Safety Enforcement for the Verification of Cyber-Physical Systems

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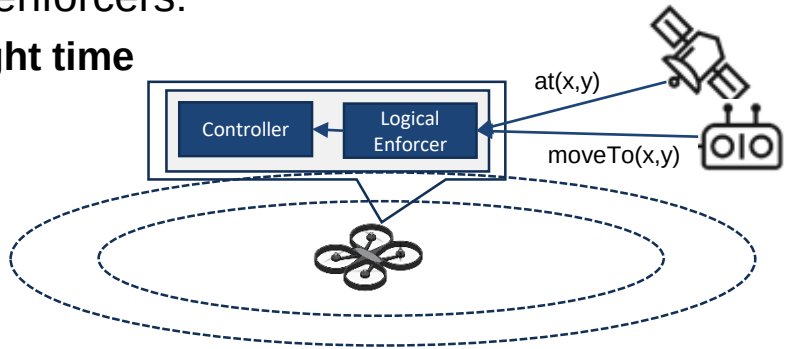
Verification of Cyber-Physical Systems

Challenge:

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

Solution:

- Add **simpler (verifiable)** runtime enforcer to make algorithms predictable
- Formally: specify, verify, and compose multiple enforcers:
  - Enforcer **intercepts/replaces** unsafe action at **right time**



Timeless Logical Model

Focus on Correct Values

Statespace

- $S = \{s\}$

Safe states

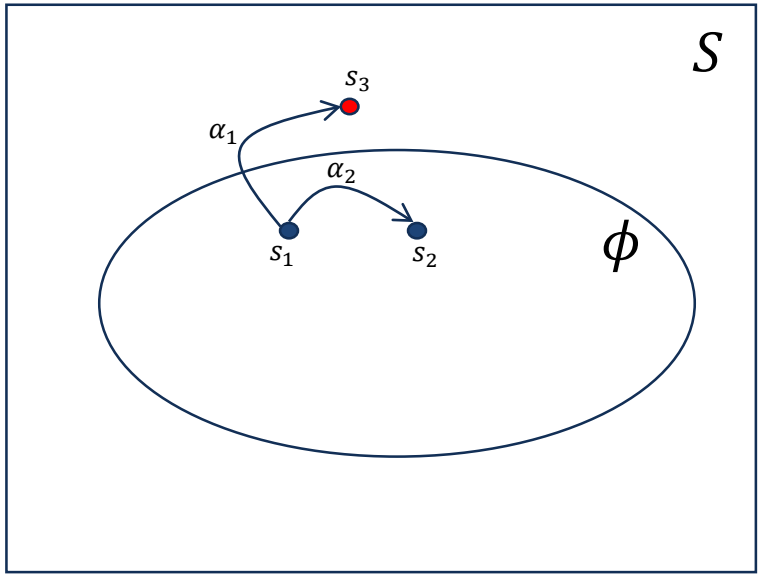
- $\phi \subseteq S$

Transitions triggered by actions

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

Safe actions from a state

- $SafeAct^*(s) = \{\alpha | R(\alpha, s) \in \phi\}$



Incorporating Time

Statespace

- $S = \{s\}$

Safe states

- $\phi \subseteq S$

Transitions triggered by actions

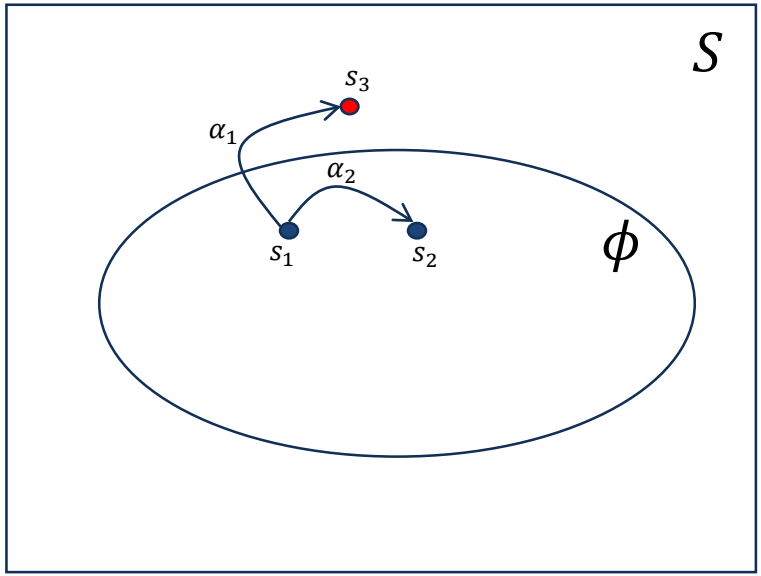
- Transition: $R(\alpha) \subseteq S \times S$
- Destination state: $R(\alpha, s) = \{s' | (s, s') \in R(\alpha)\}$

Safe actions from a state

- $SafeAct^*(s) = \{\alpha | R(\alpha, s) \in \phi\}$

Periodic Actions

- Occur every period with length P.
- $R_P(\alpha) \subseteq S \times S$
- Destination reached at P: $R_P(\alpha, s) = \{s' | (s, s') \in R_P(\alpha)\}$



