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Multi-UAV cooperative target tracking with bounded noise for connectivity preservation

Key words: Multi-UAV cooperative target tracking; Network connectivity; Kalman consensus filter; Bounded noise; Connectivity preservation

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Motivation

1. In the multi-UAV cooperative target tracking problem, each UAV in the network fuses others' information through multi-hop communication, so it is crucial to preserve network connectivity.
2. In multi-UAV cooperative target tracking, appropriate motion of UAVs can increase the network's information about the target; in turn, the information increase would also affect the UAV motion control.
3. Coupled estimation and motion control framework and algorithms for mobile sensor network flocking were studied by Olfati-Saber, but the coupled system was analyzed without taking the input noise into account and the network connectivity was not considered explicitly.

Main idea

1. The distributed Kalman consensus filter is presented, and the boundedness of the estimation errors is analyzed.

2. With the estimation of the target state, we design a potential function based distributed UAV controller that drives the network to track a mobile target and also ensures communication link maintenance and collision avoidance.

3. The stability and convergence of the coupled estimation and motion control system are analyzed.

Method

1. The distributed Kalman consensus filter

$$\dot{\hat{\boldsymbol{x}}}_i = \boldsymbol{A}\hat{\boldsymbol{x}}_i + \boldsymbol{K}_i(\boldsymbol{z}_i - \boldsymbol{H}_i\hat{\boldsymbol{x}}_i) + \gamma \boldsymbol{P}_i \sum_{j \in N_i} (\hat{\boldsymbol{x}}_j - \hat{\boldsymbol{x}}_i),$$

$$\boldsymbol{K}_i = \boldsymbol{P}_i \boldsymbol{H}_i^{\mathrm{T}} \boldsymbol{R}_i^{-1}, \gamma > 0,$$

$$\dot{\boldsymbol{P}}_i = \boldsymbol{A}\boldsymbol{P}_i + \boldsymbol{P}_i\boldsymbol{A}^{\mathrm{T}} + \boldsymbol{B}\boldsymbol{Q}\boldsymbol{B}^{\mathrm{T}} - \boldsymbol{P}_i\boldsymbol{H}_i^{\mathrm{T}}\boldsymbol{R}_i^{-1}\boldsymbol{H}_i\boldsymbol{P}_i$$

2. Motion control design of unmanned aerial vehicles

$$\phi_a(z) \begin{cases} =0, & z \in [0, \|r\|_\sigma] \cup [\|r_a\|_\sigma, +\infty), \\ <0, & z \in (\|r\|_\sigma, \|r_a\|_\sigma), \end{cases}$$

$$\phi_c(z) \begin{cases} =0, & z \in [0, \|r_c\|_\sigma] \cup [\|R\|_\sigma, +\infty), \\ >0, & z \in (\|r_c\|_\sigma, \|R\|_\sigma). \end{cases}$$

$$\begin{aligned} \boldsymbol{u}_i = & \sum_{j \in N_i} \phi_a(\|\boldsymbol{q}_j - \boldsymbol{q}_i\|_\sigma)\sigma_\varepsilon(\boldsymbol{q}_j - \boldsymbol{q}_i) \\ & + \sum_{j \in N_i \cap N_i^0} \phi_c(\|\boldsymbol{q}_j - \boldsymbol{q}_i\|_\sigma)\sigma_\varepsilon(\boldsymbol{q}_j - \boldsymbol{q}_i) \\ & + b_i \operatorname{sgn}\left(\sum_{j \in N_i \cap N_i^0} \boldsymbol{p}_j - \boldsymbol{p}_i\right) + \hat{\boldsymbol{f}}_i^{\xi} \end{aligned}$$

Method (Cont'd)

3. Analysis of the coupled system

$$\Sigma_{\mathrm{s}}:\begin{cases}\dot{\boldsymbol{x}}_i=\boldsymbol{v}_i,\\ \dot{\boldsymbol{v}}_i=-\nabla_{\boldsymbol{x}_i}V(\boldsymbol{x},\boldsymbol{x}_0)\\ \qquad\quad +b_i\mathrm{sgn}\left(\sum\limits_{j\in N_i\cap N_i^0}(\boldsymbol{v}_j-\boldsymbol{v}_i)\right)\\ \qquad\quad -c_1\boldsymbol{x}_i-c_2\boldsymbol{v}_i+\boldsymbol{\delta}_i-\bar{\boldsymbol{\delta}},\end{cases}$$

$$\Sigma_{\mathrm{t}}:\begin{cases}\dot{\boldsymbol{q}}_{\mathrm{c}}=\boldsymbol{p}_{\mathrm{c}},\\ \dot{\boldsymbol{p}}_{\mathrm{c}}=-c_1(\boldsymbol{q}_{\mathrm{c}}-\boldsymbol{q}_{\xi})-c_2(\boldsymbol{p}_{\mathrm{c}}-\boldsymbol{p}_{\xi})+\bar{\boldsymbol{\delta}},\end{cases}$$

$$\Sigma_{\mathrm{e}}:\dot{\eta}_i=\boldsymbol{F}_i\eta_i+\gamma\boldsymbol{P}_i\sum_{j\in N_i}(\eta_j-\eta_i)+\boldsymbol{\Gamma}_i\boldsymbol{\omega}_i$$

