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An attack-resilient distributed extended Kalman consensus filtering algorithm with applications to multi-UAV tracking problems

Key words: Extended Kalman consensus filtering; Hypothesis testing; Rectification strategy; Multi-UAV tracking

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Motivation

- With the rise of wireless sensor networks and multi-unmanned aerial vehicle (multi-UAV) systems, state estimation has become critical in various applications, making it a prime target for deceptive attacks.
- Deception attacks with limited energy (DALEs) are sophisticated and can bypass traditional detection mechanisms. Existing studies have focused mainly on detecting DALE, with a lack of effective strategies for handling abnormal data and system recovery.

Main idea

- To address the challenges posed by DALE in nonlinear systems, particularly within the context of multi-UAV tracking， we propose a hypothesis testing-based detection mechanism that swiftly identifies anomalies induced by DALE.
- We propose an adaptive rectification strategy that recalibrates the affected state estimation, reduces the impact of the attack, and restores system performance to its optimal state.
- Based on the detection and rectification mechanisms, we introduce the attack-resilient distributed extended Kalman consensus filtering (AR-DEKCF) algorithm, which is designed to maintain the stability and accuracy of the state estimation. The effectiveness of AR-DEKCF has been confirmed through simulations involving multi-UAV tracking problems.

Framework

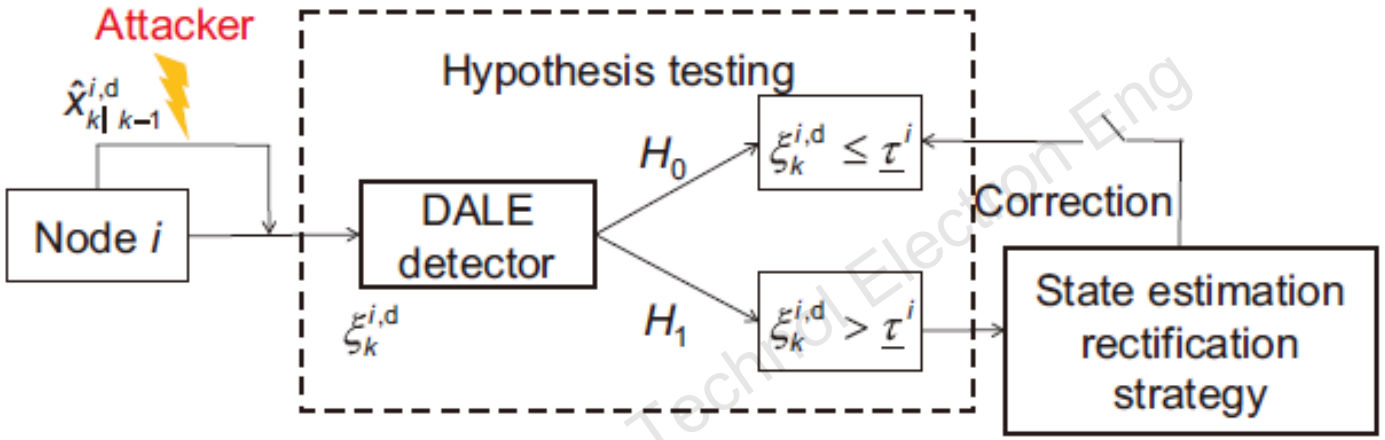

Fig. 1 Flowchart for correcting anomalous data under DALE

First, we establish a DALE within the distributed extended Kalman consensus filtering (DEKCF) framework. After that, we propose a hypothesis testing-based mechanism to detect the abnormal data generated by DALE in the presence of linearization errors in the nonlinear system. Finally, we propose the AR-DEKCF algorithm, which includes a rectification strategy that recalibrates the abnormal data once DALE is detected.

Method

To recalibrate the detected anomaly state estimates, we design a rectification strategy to adjust the data, ensuring the mean square exponential boundedness of estimation errors.

The data rectification procedure:

$$\omega^i = \begin{cases} 0, & \delta_k^i = \delta_{k-1}^i,\ \xi_k^{i,\mathrm{d}} > \underline{\tau}^i, \\ 1, & \delta_k^i = k,\ \xi_k^{i,\mathrm{d}} \le \underline{\tau}^i. \end{cases}$$

Algorithm 1 AR-DEKCF

1: **Input:** $\hat{x}_{k-1}^j$, P_{k-1}^j, F_{k-1}^j, Q_{k-1}, $\underline{\tau}^i$, L

2: **Prediction:** calculate the information pair $(\Omega_{k|k-1}^j, q_{k|k-1}^j)$ via Eqs. (3) and (4)

3: **Rectification:** for $\ell = 0, 1, \cdots, L-1$, $j \in \mathcal{N}^i$, consider that the attack events occur

