Finite Set Distributed Multi-sensor Multi-object Tracking

SAND2019-2486C

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Motivation

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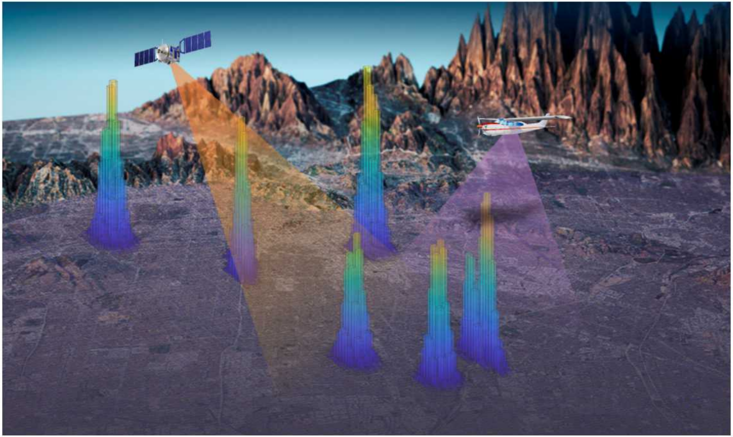
What issues prevent use of distributed multi-sensor LRFS tracking in large-scale, real-world systems?



Distributed Sensing Architecture

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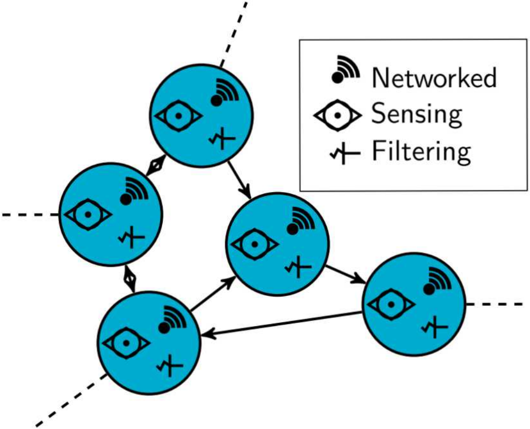
- Large number of sensors
- Large number of objects
- Fully decentralized
- Dynamic network graph
- Nodes unaware of graph structure



Example of a fully distributed network topology.

Labeled Random Finite Set Filtering

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- The labeled random finite set (LRFS)
  - Set valued random variable (i.e. random cardinality and random state values)
  - Each element of the set consists of an identifying label and a kinematic state
  - Labels facilitate recovery of object trajectories
- δ-generalized labeled multi-Bernoulli (δ-GLMB) density function

$$\boldsymbol{\pi}(\mathbf{X}) = \Delta(\mathbf{X}) \sum_{(I,\xi)\in\mathcal{F}(\mathbb{L})\times\Xi} \omega^{(I,\xi)}\delta_I(\mathcal{L}(\mathbf{X}))\left[p^{(\xi)}\right]^{\mathbf{X}}$$

- Truncation of the filtering density required to maintain feasibility
- **Finite set statistics (FISST) framework enables principled fusion of full multi-object densities**

Approaches to Distributed LRFS Filtering

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- Optimal Bayesian fusion

$$\boldsymbol{\pi}\left(\mathbf{X}|\bigcup_{s=1}^{\mathcal{S}} Z^{(s)}\right) \propto \frac{\prod_{s=1}^{\mathcal{S}} \boldsymbol{\pi}^{(s)}(\mathbf{X}|Z^{(s)})}{\boldsymbol{\pi}\left(\mathbf{X}|\bigcap_{s=1}^{\mathcal{S}} Z^{(s)}\right)}$$

- Arithmetic mean density (AMD) fusion

$$\boldsymbol{\pi}(\mathbf{X}) = \sum_{s=1}^{\mathcal{S}} w^{(s)} \boldsymbol{\pi}^{(s)}(\mathbf{X})$$

- Geometric mean density (GMD) fusion

$$\boldsymbol{\pi}(\mathbf{X}) \propto \prod_{s=1}^{\mathcal{S}} \left(\boldsymbol{\pi}^{(s)}(\mathbf{X})\right)^{w^{(s)}}$$

