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Safety-Critical Control for Nonlinear Affine Systems with Robustness and Attack Recovery

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Research Motivation

- **System Vulnerabilities of Cyber-Physical Systems under Cyberattacks**
  - Modern aircrafts (e.g., quadrotor UAVs), are typical examples of cyber-physical systems (CPSs) where physical and computational layers are closely intertwined.
  - Cyberattacks can cause detrimental situations, such as crashes and collisions by disrupting/compromising the actuators and sensors of CPSs.

Fig 1. Possible detrimental scenarios in the presence of cyberattacks

- **Related Research for Assuring System Safety**

	Reachability Analysis	Control Barrier Function (CBF)
Pros	Predictive capability Comprehensive safety check	Real-Time Safety Assurance Integration with control laws
Cons	Computational Complexity Model Accuracy	Design complexity Tuning Challenges

- **Limitation of Previous Studies**
  - While CBF has been widely used in various domains, such as robotics and aerospace engineering, previous research on CBF cannot handle malicious impact on systems (e.g., model uncertainties, actuator faults, and cyberattacks).
  - We propose a CBF-based safety-critical controller based on an actuator attack detector to enhance the system safety and control performance.

Problem Formulation

- **Control Barrier Function Formulation**
  - Exponential CBF with relative degree (r) 2 or more [1]

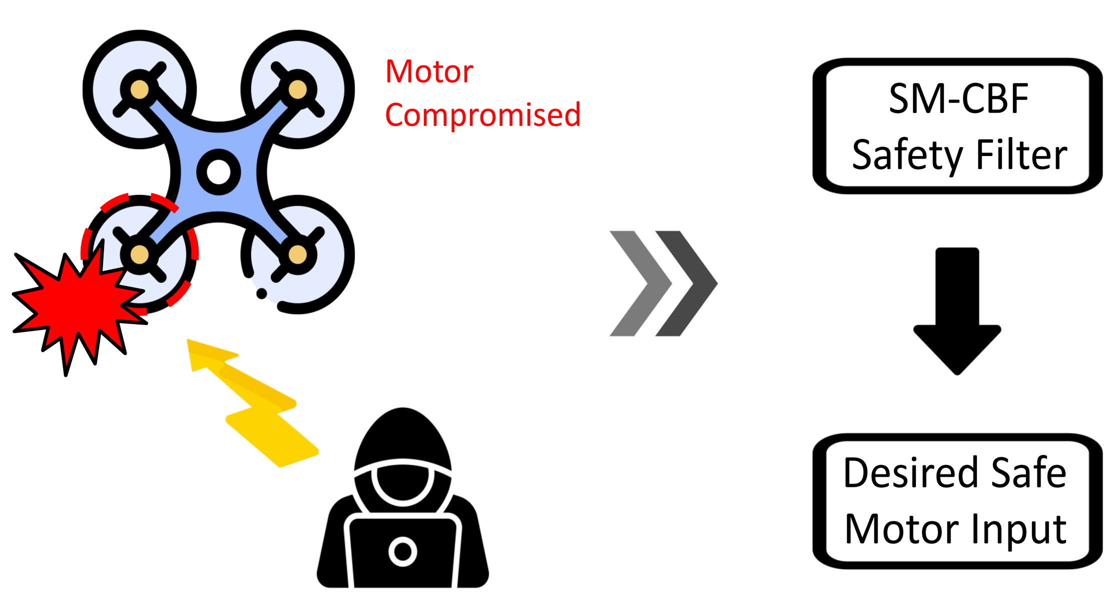
$$\sup_{u \in \mathcal{U}} \left\{ L_f^r H(x) + L_g L_f^{r-1} H(x) u \right\} \geq K_\mu \rho(x)$$

  - Proposed Sliding-Mode approach CBF [2]

