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Resilient Supervisory Control of Autonomous Intersections in the Presence of Sensor Attacks

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Motivation

* Cyber-physical systems (CPS), such as autonomous vehicles crossing an intersection, are vulnerable to sensor attacks.
* In autonomous intersections, the aim is to provide a **safe**, **scalable**, and **efficient** framework for coordinating autonomous vehicles.
* Supervisory control of discrete event systems (DES) allows incorporating the continuous dynamics and formally analyzing system safety.

Resilient Supervisory Control

* Resilient supervisory control design steps:
  1. Show supervisory control is vulnerable to sensor attacks
  2. Introduce a **detector** in the control architecture with the purpose of detecting sensor attacks
  3. Characterize **stealthy attacks** that cannot be detected but are capable of compromising safety
  4. Present a **resilient supervisory controller** that is secure against stealthy attacks
  5. Demonstrate functionality using examples and simulations

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System Model

* Vehicles are modeled as single integrators. For a set of vehicles, their dynamics are described by

$$\dot{x} = v + d$$

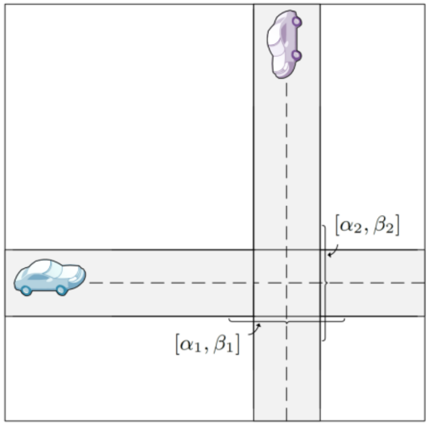
* Assuming the input is kept constant over each time interval, the time discretization is

$$x_{k+1} = x_k + u_k + \delta_k$$

* Sensor attacks on measurements are described as

$$\tilde{x}_k = x_k + e_k, \; k \in [k_s, k_e]$$

* They can lead to collision or deadlock among cars.



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Supervisory Control System

* Supervisory control has three operational goals:
  1. **Safety**: collisions must be avoided.
  2. **Non-blockingness**: vehicles must eventually cross the intersection.
  3. **Maximal-permissiveness**: vehicles must not be restricted unless necessary.
* In order to achieve these requirements, a supervisory controller disables inputs that lead to unsafety and deadlock based on the estimates.

Detector

* Detects attacks before they can cause significant damage.
* Nonparametric **Cumulative sum (CUSUM)** statistic as detection method.
* Incorporates knowledge of the physical system with the previously received data.
* Expected value is less than zero in the case of normal behavior.

$$z(k) := \inf_{\hat{x}(k) \in \mathbf{Post}_u \tilde{x}_{k-1}} ||\tilde{x}(k) - \hat{x}(k)|| - b$$

* Upon detection, vehicles are controlled by a fail-safe controller.

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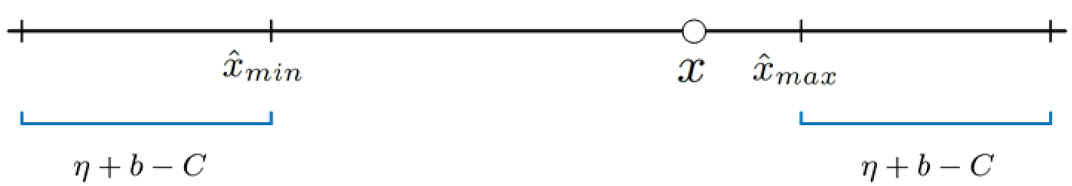
Stealthy Attacks

- Cannot be detected but are capable of compromising safety.
- They exist because of the following factors:
  1. Detector's threshold
  2. Disturbances and uncontrolled vehicles
- We characterize the **set of stealthy attacks** that contains all the corrupted measurements that cannot be detected.

$$I_k^s(\tilde{x}_{k-1}, u_{k-1}, C_{k-1}) = [\hat{x}_{min} - \eta - b + C, \hat{x}_{max} + \eta + b - C]$$



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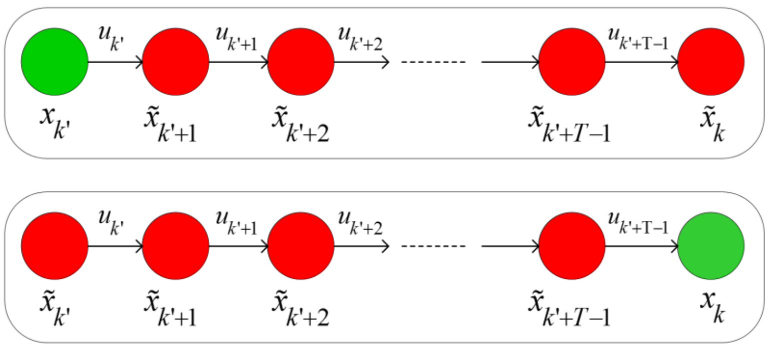
Resilient Supervisor Design

* Maintains safety even in the presence of stealthy attacks.
* Resilient supervisor design:
  1. Constructing an **estimator system** that computes the smallest state estimate containing the actual state taking into consideration possibly corrupted measurements.
  2. Creating a **finite DES abstraction** of the estimator system.
  3. Translating the control problem to the DES domain, solving it, and translating the results back to the continuous domain.

