Distributed Estimation for Coordinated Target Tracking in a Cluttered Environment

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Motivation

- Scope is multi-robot systems coupled by communication
- Specific application is target tracking in cluttered environment
- A multi-agent approach is advantageous
  - Agents can spread out around the target
  - Inter-vehicle communication improves target state estimates
- But, a number of fundamental questions arise:
  - What should each vehicle “say”? 
  - How frequently should communication events occur? 
  - How much does communication really help?

Objective

The objective of this work is to explore these and other questions...
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Problem Overview: Coordinated Target Tracking

Consider a target tracking scenario
- One target vehicle
- $N$ non-holonomic pursuit vehicles

Task: estimate the target state

Main challenges stem from
- Communication limitations
- Sensor occlusions and failures

Three main components:
- Communication
- Estimation
- Control
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## Related work

- **Campbell and Whitacre\(^1\)**
  - \(N\)-UAVs tracked a single target
  - **Communication**
    - Transmitted information state, after *every* measurement
    - Necessarily all-to-all communication
  - **Estimation**
    - Distributed square root sigma-point information filter
    - Centralized estimate was recovered by each agent
  - **Control**
    - For \(N = 2\), maintain 90° clock angle

- **Eickstedt and Benjamin**
- **Olfati-Saber**

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Related work

- Campbell and Whitacre
- Eickstedt and Benjamin\(^2\)
  - Two pursuit vehicles tracked a target
  - Vehicles were coupled to a central database
  - **Communication** was every measurement
  - **Estimation** was done with a centralized EKF
  - **Control** was behavior based, but also centralized
- Olfati-Saber

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Related work

► Campbell and Whitacre
► Eickstedt and Benjamin
► Olfati-Saber\(^3\)

- \(N\) nodes estimated the state of a target
- Objective was to *agree*, not get best estimate
- **Communication**
  - Communicated only with neighbors
  - Information was transmitted after *every* measurement
  - Linear target dynamics, undirected topology, no delay
- **Estimation**
  - Distributed Kalman Filtering
- **Control** was not considered

Novel aspects of this work

► The work in this paper explores a novel area

► **Communication**
  - Communication occurs *less frequently* than measurements
  - Sequential one-to-all directed broadcast topology
  - Information arrives delayed

► **Estimation**
  - EKF runs on each agent to estimate the target state

► **Control**
  - Behavior based (computed locally)
  - Uses local target state estimate

► Compare several communication protocols and communication timings in simulation
Outline

1. Introduction
2. System Description
3. Estimation
4. Control
5. Results
6. Summary and Future Work
Vehicle Dynamics

**System Description**

- Vehicles are air, ground, or underwater vehicles
- Steering control inputs
- Pursuit vehicles are constant-speed unicycles
- Target is variable-speed unicycle
- $x_k = [x, y, \theta, v]$ of the target
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\[
\begin{align*}
\dot{x}^i &= v \cos(\theta^i), \quad i = 1 \ldots N \\
\dot{y}^i &= v \sin(\theta^i), \\
\dot{\theta}^i &= u_{\text{steer}}^i, \quad u_{\text{steer}}^i \in \bar{u}_{\text{steer}} [-1, 1] \\
\dot{v} &= 0
\end{align*}
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\]
Each pursuit vehicle makes a measurement every $T_s$ sec

$$\tilde{y}_k^i = H x_k + v_k^i, \quad v_k^i \sim N(0, R^i)$$

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

- Sensors fail stochastically
- Clutter impedes vehicles and occludes sensors
Communication via a sequence of one-to-all broadcasts

- Broadcasts occur every $T_b = n_b T_s$ seconds, $n_b \in \mathbb{N}$
- Three communication protocols are considered:
  - No communication (local estimates only)
  - Transmit one, two, or three recent measurements
  - Transmit the local target state estimate
- Communications arrive delayed by $T_s$ seconds
Communication Network

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2. System Description
3. Estimation
   - Shared Measurements
   - Shared Estimates
4. Control
5. Results
6. Summary and Future Work
Coordinated Target State Estimation

- An Extended Kalman Filter (EKF) runs on each vehicle
- Target state estimate propagation
  - Substitutes noise for actual control input
  - Uses linearization of target estimate error dynamics

\[
F(\hat{x}^i_k) = \begin{bmatrix}
0 & 0 & -\hat{v}^i_k \sin \hat{\theta}^i_k & \cos \hat{\theta}^i_k \\
0 & 0 & \hat{v}^i_k \cos \hat{\theta}^i_k & \sin \hat{\theta}^i_k \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