Incorporating Inertia

Statespace

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

Periodic actions

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

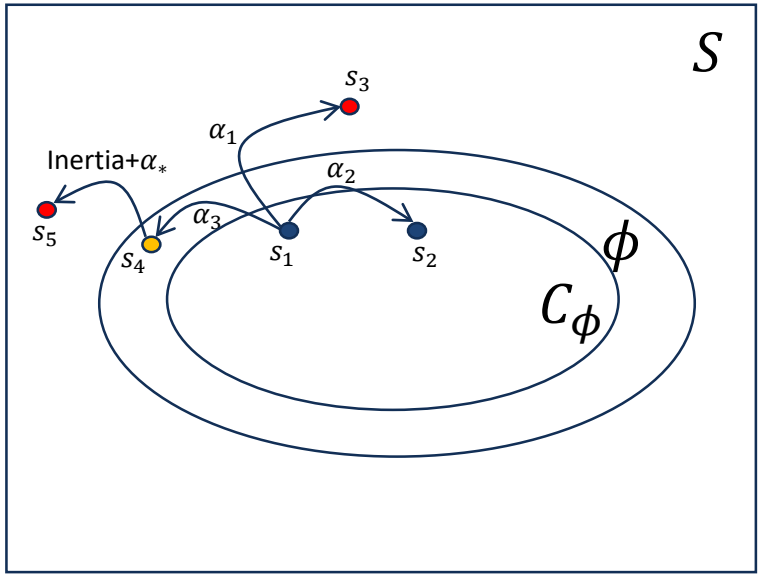
Identify states too close to safety border

- 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:

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

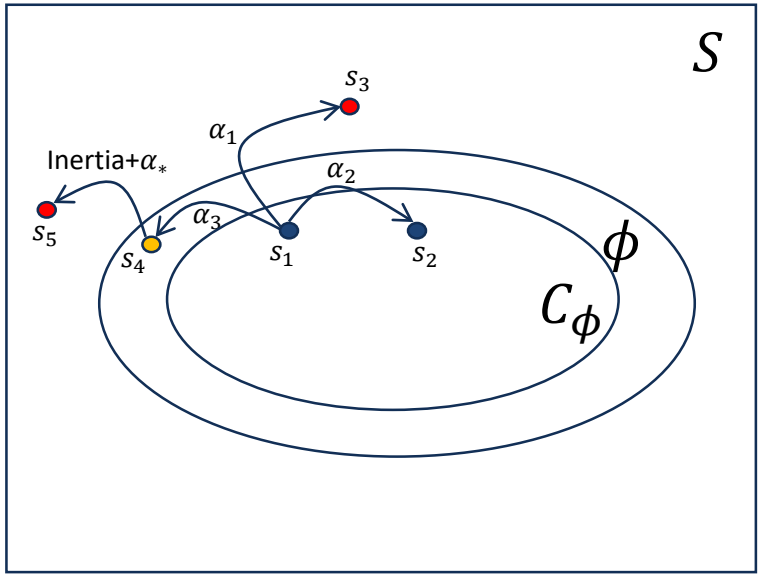
Logical Enforcer: $E = (P, C_\phi, \mu)$

- Set of safe actions:

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

- Monitor and enforce safe action:

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

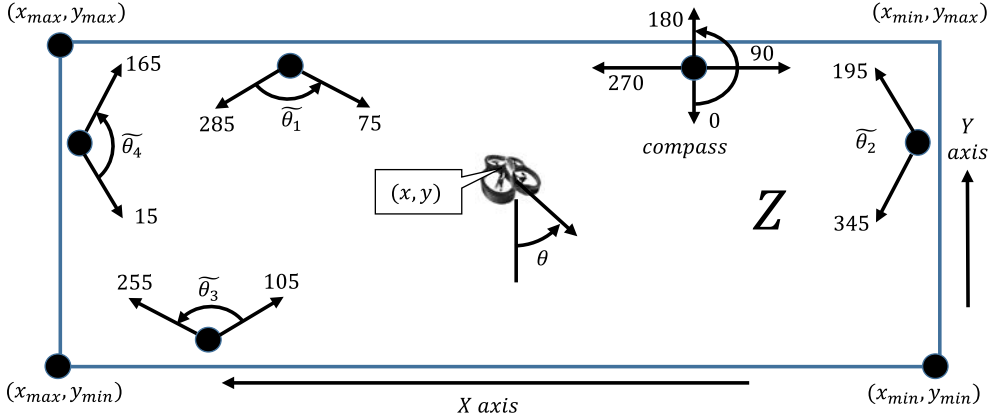


Verification with SMT (Z3)

Drone Example

Statespace

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



Enforceable states

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

Action: constant speed at angle θ

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

Are We Done Yet?