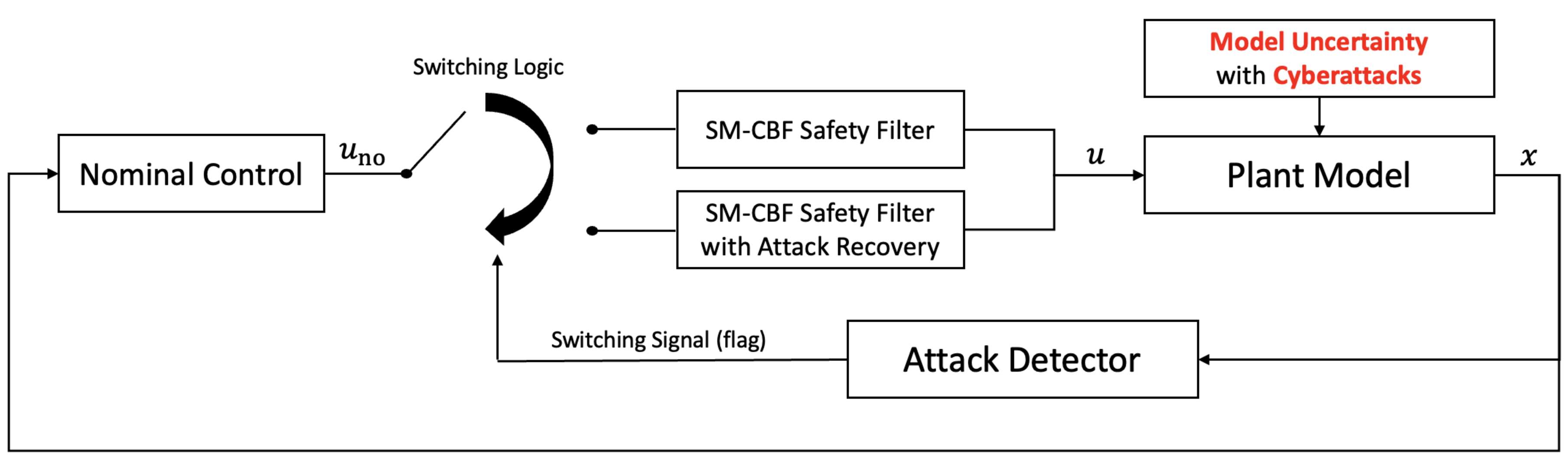
$$u^*(x) = \arg\max_{u \in \mathcal{U}} \frac{1}{2} ||u - u_{\text{no}}||^2$$

$$\text{s.t.} \quad L_f^r H(x) + L_g L_f^{r-1} H(x) u \geq \bar{\mu} - \bar{K} \text{sign}(S_H(x))$$

- **Attack Scenario: Cyberattacks on Actuators**
  - We assume that attackers can target a specific actuator (i.e., motor), to launch cyberattacks at random times and for variable durations.