Estimator

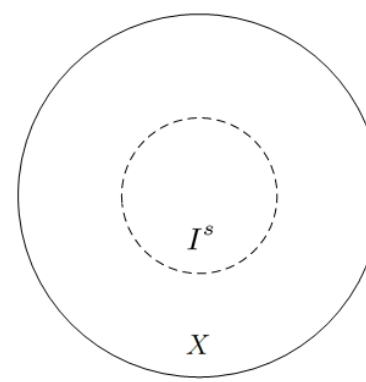
- Assuming $k' = k - T_{max}$, either $\tilde{x}_k$ or $\tilde{x}_{k'}$ is not attacked.



$$\hat{I}_k(\tilde{x}_{k'}, \tilde{x}_k) = \{\mathbf{Post}_{u_{k'} \ldots u_{k-1}} \tilde{x}_{k'}\} \cup \tilde{x}_k$$

- The set $\hat{I}$ contains the true state despite the attack.
- The estimator **predicts** a set of states and then **corrects** it:

$$I_k(I_{k-1}, I_k^s, \tilde{x}_k) = \begin{cases} \{\mathbf{Post}_u I\} \cap \hat{I}_k & \tilde{x}_k \in I_k^s \\ \text{detection} & \text{else} \end{cases}$$

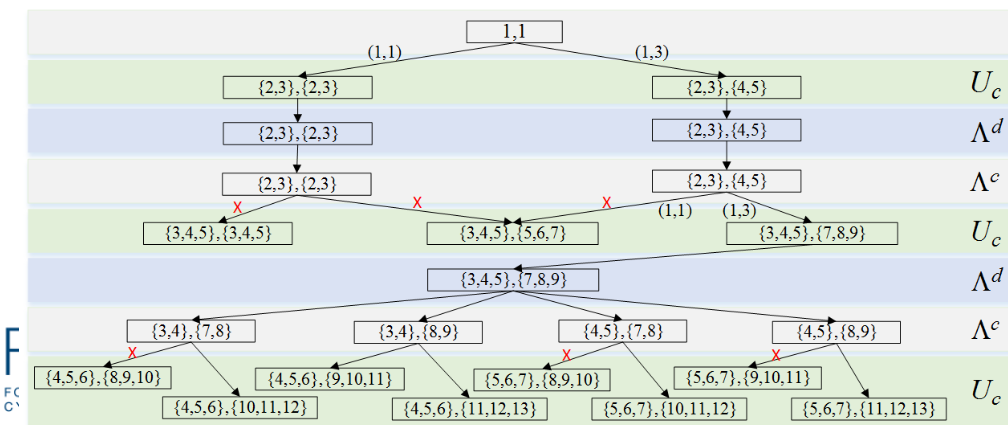


Discrete Event System (DES)

- Consider the **DES** $G := (Q, E, \psi, q_0, Q_m)$ with discrete states Q defined using the map $\ell(x) := \min_{q \in Q} \{q : \|x - q\| \leq \tau\mu/2\}$.

- The five-layer event set is shown in the table.
- An **Observer** of G is constructed using the notion of information states.
- Example of an observer:

Event	Controllable	Observable
Controlled input	✓	✓
Uncontrolled input	×	×
Disturbance	×	×
Prediction-Correction	×	✓
Detection	×	✓



Supervisor Construction

* Theorem: The relation between the observer and the estimator system is **simulation/alternating simulation.**
* Supervisory controller solution:
  1. Translating safety and non-blockingness specifications to the DES domain
  2. Solving the problem using the Basic Supervisory Control Problem in the Non-Blocking (BSCP-NB) algorithm and obtaining a supervisor S such that:

$$\mathcal{L}_m(S/G) = (\mathcal{L}_m(H))^{\uparrow C} \text{ and } \mathcal{L}(S/G) = \overline{(\mathcal{L}_m(H))^{\uparrow C}}$$

