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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

Corresponding author: Wangyan LI

E-mail: wangyan_li@usst.edu.cn

 ORCID: <https://orcid.org/0000-0002-0068-1059>

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

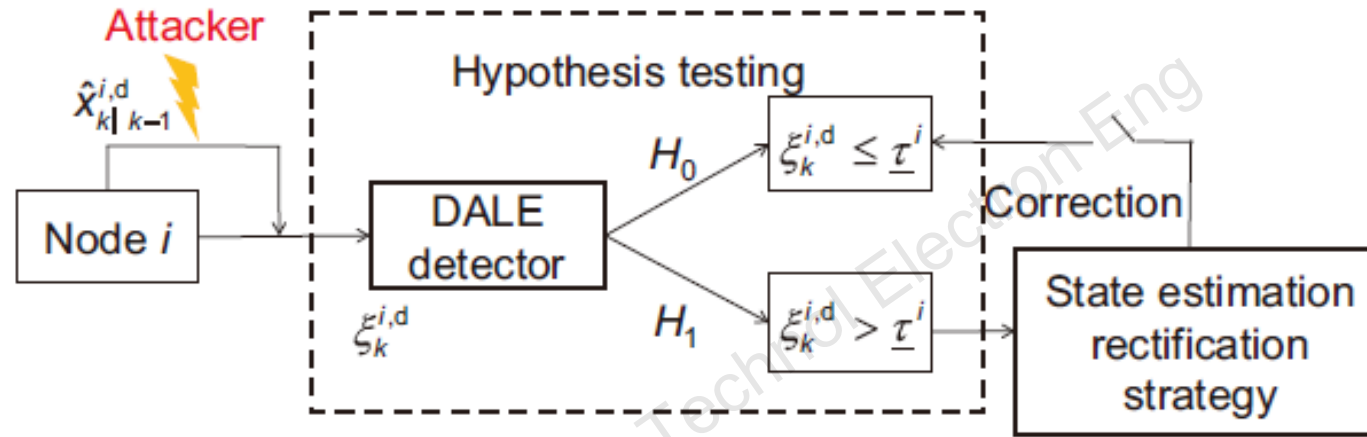


Fig. 1 Flowchart for correcting anomalous data under DALE

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:

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

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 $\ell = 0, 1, \dots, L-1, j \in \mathcal{N}^i$, consider that the attack events occur
 - 4: **if** $\xi_k^{i,d} > \underline{\tau}^i$ **then**
 - (1) trigger $\omega^j = 0$
 - (2) correct the information pair $(\Omega_{\ell,k|k-1}^{j,d}, q_{\ell,k|k-1}^{j,d})$ 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:** $P_k^i, \hat{x}_k^i$
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Results