Major results

Example 1

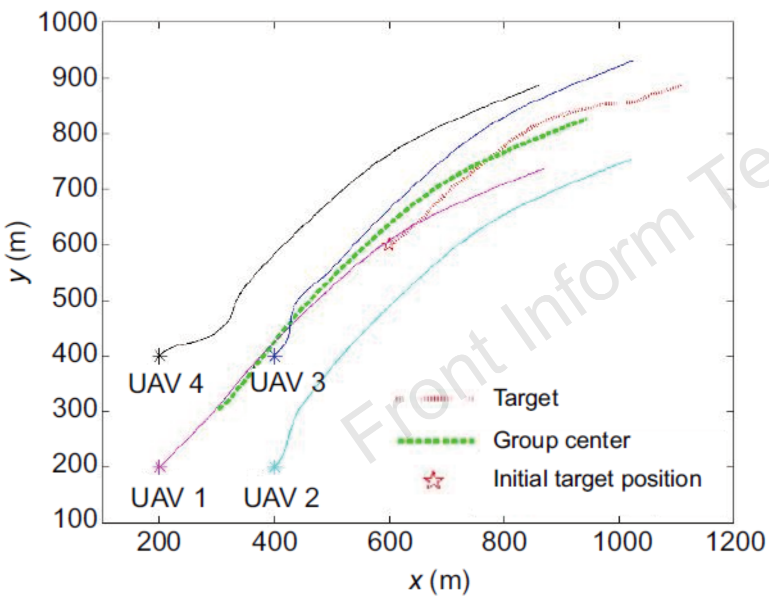

Fig. 1 Trajectories of the target and UAVs in Example 1

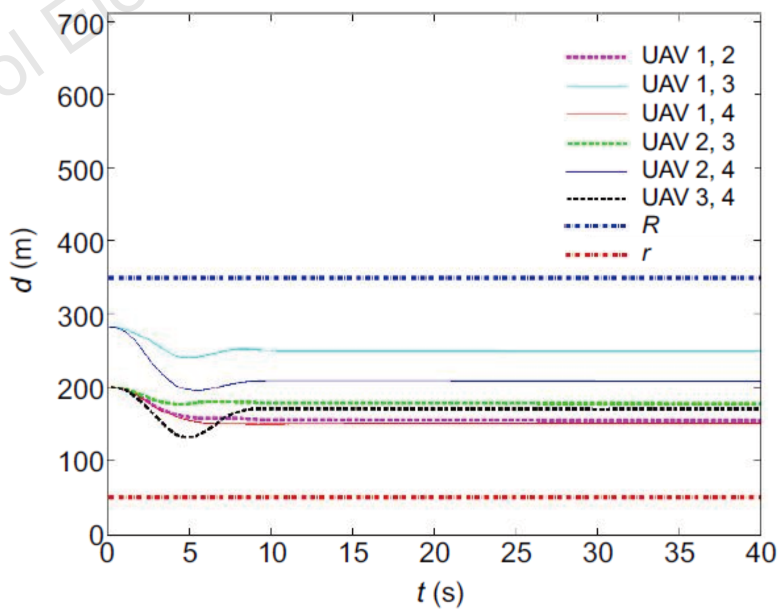

Fig. 2 Inter-UAV distances in Example 1

Major results (Cont'd)

