plant Model

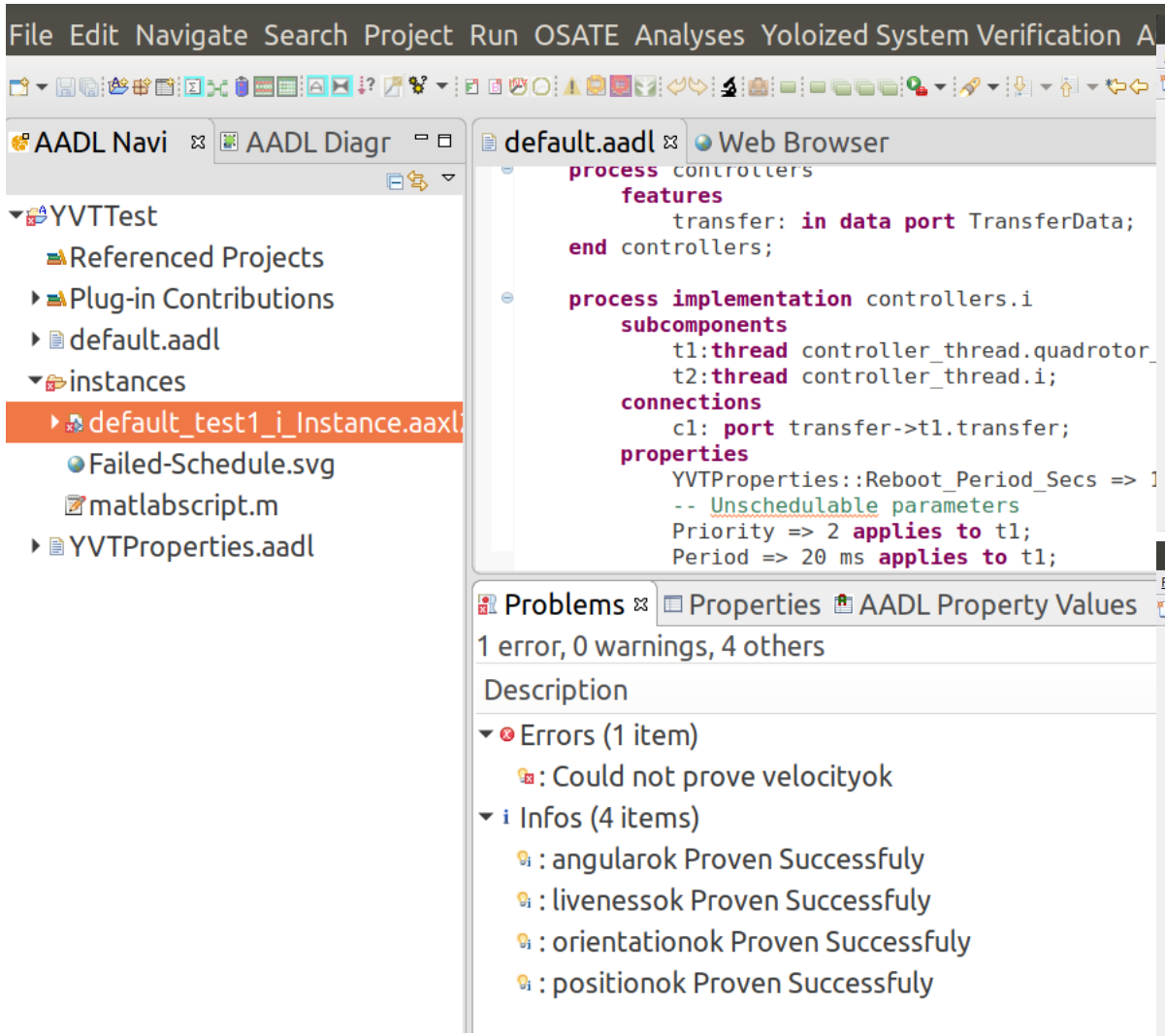
```
system implementation quadrotor.i
        annex matlab {**
                %% Quadrotor Example - Invariant Ellipsoids - version 1.1
                % Author: Raffaele Romagnoli  Date: 09/04/18
                %% Note:
                %%  xx_v: the equilibrium point due to the gravity force is considered


                %% Quadcopter: Linearized Dynamics + LQR controller

                %% Generic Quadrotor X PX4 Parameters
                % no integrator
                m = 0.8;      % mass (Kg)
                L = 0.33/2;   % arm length (m)
                Jx = 0.005;   % inertia seen at the rotation axis. (Kg.m^2)
                Jy = 0.005;   % inertia seen at the rotation axis. (Kg.m^2)
                Jz = 0.009;   % inertia seen at the rotation axis. (Kg.m^2)
                g  = 9.81;    % acceleration due to gravity m/s^2
                ...
        **};
end quadrotor.i;
```

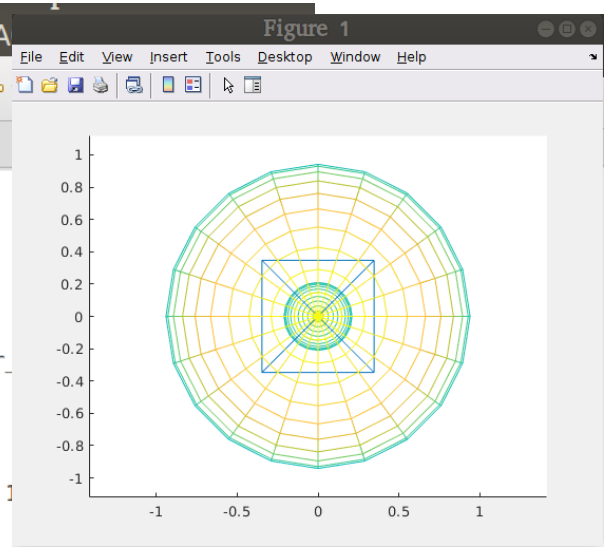
Physics Verification (2)