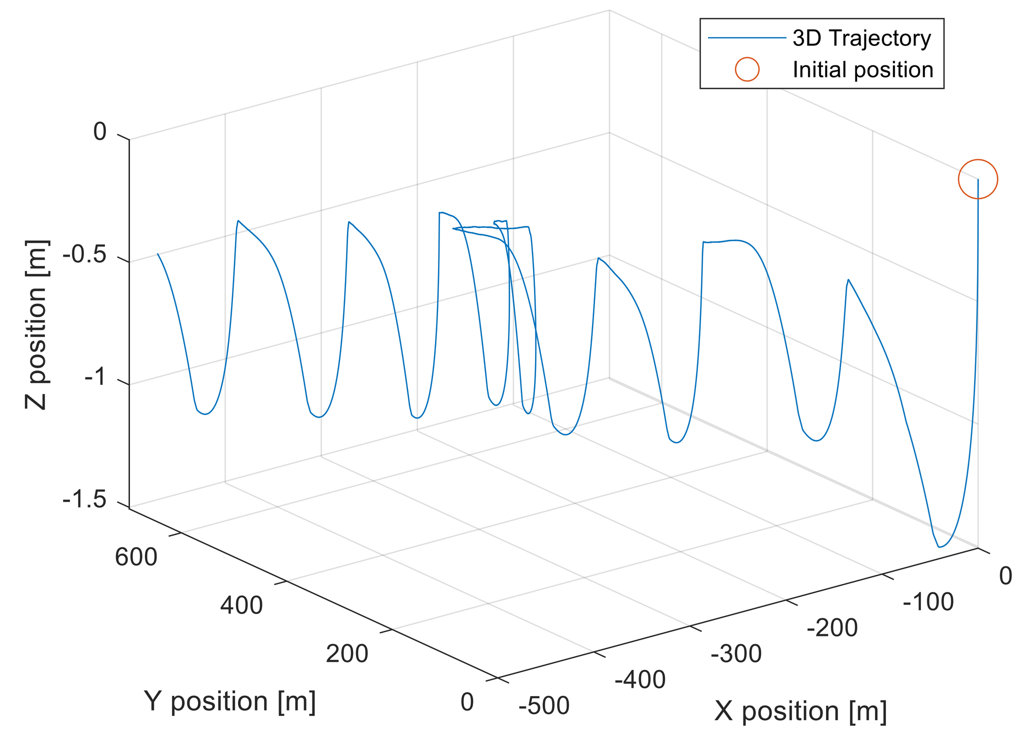


- **Block diagram of the proposed safety-critical control algorithm**



Main Results

- The quadrotor UAV equipped with the SM-CBF-based safety filter and the attack detector can successfully recovers from the attack.
- When the safety filter is reconfigured to the attack detected mode, the thrust of the second rotor becomes zero during the attack as shown in the figure below, which leads to the attenuation of roll angle decrease and pitch angle increase.



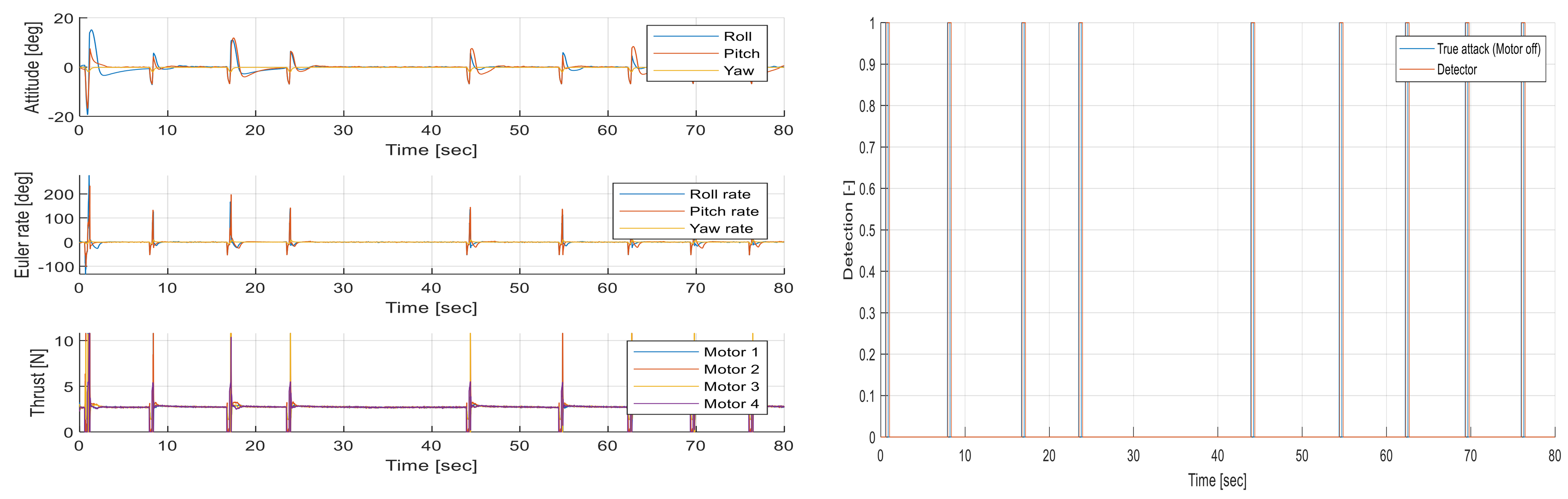


Fig 2. MATLAB simulation: Trajectory of the quadrotor UAV when the actuator cyber attack is applied and mitigated (top-right); Euler angles, Euler rate and thrust of the quadrotor (bottom-left); Comparison between true attacks and detections using the attack detector (bottom-left);

Real-World Simulation (Gazebo)

- To enhance the practicability, we develop the Gazebo simulation environment, renowned for its real-world simulation capabilities, to validate the real-time performance of our proposed SM-CBF safety-critical controller.
- In our study, we implemented the proposed SM-CBF safety filter only with a position controller to conduct a validation test on a circular trajectory within the Gazebo simulation. The results demonstrate that the proposed SM-CBF safety filter operates effectively in Gazebo.
- As a future direction, we plan to develop an attitude controller and integrate it with our proposed method. We anticipate that transitioning to Gazebo will demonstrate equivalent performance with the MATLAB results.
- **Gazebo simulation with Sliding Mode Based Control Barrier Function (Base: PID Controller)**