- The filter is backed up to fuse received (delayed) information
When sharing measurements, broadcasting vehicle transmits:

1. One, two, or three most recent measurements
2. The corresponding time indices
3. The sensor error covariance matrix (if necessary)

Easy to adapt EKF because errors are *uncorrelated*

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When sharing estimates, broadcasting vehicle transmits:

1. Target state estimate (mean and error covariance)
2. Corresponding time index

**Problem:** Received estimate is *correlated* with local estimate

Maximum-likelihood (ML) fusion requires knowledge of\(^1\):

- Linearized target error dynamics ← mean target state estimate
- Kalman gain ← estimate and sensor error covariance matrices
- ... at every measurement step

Theory supports *pairwise* fusion only

**OEF is not practical**, used as a benchmark

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Coordinated Target Pursuit

- Control is based on the local target state estimate
- Assume pursuers know other pursuers’ state
- **Coordinated** control is composed of three behaviors:

\[ u^i_{steer} = (1 - w)(u^i_{ct} + u^i_{space}) + u^i_{oa} \]

1. Centroid to Target Control \((u_{ct})\)
2. Inter-Vehicle Spacing \((u_{space})\)
3. Obstacle Avoidance \((u_{oa})\)

- **Uncoordinated** control is composed as:

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Coordinated Target Pursuit

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  1. **Centroid to Target Control** \(u_{ct}^i\)
     - Brings the group centroid to the target
     - \(u_{ct}^i = k_{ct} \sin(\theta_{ct} - \theta^i)\)

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1. **Centroid to Target Control** \((u_{ct})\)
2. **Inter-Vehicle Spacing** \((u_{\text{space}})\)
   - Keeps vehicles dispersed
   - \( u_{\text{space}}^i = \sum_{j \neq i}^N \left(1 - \left(\frac{r_{s0}}{d_{ij}}\right)^2\right) \sin(\theta_{ij}^i - \theta^i) \)
3. **Obstacle Avoidance** \((u_{oa})\)

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1. **Centroid to Target Control** \((u_{ct})\)
2. **Inter-Vehicle Spacing** \((u_{space})\)
3. **Obstacle Avoidance** \((u_{oa})\)
   - Prevent vehicles from colliding with obstacles
   - \( u_{oa}^i = \begin{cases} 
   0 & \text{if } d_{oj}^i > r_{oT}^j \\
   \sum_{j \in N_o} \cos(\Delta \theta_{oj}^i) \text{sgn}(\Delta \theta_{oj}^i) f_d(d_{oj}^i) & \text{otherwise}
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5. Results
   - Isolated Estimator Experiments
   - Pursuit Vehicle Coordination
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Overview of Experiments

- **Isolated estimator experiments:**
  - Designed to compare the various communication protocols
  - Sensor reliability curve is not used
  - No sensor occlusions or obstacles

- **Pursuit vehicle coordination:**
  - Designed to test a more realistic scenario
  - Sensor reliability curve *is* used
  - Obstacles are present

- **Default simulation parameters:**
  - Broadcast sequence is sequential
  - $N = 3$, $v^i = 1$, $v^{target} = 0.5$, $T_s = 1$, $T_b = 4$

- **Performance metrics**
  - Mean log likelihood (Across all agents and time)
  - Mean integrated position error
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Isolated Estimator Experiments

Results: Sensor Reliability

- Transmitting more measurements yields better estimates
- Transmitting three measurements ≈ OEF
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- Transmitting more measurements yields better estimates
- Transmitting three measurements $\approx$ OEF
Results: Communication Period

- Communication period is varied
- Sensor measurement period $T_s = 1$
- Fixed sensor reliability of 70%
- **Unexpected**: Measurement transmission degrades similarly to estimate transmission
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- Sensor measurement period $T_s = 1$
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Results: Coordination

Uncoordinated

Coordinated
Results: Coordination

- Coordinated vs. Uncoordinated
- Clutter density is varied
- Three-measurement communication protocol
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Summary and Future Work

▶ Summary

- Vehicles measure more frequently than they communicate
- Compared measurement and estimate transmissions
- Found communication helps significantly
- Transmitting recent measurements is quite good
- Coordinated control improves estimates

▶ Future work

- Explore estimation performance vs. $N$
- Select optimal broadcast sequences
- Improve upon estimate fusion
  - Extend beyond pairwise fusion
  - May require conservative approximations

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