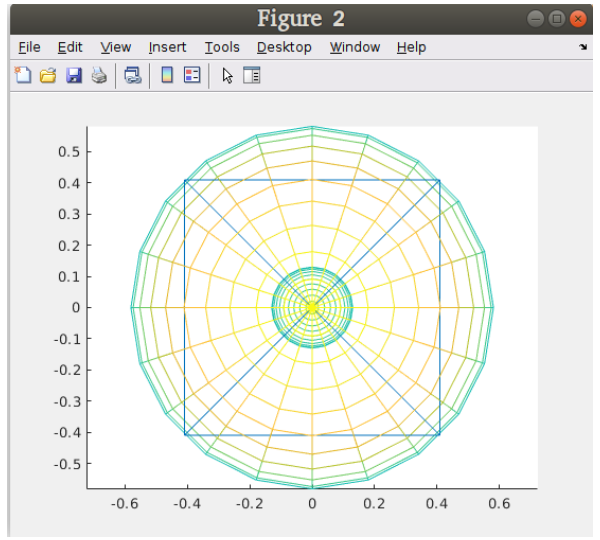
Controller Model

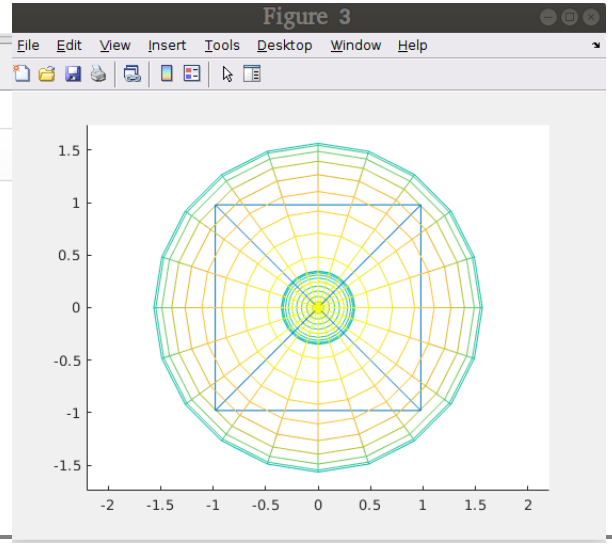
```
thread implementation controller_thread.quadrotor_controller2
        annex matlab {**
                %@output:positionok, orientationok, velocityok, angularok, livenessok
                %@input:reboot_period_secs
                %% LQR Controller
                Q=50*eye(n);
                R=100*eye(p);
                [K_hat,S,E] = lqr(hat_sys,Q,R);
                ...

        **};
end controller_thread.quadrotor_controller2;
process implementation controllers.i
        subcomponents
                t1:thread controller_thread.quadrotor_controller2;
                t2:thread controller_thread.i;
        connections
                c1: port transfer->t1.transfer;
        properties
                YVTProperties::Reboot_Period_Secs => 180 ms applies to t1;
end controllers.i;
```

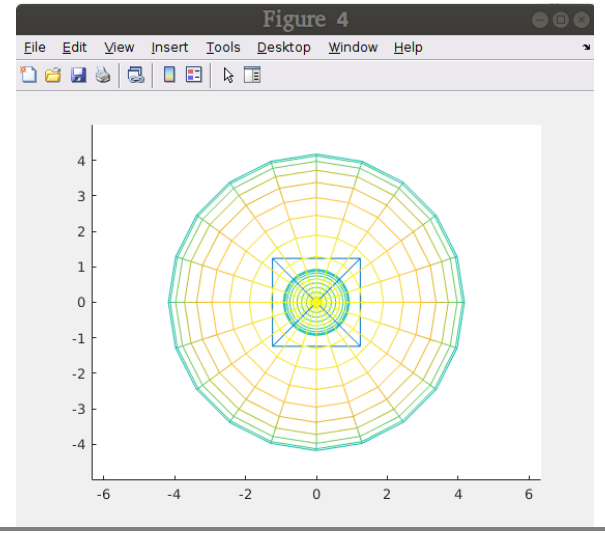
Physics Verification (3)
Proven properties / Safe ellipsoids











Summary and Status (1)
So Far

Control Verification of Software Rejuvenation
- Verified refresh frequency
- Verified control blackout duration
- Verified trajectory tracking

Timing Verification
- Resilience Timing Verification
- Temporal Protection

Protection
- Efficient memory isolation (HV)
- VM+HV scheduling coordination
- Micro-reboot and persistent state implementation

Verification tool (YVT)
- Architectural model with timing and control models
- Integration of verification algorithms driven by AADL tool (OSATE)

Summary and status (2)
Looking ahead

System state recovery
- Smart Kalman Filter Initialization
- Multiple checkpoints

Scheduling
- Optimize control actuation update frequency for single setpoint
- Optimize control actuation update frequency for control trajectories

YVT Enhanced Verification Techniques
- YVT already contains some new techniques
  more to come:
  - Timing verification of control trajectories

Extended Enforcement Techniques
- To explore: enabling trajectories with multiple checkpoints

Verified Transition Target Rejuvenation
- Implementation
- Verified YVT Model