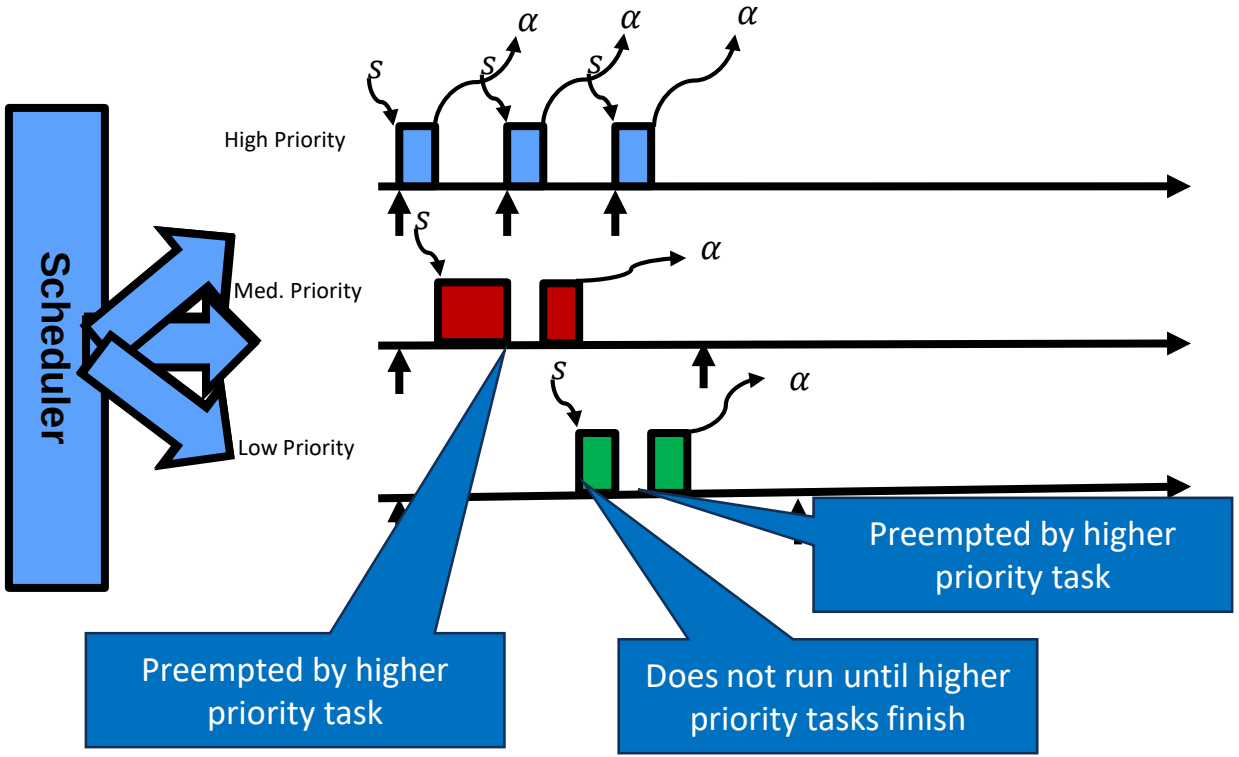
Timing Assumption:

- Unverified software finishes execution and enforcer evaluates output every P period.
- Software is guaranteed to finish executing by the next period (schedulable)
  - Unverified software executes for less than its Worst-Case Execution Time (WCET)
  - Other software running also 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 an output that can be evaluate by enforcer: late action + old sensing
    - **Inertia** takes it to **unsafe state**

Fixed-Priority Scheduling + Rate Monotonic



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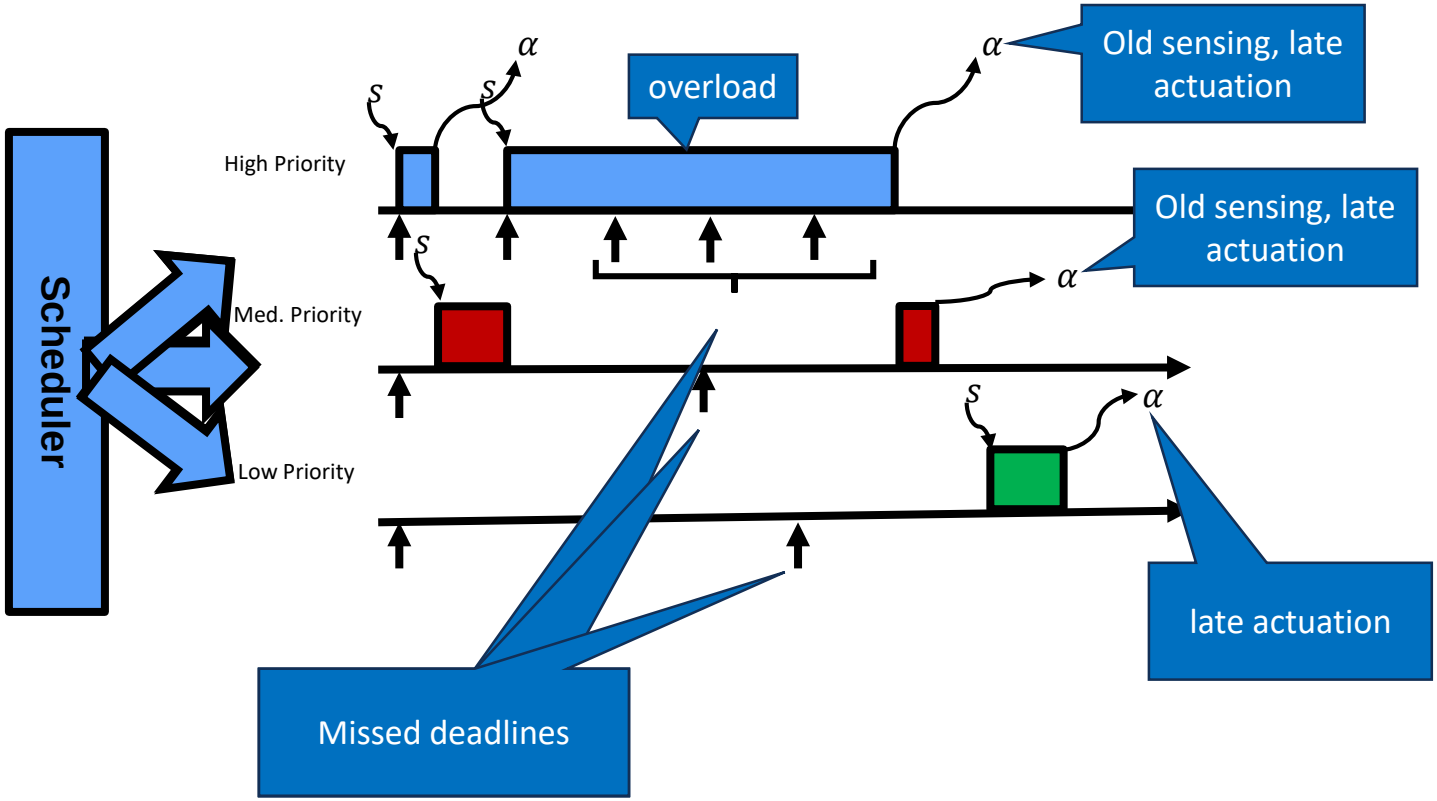
Overload -> old sensed data + late actuation