4: **if** $\xi_k^{i,\mathrm{d}} > \underline{\tau}^i$ **then**

(1) trigger $\omega^j = 0$

(2) correct the information pair $(\Omega_{\ell,k|k-1}^{j,\mathrm{d}}, q_{\ell,k|k-1}^{j,\mathrm{d}})$ by Eqs. (22) and (23)

(3) update the information pair $(\Omega_{\ell,\delta_k^j}^j, q_{\ell,\delta_k^j}^j)$

else

(1) trigger $\omega^j = 1$

(2) compute the information pair $(\Omega_{\ell,k|k-1}^j, q_{\ell,k|k-1}^j)$ by Eqs. (3) and (4)

(3) update the information pair $(\Omega_{\ell,k}^j, q_{\ell,k}^j)$

5: **Fusion:** set $L = \ell + 1$, update $P_k^i = (\Omega_{L,k}^i)^{-1}$, $\hat{x}_k^i = P_k^i q_{L,k}^i$ by Eq. (24)

6: **Update:** set $k = k + 1$, and repeat lines 3–5

7: **Output:** P_k^i, $\hat{x}_k^i$

Results

To validate the effectiveness of the AR-DEKCF algorithm, we select five UAVs with range-bearing sensors to cooperatively track the target.

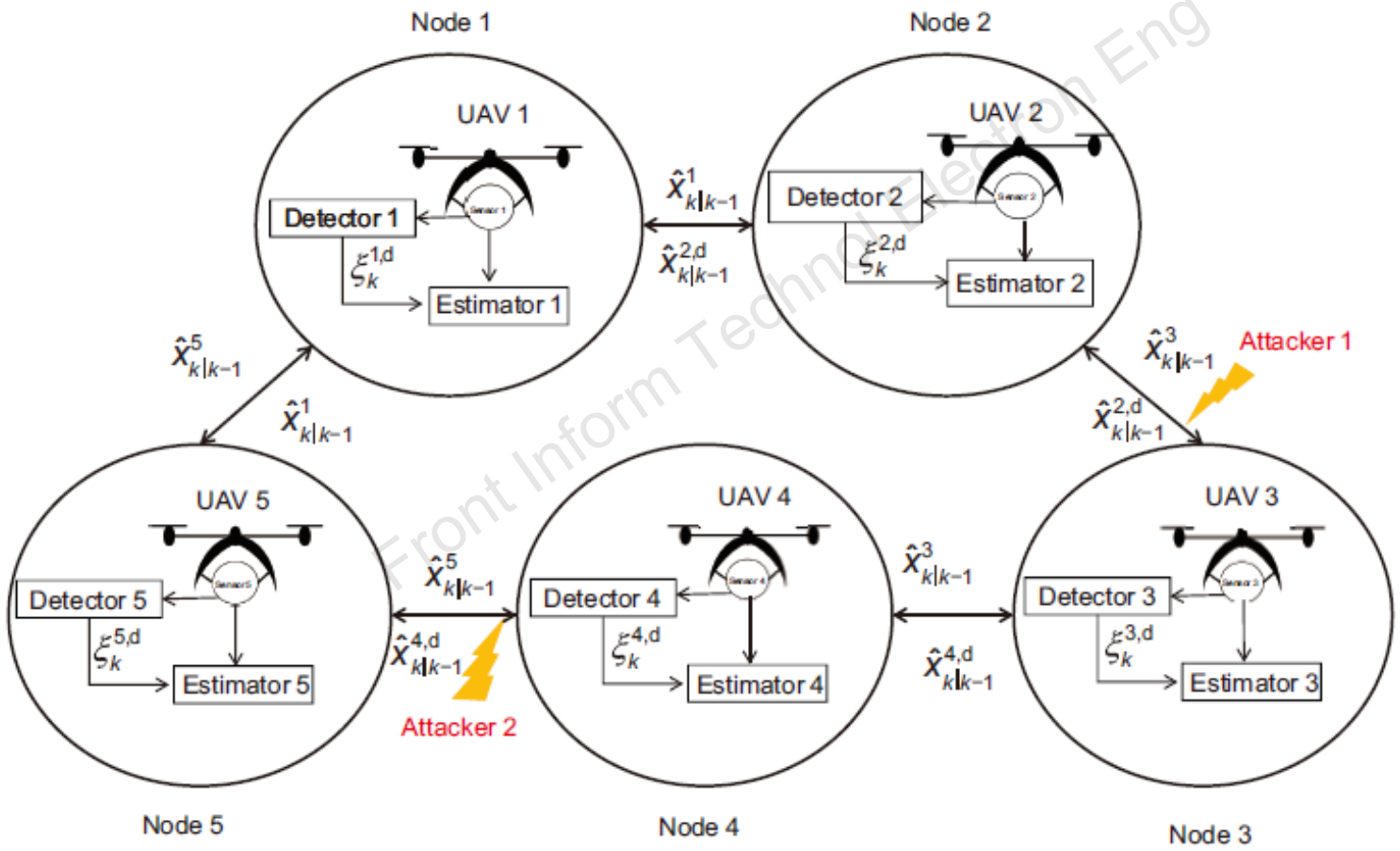

Fig. 2 UAV topology under DALE

Results

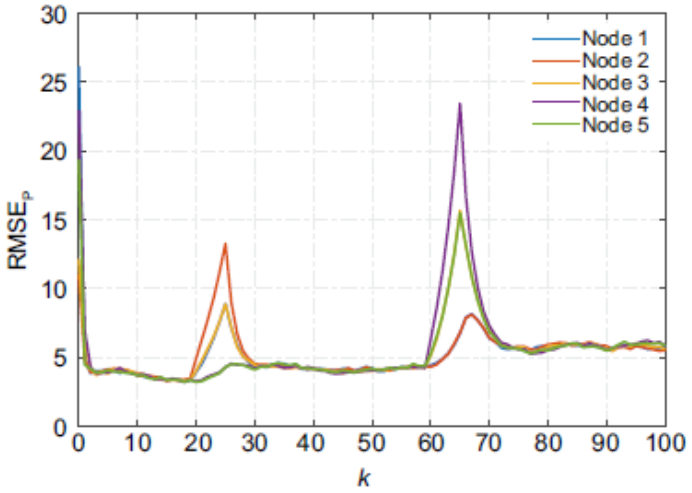

Fig. 3 $\mathrm{RMSE_P}$ of the AR-DEKCF algorithm for $L = 4$

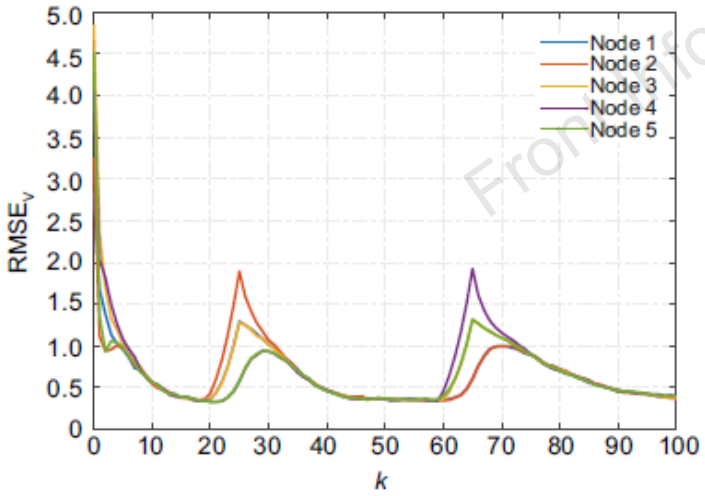

Fig. 4 $\mathrm{RMSE_V}$ of the AR-DEKCF algorithm for $L = 4$

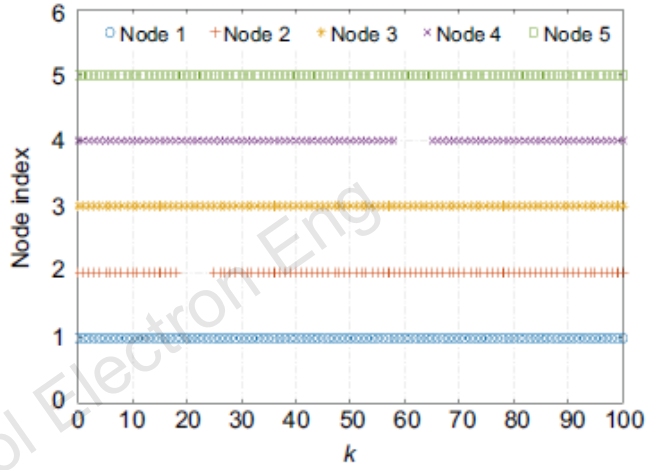

Fig. 5 State estimation rectification time under DALE

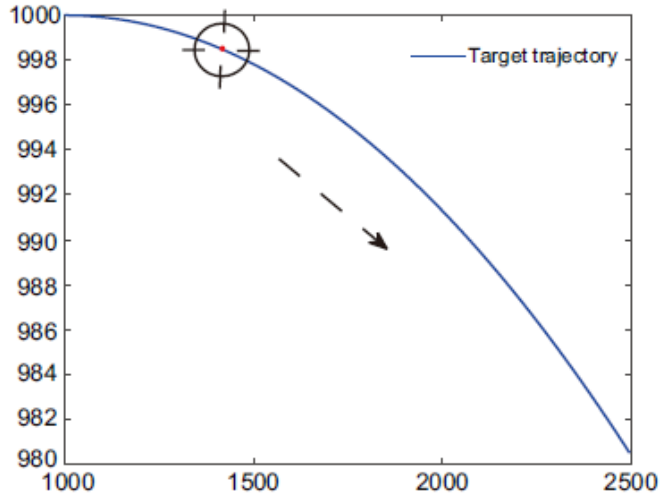

Fig. 6 Target unspecified constant turning rate trajectory within 20 m by 1500 m area

