Certifiable Distributed Runtime Assurance

Challenge

Assure Safety of Distributed Cyber-Physical Systems

- Unpredictable Algorithms (Machine Learning)
- Coordinating multiple vehicles (distributed) to achieve mission

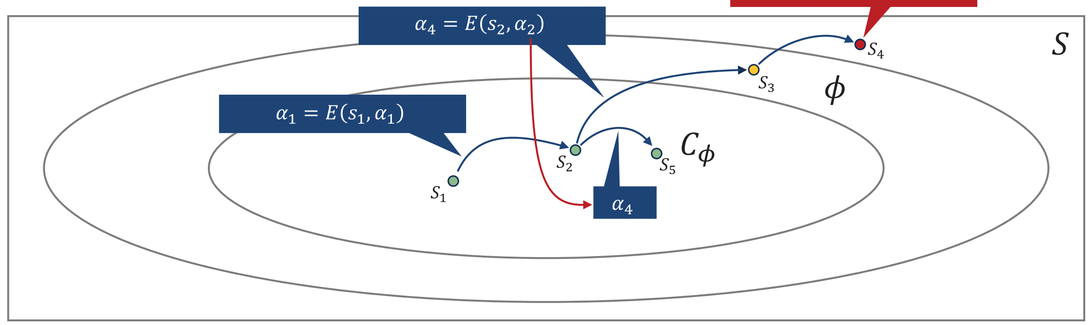
Solution

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

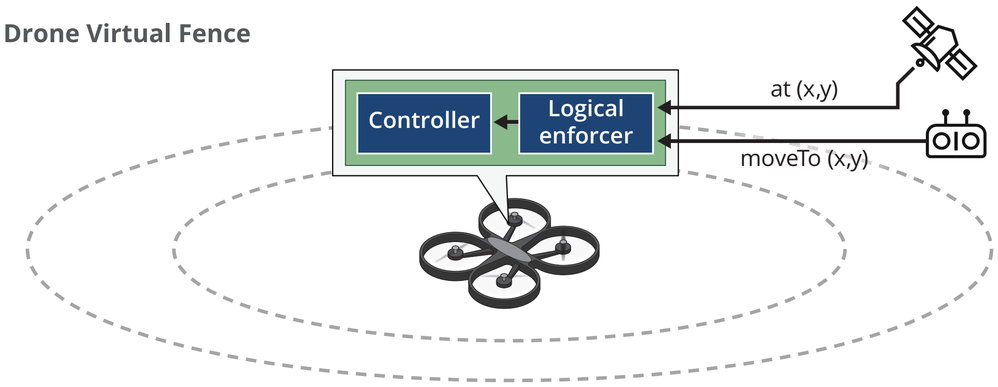
Formalization (Time-Aware Logic)
State of system: variable values

- State variables: V_S
  e.g., (x,y) position
- Action variables: V_Σ
  e.g., move-to(x,y) action
- System state: $s{:}V_S \mapsto D \in S$
- Actions: $\alpha{:}V_\Sigma \mapsto D$
- Behavior: periodic state transition
  $R_P\,(\alpha) \subseteq S{\times}S$
  $R_P\,(\alpha,s) = \{s' | (s,s'\,) \in R_P\,(\alpha)\}$
- Safe state: $\phi \subseteq S$
- Enforceable state:
  $\phi \supseteq C_\phi = \{s \mid \exists \alpha \in \Sigma{:}R_P\,(\alpha,s) \in C_\phi\,\}$
- Safe Actuation
  $SafeAct(s) = \{\alpha | R_P\,(\alpha,s) \in C_\phi\}$

Enforcer $\mathrm{E}(s,\alpha){:}\ \alpha \in SafeAct(s)\ ?\ \alpha : \alpha' \in SafeAct(s)$



Enforcing Drone Virtual Fence



Timing enforcement

- Unverified software may never finish!
- => No action produced to be enforced!

Temporal enforcer

- Protect other tasks from bogus never-ending (or large) executions
- Produce default safe actuation if task takes too long

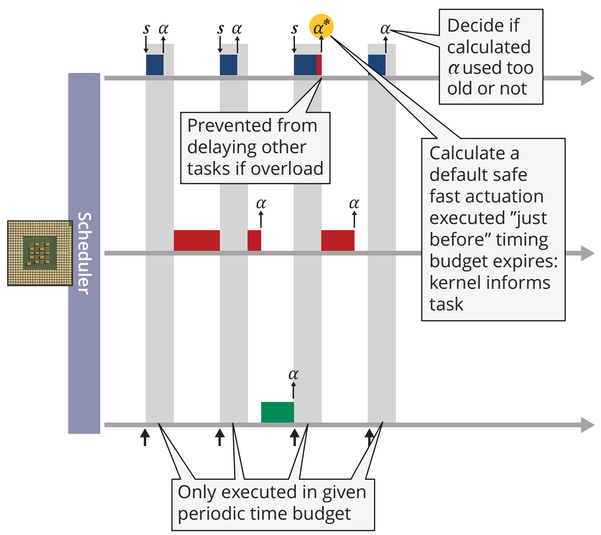
How

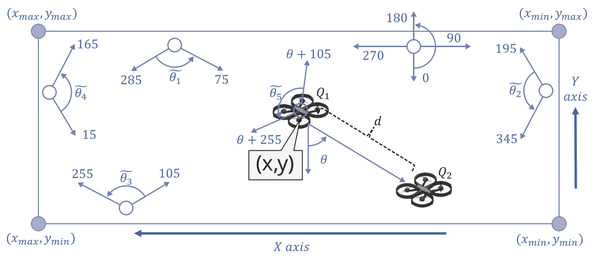
- Each task gets a CPU budget
  stop task if budget exceeded
- If task about to exceed budget
  execute safe action

Timing guarantees

- Never allow task to exceed budget
- Always execute actuation

Safe actuation on timing enforcement





Composing enforcers

- System with multiple enforcers:
  virtual fence+ collision avoidance
- Safe actions from different enforcers may conflict
  Drone at fence limit + other drone approaching
- Enforcer composition to resolve conflicts
  (1) priority based (2) utility maximization

Formalization

Enforcer: $\boldsymbol{E}{:}(\boldsymbol{P}, \boldsymbol{C_\phi}, \boldsymbol{\mu}, \boldsymbol{U})$

$\mu(s) \subseteq SafeAct(s)$; U: utility

No conflict:

$E_1\,(P_1, C_{\phi_1}, \mu_1, U_1\,), E_2(P_2, C_{\phi_2}, \mu_2, U_2\,)$

$\mu_{1,2} : \mu_1 \cap \mu_2$

Conflict: Priority resolution

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

Conflict: Utility maximization

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

Enforcers allows verification of complex CPS: Autonomous Vehicles

- Limit misbehavior
- With Verifiable Enforcers
- Result: Verified whole system

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