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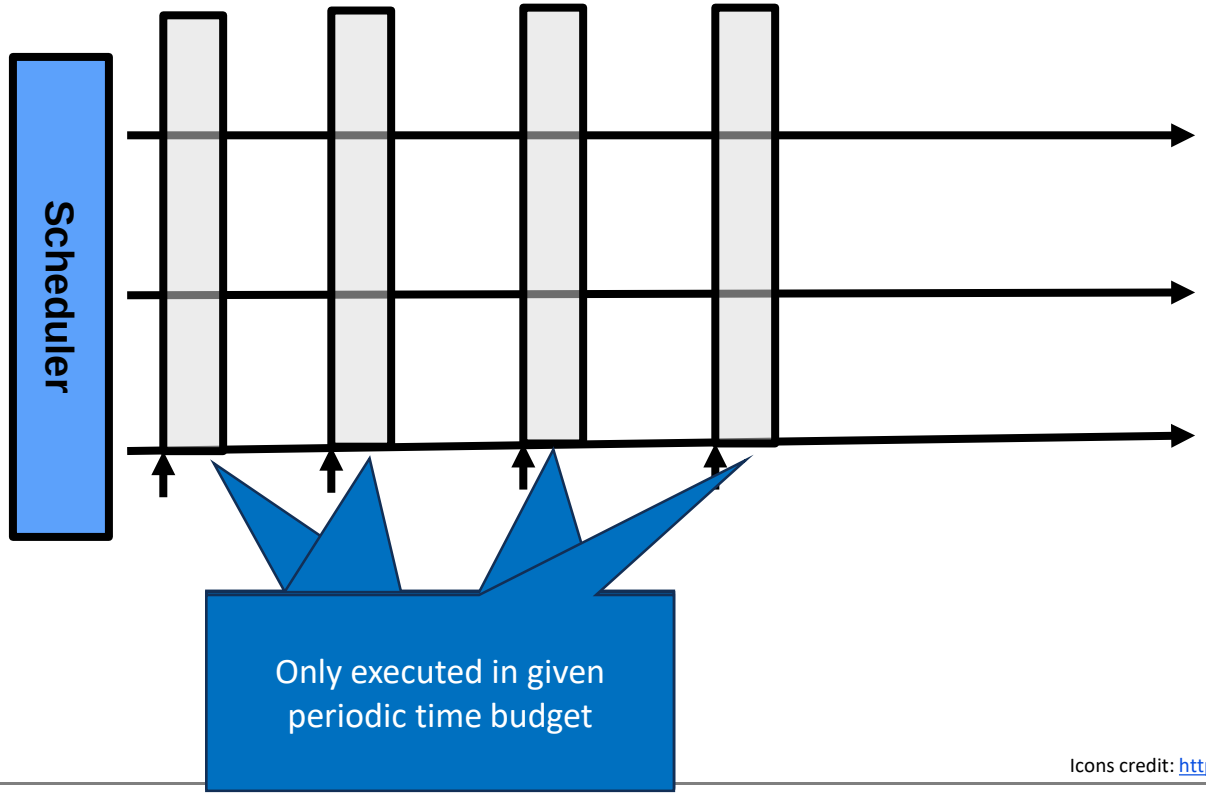
Unbounded preemption
Solution: Enforce timing budgets (timing enforcement)