Results

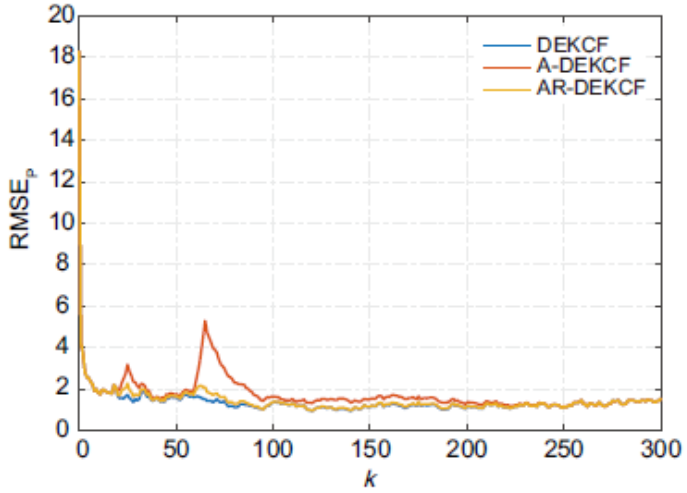

Fig. 7 $\mathrm{RMSE_P}$ comparison among different algorithms for UAV 2

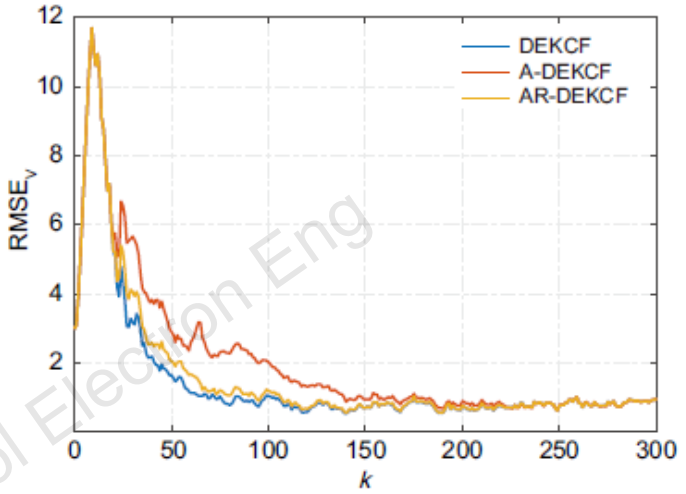

Fig. 8 $\mathrm{RMSE_V}$ comparison among different algorithms for UAV 2

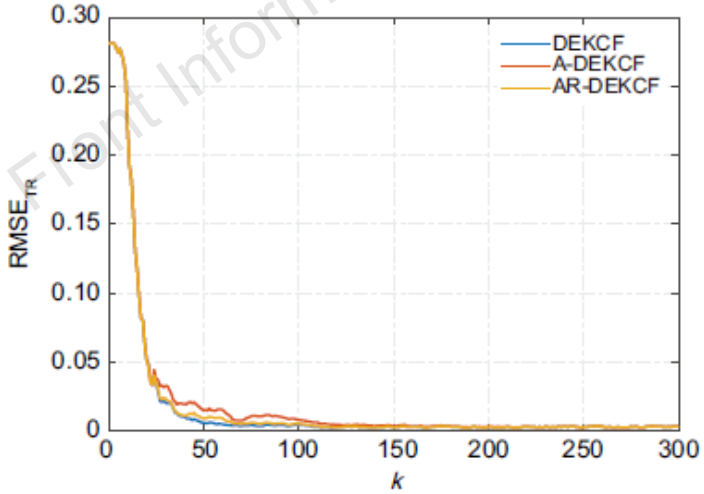

Fig. 9 $\mathrm{RMSE_{TR}}$ comparison among different algorithms for UAV 2

Conclusions

In this work, we have devised an innovative approach to tackle deception attacks with limited energy (DALE) in distributed multi-sensor fusion. We proposed a hypothesis testing-based mechanism for DALE detection and a rectification strategy to mitigate its impact. We introduced the AR-DEKCF algorithm, and the simulation results in multi-UAV tracking scenarios confirmed the AR-DEKCF's superior performance and stability, enhancing the reliability of state estimation in adversarial environments.

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