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

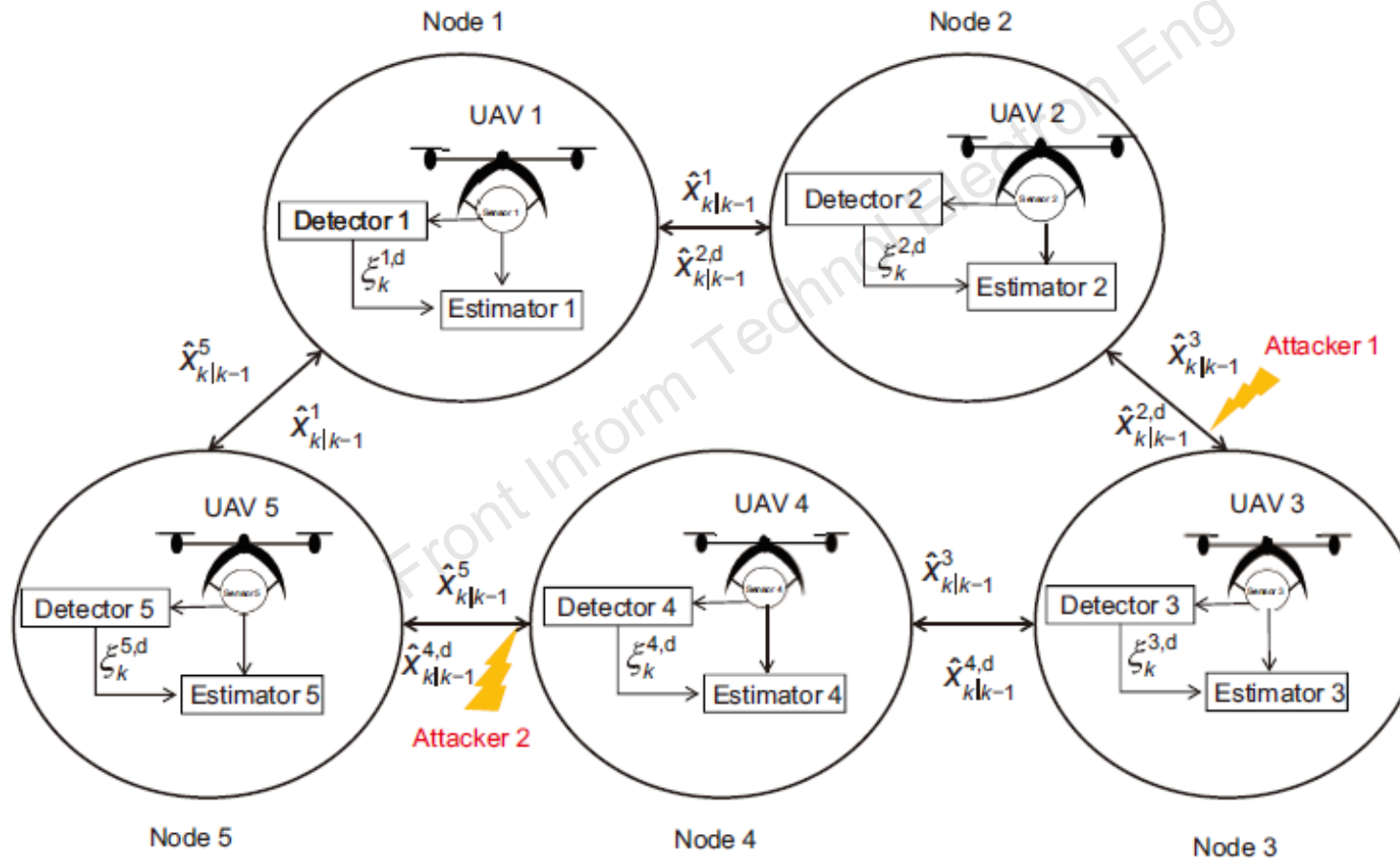


Fig. 2 UAV topology under DALE

Results

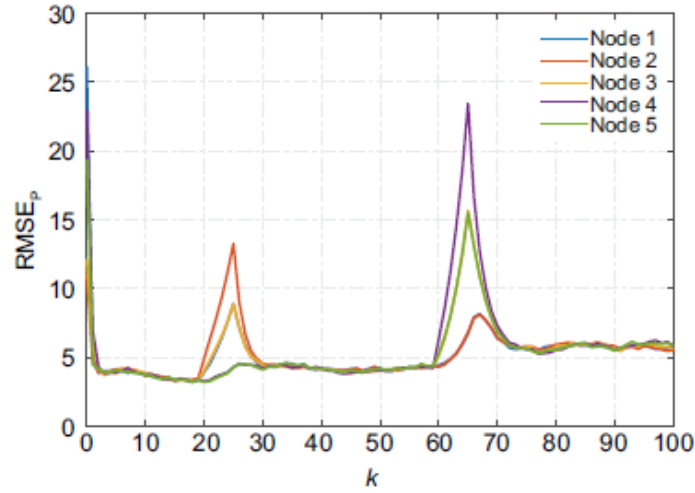


Fig. 3 RMSE_P of the AR-DEKCF algorithm for $L = 4$

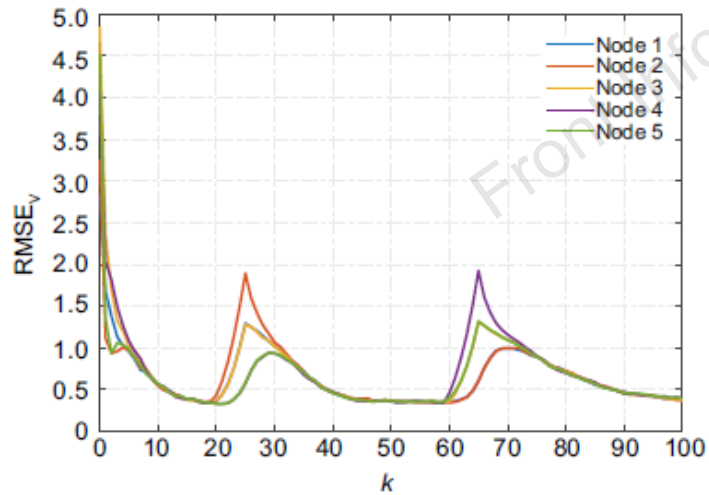