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Unbounded preemption
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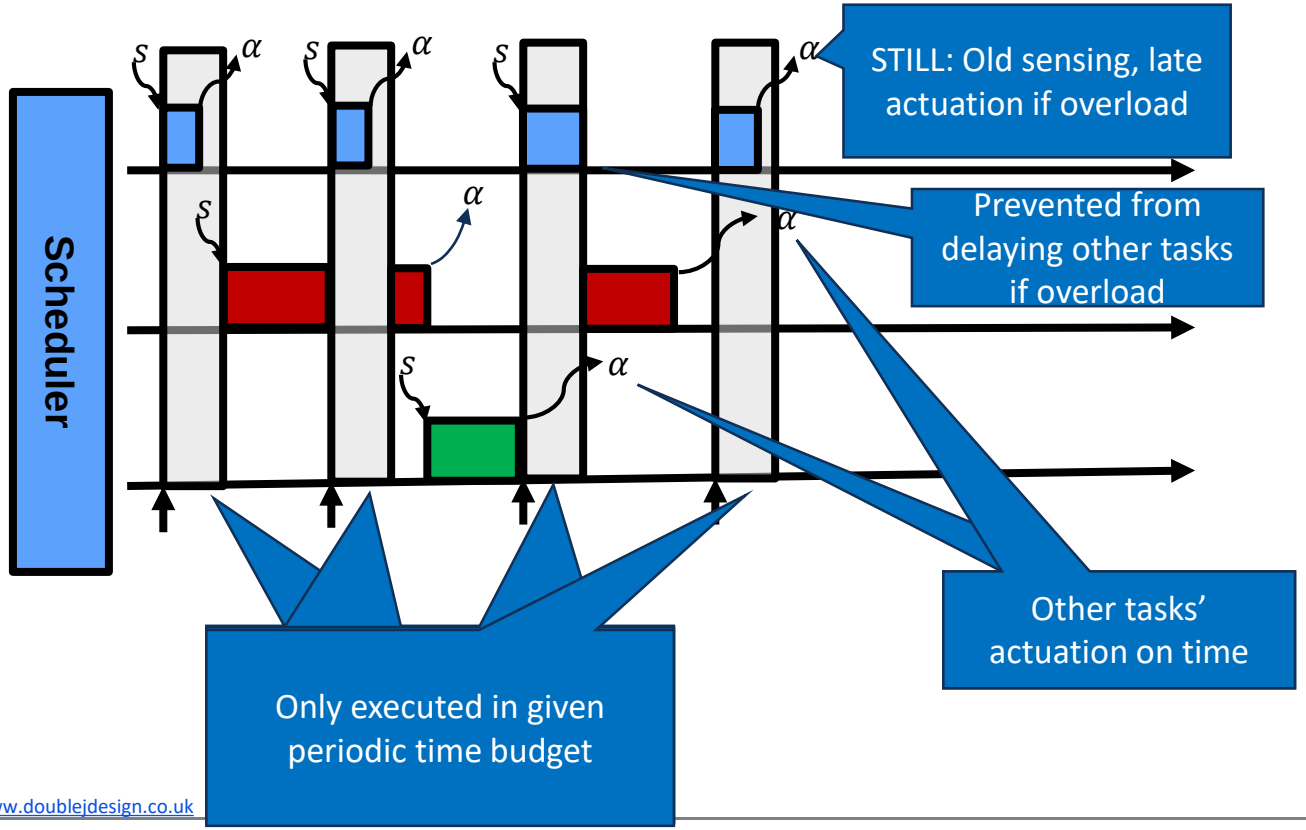

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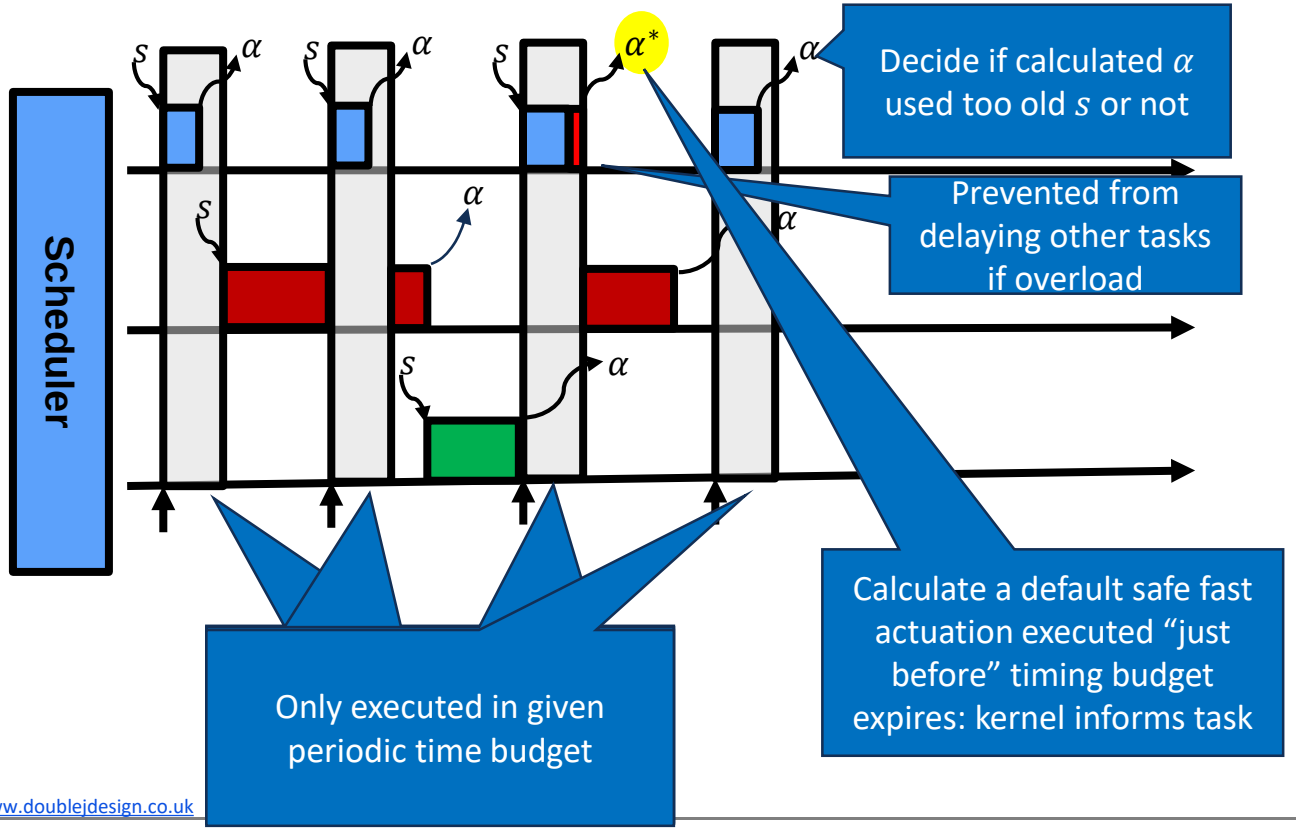
Unbounded Execution:
Solution: safe actuation on timing enforcement