Example 1

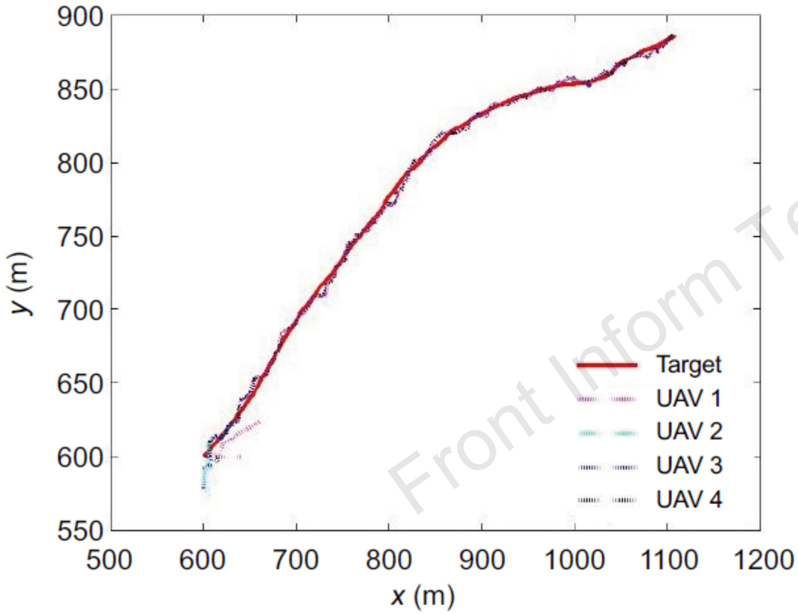

Fig. 3 Target trajectory and estimated trajectories of the four UAVs in Example 1

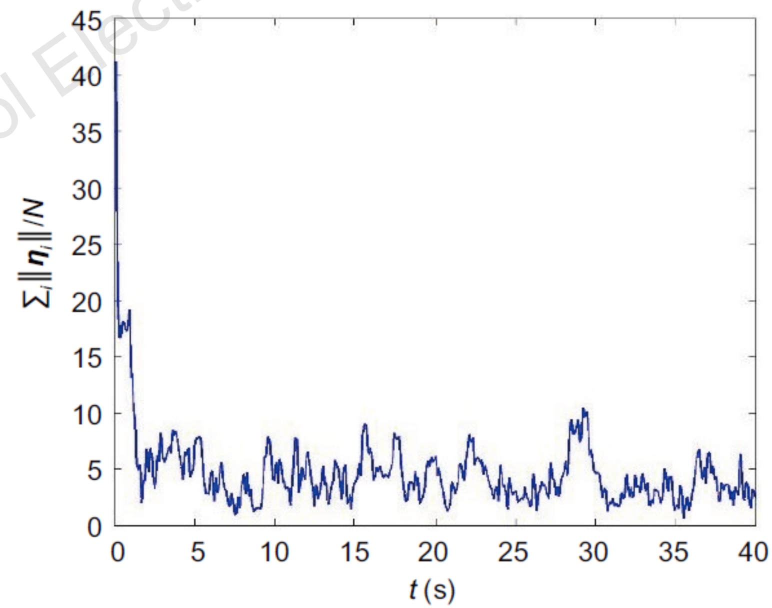

Fig. 4 Mean of norm of the estimation errors in Example 1

Major results (Cont'd)