Fig. 4 RMSE_V of the AR-DEKCF algorithm for $L = 4$

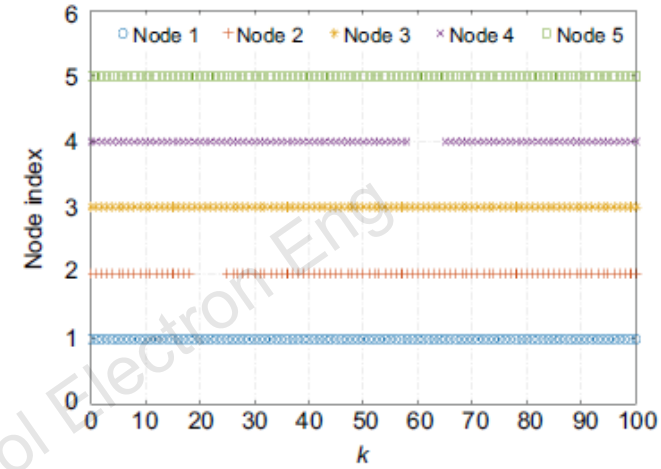


Fig. 5 State estimation rectification time under DALE

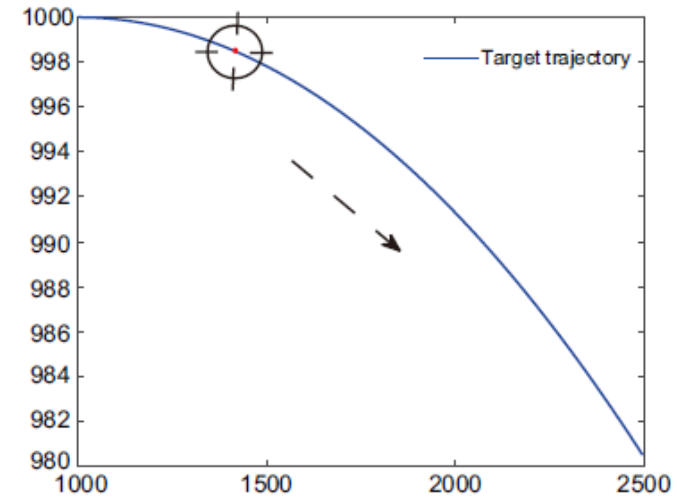


Fig. 6 Target unspecified constant turning rate trajectory within 20 m by 1500 m area