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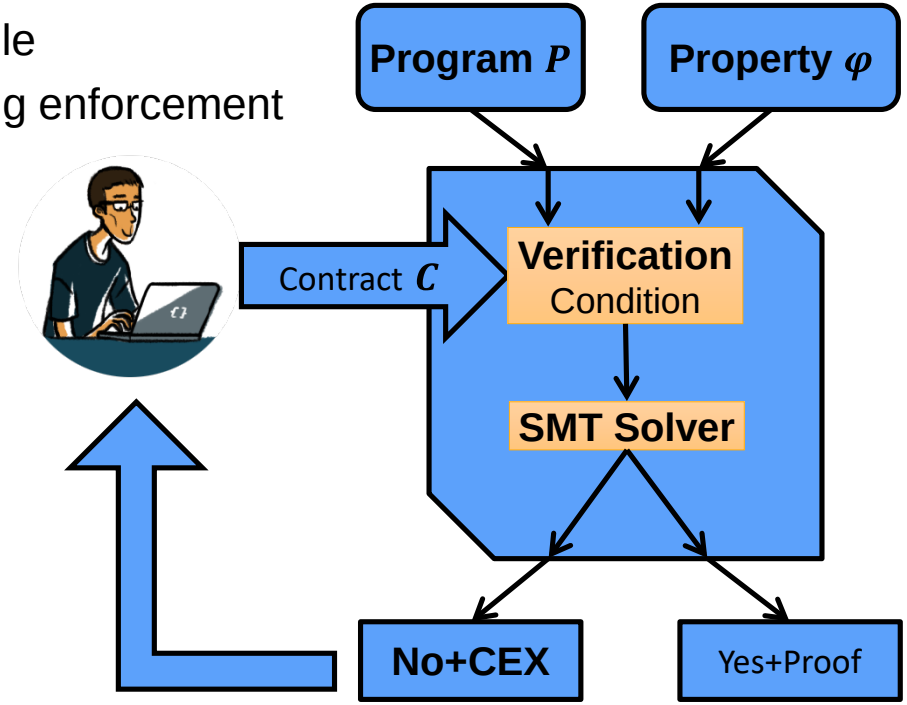
Who Verifies the Temporal Enforcer?

Implementation:

- Extension to Mixed-Criticality Zero-Slack Rate Monotonic Scheduler
- Implemented in C as a loadable kernel module
- Uses timer and clocks to implement the timing enforcement

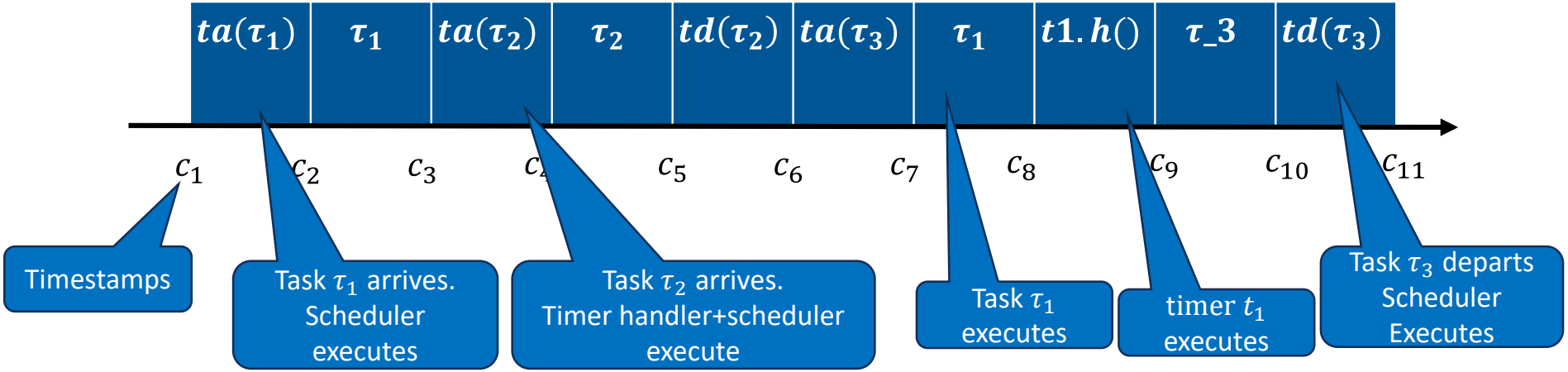
Verification of C code

- With FRAMA-C (auto-active verification)
- C code simplified to enable verification
- FRAMA-C encoding of timing model