  1. Translating the obtained supervisor to the continuous domain

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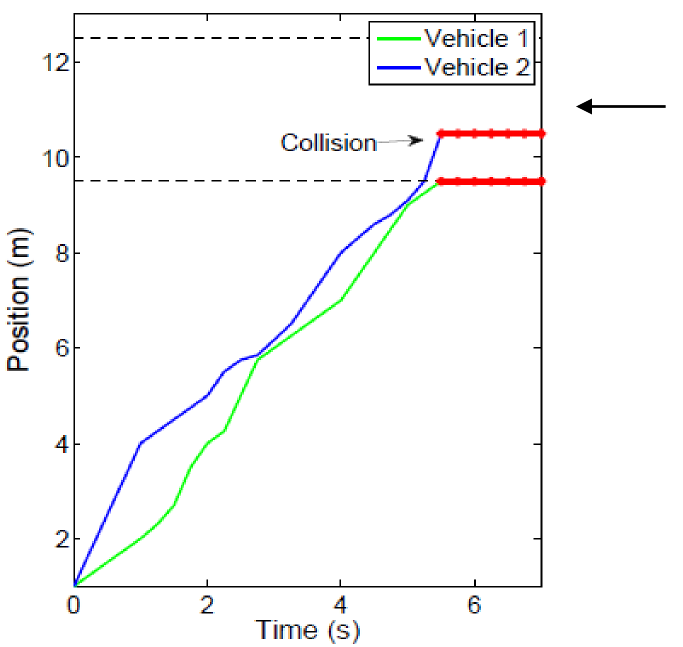
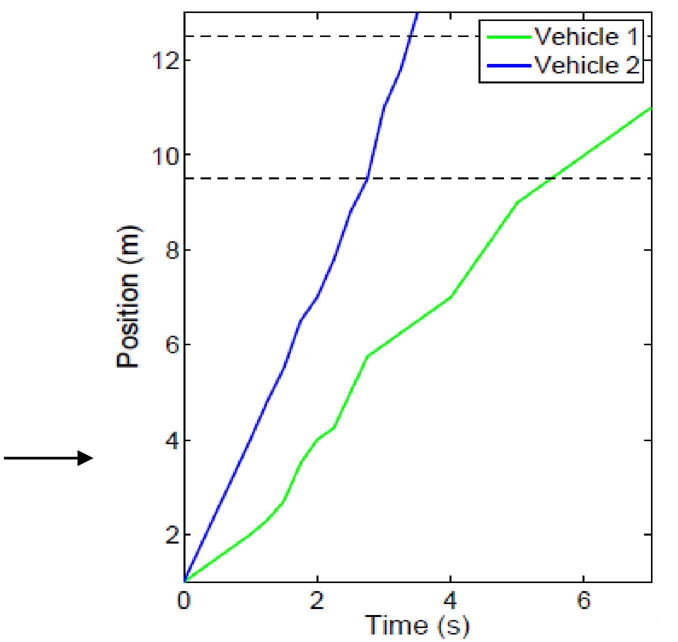
Example

* Intersection with a controllable and an uncontrollable car
* Surge attack on the controllable car: $\tilde{x}_k = \begin{cases} \hat{x}_{max,k_s} + \eta + b & k = k_s \\ \tilde{x}_{k-1} + u_{k-1} + d_{max} + b & \text{else} \end{cases}$
* **Simulation** in SUMO using TraCI4MATLAB

Non-resilient Supervisor



Resilient Supervisor



Conclusion

* Supervisory control of autonomous intersections is vulnerable to sensor attacks. To improve the system resilience:
  * Introduced a **detector** in the control architecture
  * Characterized **stealthy attacks** that bypass the detector
  * Presented a **resilient supervisory controller** that is safe, non-blocking, and maximally permissive, despite the presence of sensor attacks
  * Demonstrated functionality using **simulations** in SUMO
* Future work: actuator attacks, decentralized resilient controllers, other control protocols

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Thank you!

Questions?

Appendix

1. Safety: $\inf_{t \geq 0, b' \in B} ||x(t) - b'||_\infty > 0$
2. CUSUM: $C_i(k) = (C_i(k-1) + z_i(k))^+$
3. Detector Decision: $d(C_i(k)) = \begin{cases} H_1 & \text{if } C_i(k) > \eta_i \\ H_0 & \text{otherwise} \end{cases}$
4. Event set: $E = \Lambda^d \times \Lambda^c \times U_c \times U_{uc} \times W$
5. Transition:

$$\psi(q, \lambda^d, \lambda^c, u_c, u_{uc}, w) = \psi_3(\psi_2(\psi_1(\psi^c(\psi^d(q, \lambda^d), \lambda^c), u_c), u_{uc}), w)$$

6. Supervisor map: $\sigma(I) = \{u_c/\tau : u_c \in S(\ell(I))\}$