Example 2

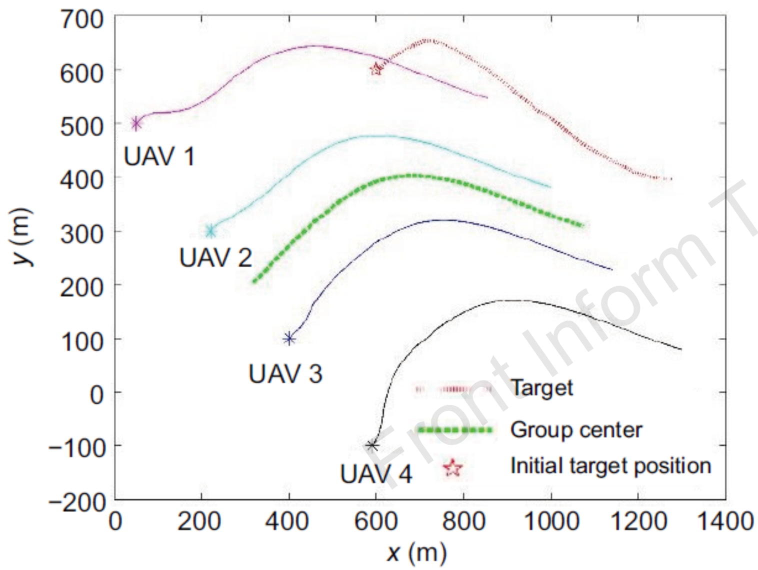

Fig. 5 Trajectories of the target and UAVs in Example 2

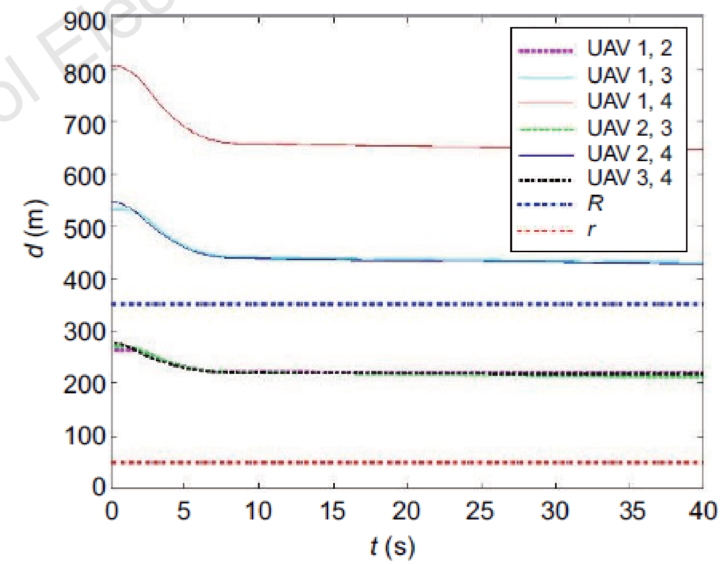

Fig. 6 Inter-UAV distances in Example 2. Dashed lines represent that there exist initial communication links between UAVs, while solid lines represent that there do not exist initial communication links between UAVs

Major results (Cont'd)

Example 2

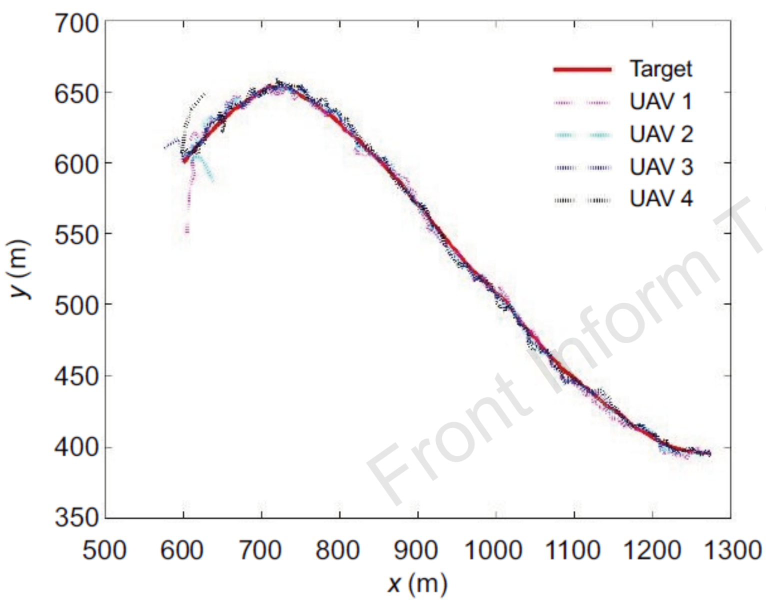

Fig. 7 Target trajectory and estimated trajectories of the four UAVs in Example 2

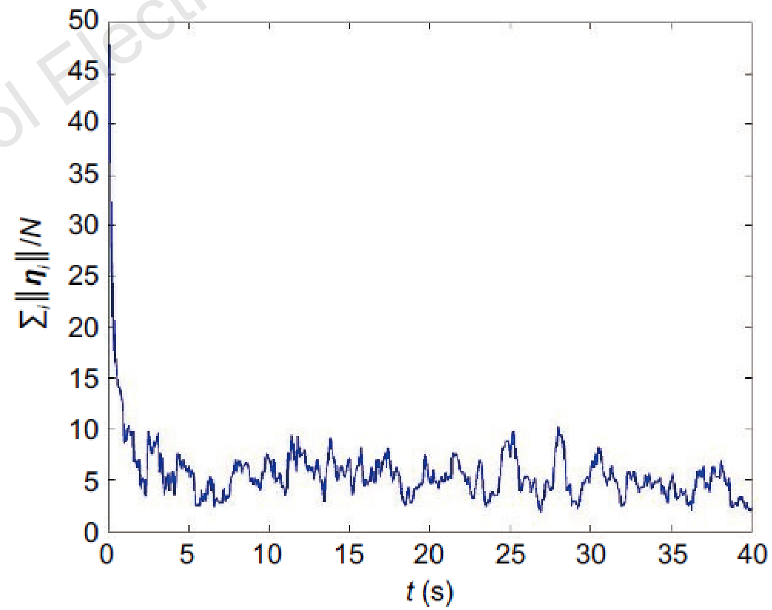

Fig. 8 Mean of norm of the estimation errors in Example 2

Conclusions

1. The distributed potential-based UAV motion controller for target tracking, connectivity maintenance, and collision avoidance has been designed.

2. The analysis of the multi-UAV target tracking system which integrates estimation and motion control showed that the network connectivity and collision avoidance can be guaranteed, and that the estimation errors would converge.

3. For a mobile target with bounded noise as acceleration input, the group of UAVs would track the target stably.

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