Execution Timeline Model

Newtonian Time: flows monotonically, dense time

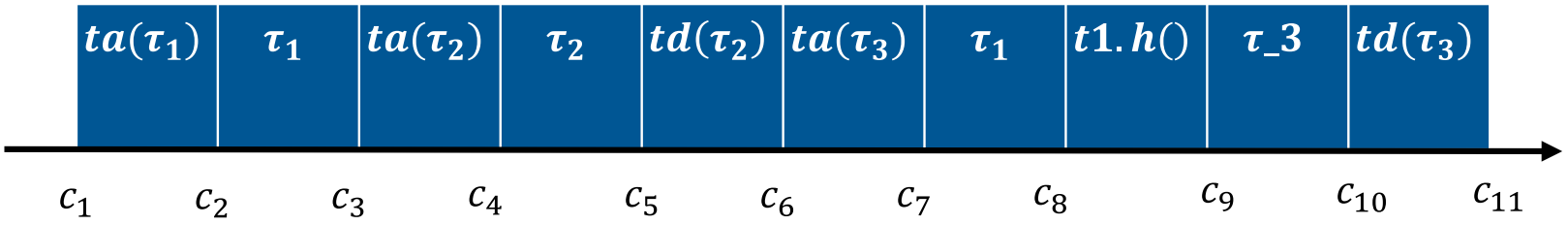


Execution $\pi = s_1 \xrightarrow{\alpha_1} s_2 \xrightarrow{\alpha_2} s_3 \ldots s_{n-1} \xrightarrow{\alpha_{n-1}} s_n$: α_i: action(enforcer|task)

State $s_i = (c_i, r_i, a_i) = (c_i$:timestamp, r_i:readyq, a_i:timerq)

$sched(s_i, \tau)$ means that τ is at the head of r_i

Task CPU Usage



$C(\pi, \tau_i)$ = total cpu usage by task τ_i over execution π

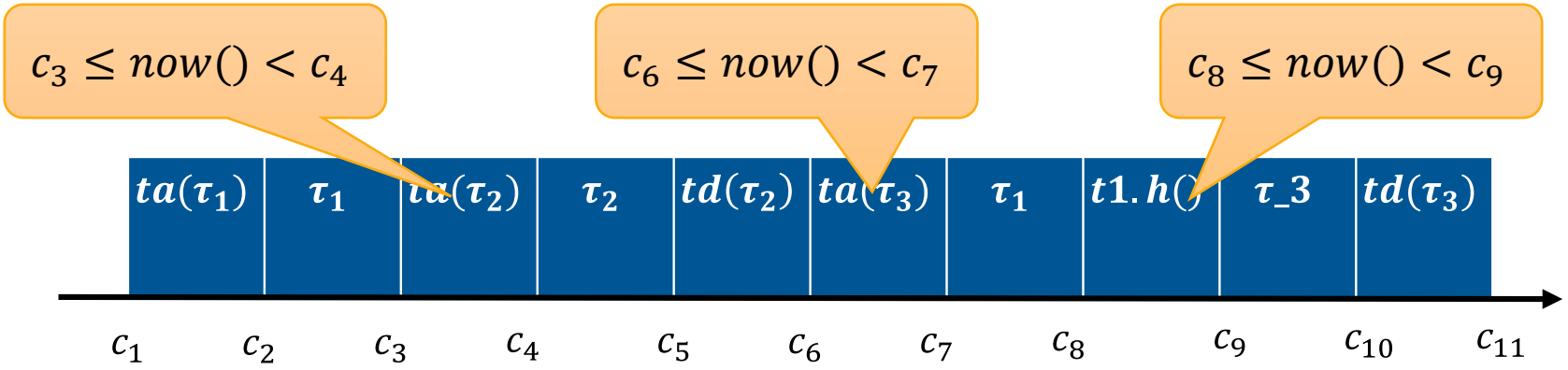
Add up durations of all the transitions labeled by τ_i

$C(\pi, \tau_1) = (c_3 - c_2) + (c_8 - c_7)$ *STOPPED by timer t_1

$C(\pi, \tau_2) = (c_5 - c_4)$

$C(\pi, \tau_3) = (c_{10} - c_9)$

Linking Time Model to Code



When task τ_1 starts executing

```
if (tau_1 ==readyq.head)
   tau_1.start = now()
```

When task τ_1 preempted/stopped

```
if (tau_1 ==readyq.head)
   tau_1.usage = now() − tau_1.start
```