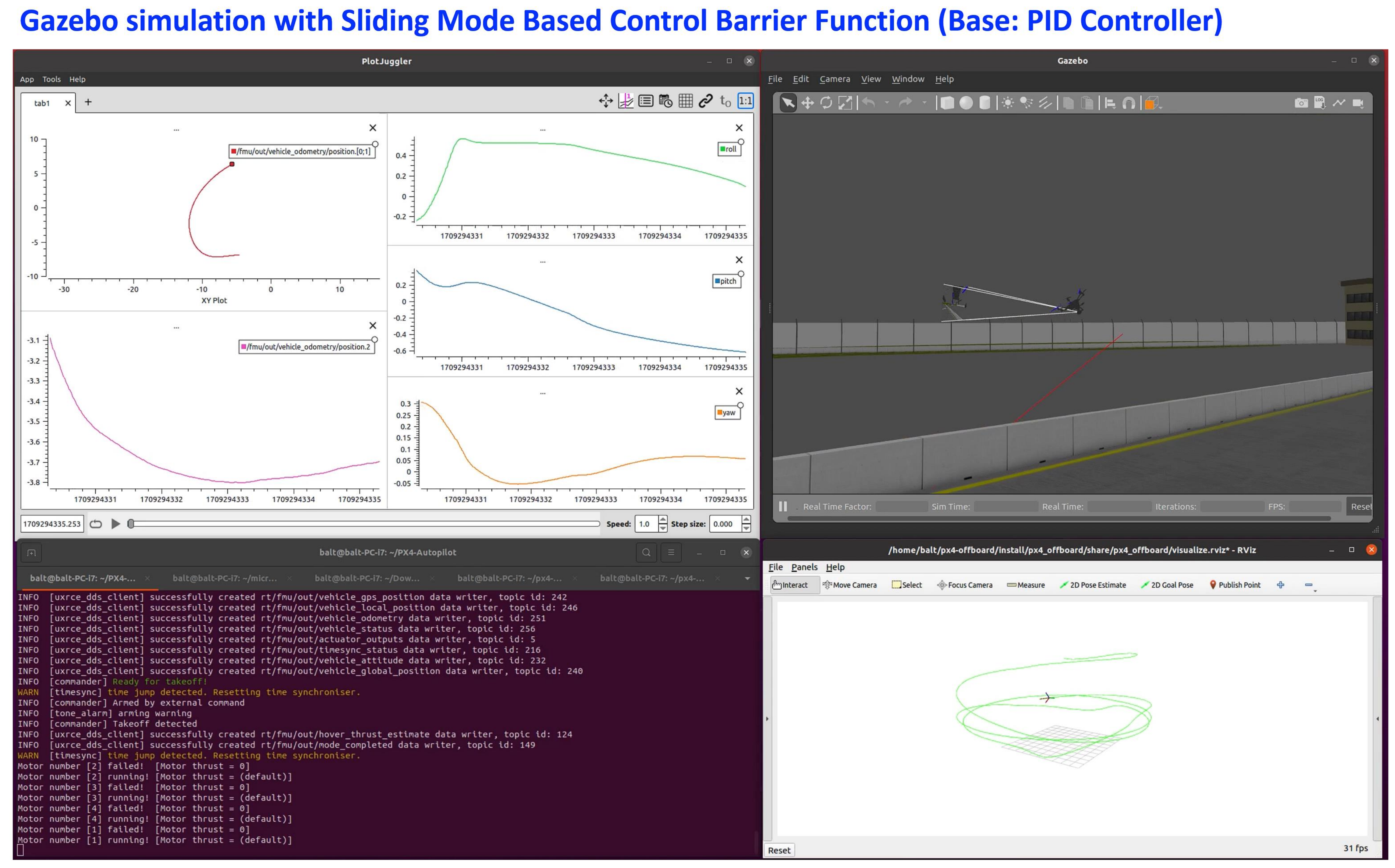


Fig 3. Live monitoring for roll, pitch, yaw angles and altitude of the quadrotor UAV (top-left); 3D simulation of the quadrotor with Gazebo (top-right); An illustration of a specific motor being targeted by an attacker at a random time (bottom-left); The quadrotor's trajectory alongside its desired position (bottom-right)

References

1. A., Ames, et al., "Control Barrier Functions: Theory and Applications," *18th European Control Conference (ECC)*, Naples, Italy, 2019, pp. 3420-3431.
2. Q., Nguyen, K., Sreenath, "Exponential Control Barrier Functions for enforcing high relative-degree safety-critical constraints," *2016 American Control Conference (ACC)*, Boston, MA, USA, 2016, pp. 322-328.

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