Results

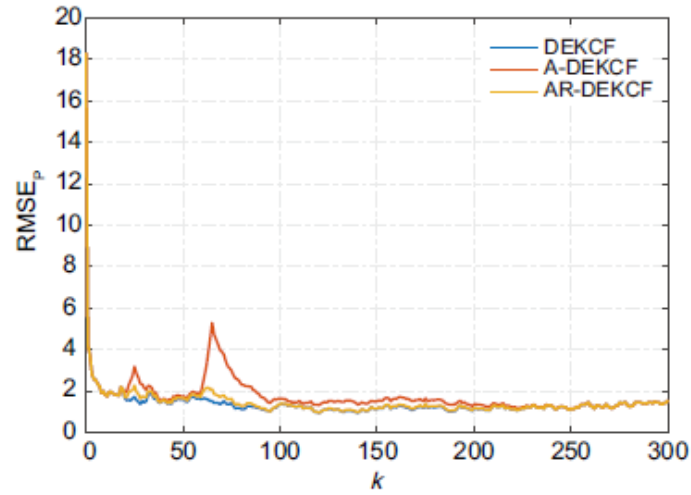


Fig. 7 $RMSE_P$ comparison among different algorithms for UAV 2

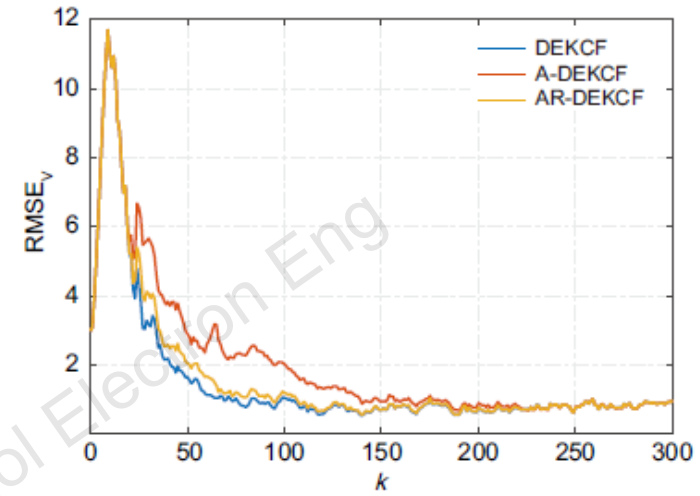


Fig. 8 $RMSE_V$ comparison among different algorithms for UAV 2

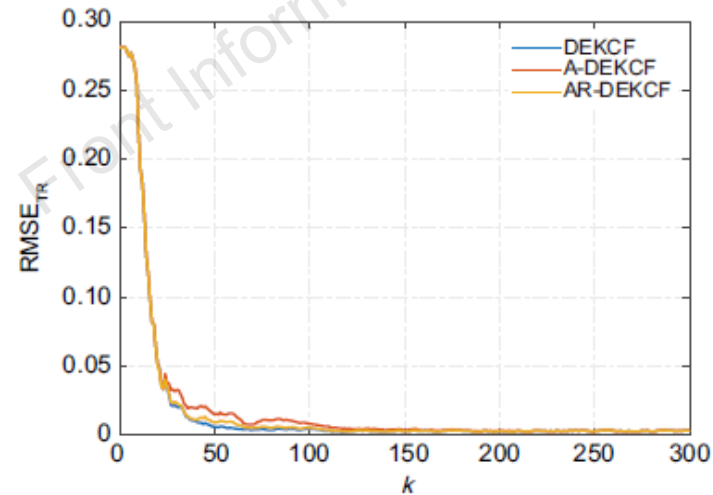


Fig. 9 $RMSE_{TR}$ comparison among different algorithms for UAV 2

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.



Yuru HU received her MS degree in mathematics from the University of Shanghai for Science and Technology (USST), Shanghai, in 2024. Her research interests include distributed Kalman filtering and information fusion.



Wangyan LI received his BS degree from Yangzhou University in 2010 and his PhD degree from USST in 2017. He is currently an associate professor in the Department of Mathematics at USST. Previously, he was a postdoctoral fellow in the School of Chemical Engineering at the University of New South Wales. His research interests include dissipativity, fault detection and diagnosis, and distributed filtering.



Lifeng WU received his BS degree in mathematics from the Southwest Jiaotong University, Chengdu, China, in 2021. He is currently working towards the MS degree in mathematics with USST, Shanghai. His current research interests include visual-inertial SLAM, sensor fusion, and autonomous navigation.



Zhensheng YU received his PhD degree from Dalian University of Technology in 2004. He is currently a professor in the Department of Mathematics at USST. His research interests include optimization theory and methods, statistical optimization, and machine learning.