Proving Tasks Never Exceed Budgets

Each task τ_i has a time budget $B(\tau_i)$

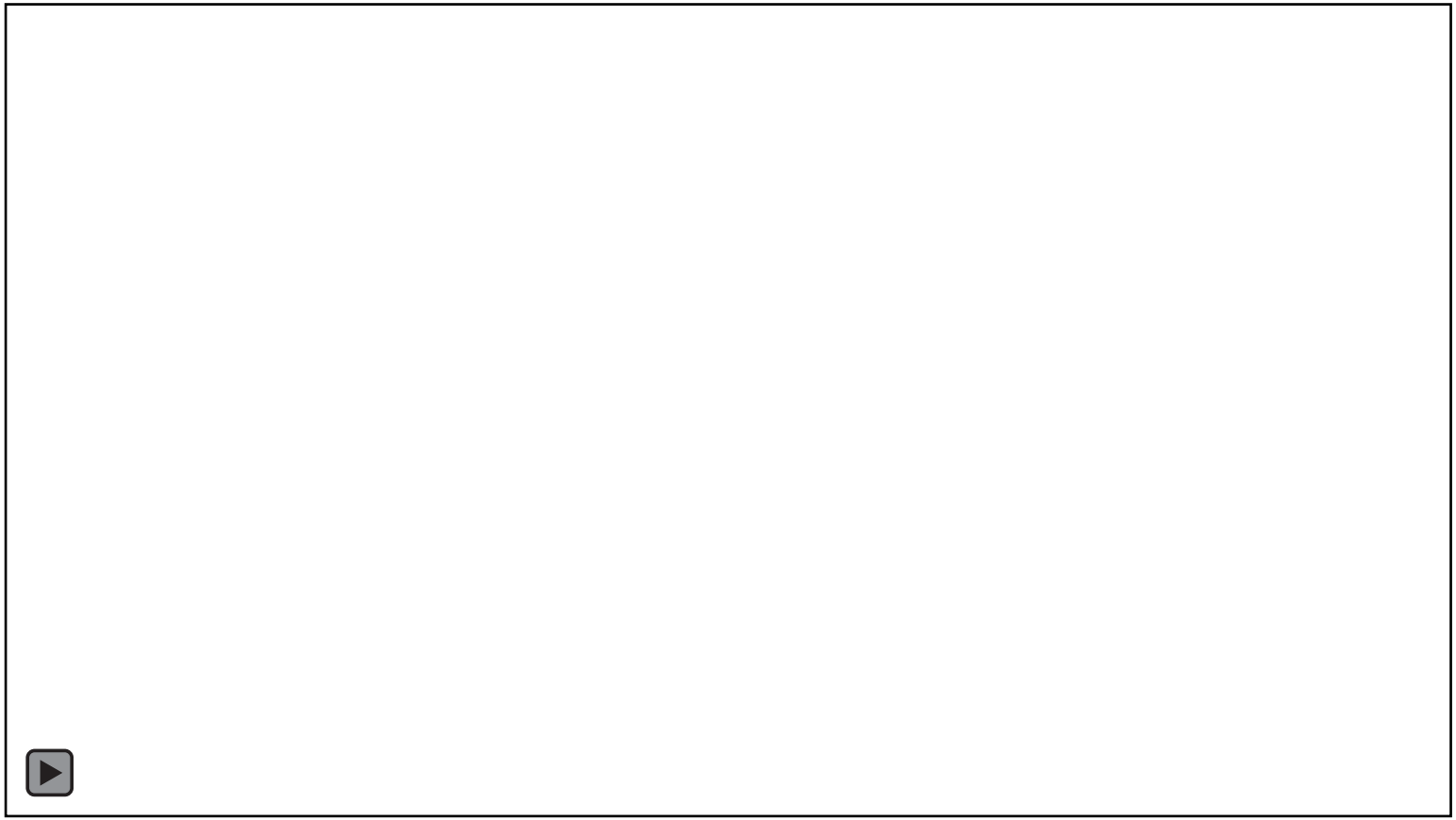
Definition 3 (Timer). *We say that a budget timer is always properly activated for a thread τ, denoted $Timer(\tau)$, if at the end of each execution $\pi = s_1 \xrightarrow{\alpha_1} s_2 \ldots s_{n-1} \xrightarrow{\alpha_{n-1}} s_n$ such that $\alpha_{n-1} \in F \wedge sched(s_n, \tau)$ there exists an active timer $t \in a_n$ such that $t.c \leq c_n + B(\tau) - \tau.usage$.*

Theorem 2. *For any thread τ, if $Timer(\tau)$, then τ never exceeds its budget, i.e., at the end of each execution π, we have $C(\pi, \tau) \leq B(\tau)$.*

Enforcer C implementation:

- Added ghost variables to follow time
- Verified correct “rounding” of timestamps (ticks to ns)
- Correct programming of timers
- Correct usage calculation

Drone Demo



Conclusions

Verification of Autonomous Systems is Challenging

- Verification technologies does not scale
- Behavior not fully defined at design time (machine learning)

Enforcement-Based Verification Makes it Possible & Practical

- Logical enforcement
- Temporal enforcement

Presented the formalization of enforcement-based safety verification

- Logical formulation: time-aware logic
- Temporal enforcement to deal with CPS inertia

Presented implementation in drone system