- Measurement information fusion

Challenge: Label Consistency

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- What happens when fusing LRFS densities that have different labels for the same target?
  - Generally: significant cardinality errors
  - GMD fusion of GLMB family densities: hypotheses containing inconsistent labels are dropped

$$\mathbb{L}_a = \{\ell_a\}, \mathbb{L}_b = \{\ell_b\}, \Xi_a = \Xi_b = \{0\}$$

$$\omega_a^{(\ell_a,0)} = 1, \omega_b^{(\ell_b,0)} = 1$$

$$\boldsymbol{\pi}_a(\mathbf{X}) = \Delta(\mathbf{X})\omega_a^{(\{\ell_a\},0)}\delta_{\{\ell_a\}}(\mathcal{L}(\mathbf{X}))\left[p_a^{(0)}\right]^{\mathbf{X}}$$

$$\boldsymbol{\pi}_b(\mathbf{X}) = \Delta(\mathbf{X})\omega_b^{(\{\ell_b\},0)}\delta_{\{\ell_b\}}(\mathcal{L}(\mathbf{X}))\left[p_b^{(0)}\right]^{\mathbf{X}}$$

$$\boldsymbol{\pi}_a(\mathbf{X})\boldsymbol{\pi}_b(\mathbf{X}) = [\ldots]\delta_{\{\ell_a\}}(\mathcal{L}(\mathbf{X}))\delta_{\{\ell_b\}}(\mathcal{L}(\mathbf{X})) = 0 \text{ if } \ell_a \neq \ell_b$$

Sources of Label Inconsistency

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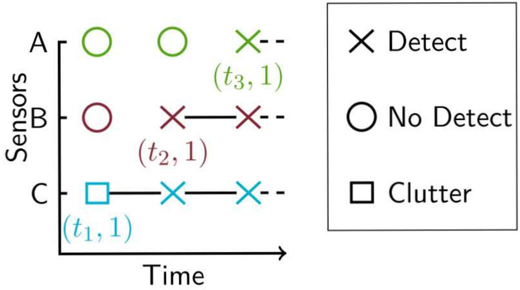
- Inconsistent initial priors
- Measurement variation $\rightarrow$ different label time stamps
  - Missed first frame(s) detection
  - "Lucky" clutter
  - Erroneous death (not in figure)



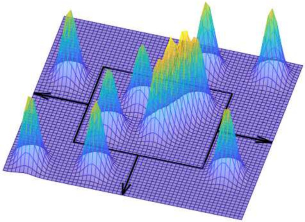
- Birth model inconsistency $\rightarrow$ different labels for the same object

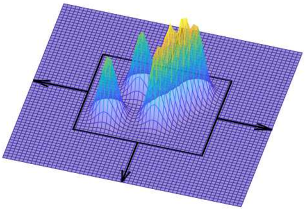
Birth Model Consistency

- Target appearance is handled through a "birth model" LRFS

$$\mathbf{f}_B(\mathbf{X}) = \Delta(\mathbf{X}) w_B(\mathcal{L}(\mathbf{X})) \left[p_B\right]^{\mathbf{X}} ,$$

- Birth models must be identical across all nodes for GMD/AMD fusion
  - Necessary to ensure consistency of labels of newborn targets
  - Requirement causes limited scalability and system flexibility





Birth Model Consistency

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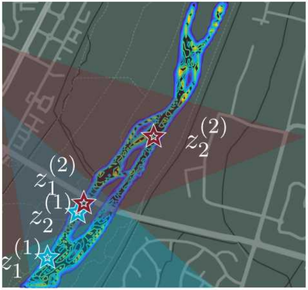
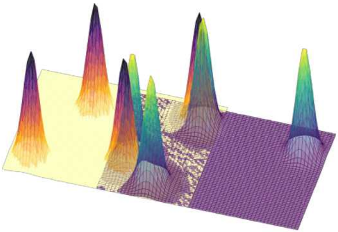
- No measurement driven birth
- Restricts systems that may participate in a network
- Infeasible for large numbers of measurements or targets
- May force modeling birth in regions that aren't of interest

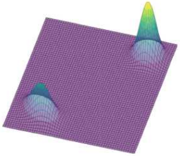


$$N_{\text{possible}} = 1 + \sum_{M=\max(|\mathbb{B}|-|Z|,0)}^{|\mathbb{B}|-1} \frac{|\mathbb{B}|!|Z|!}{M!(|\mathbb{B}|-M)!(|Z|-|\mathbb{B}|+M)!}$$

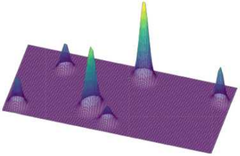
Challenge: Support Diversity

- Densities naturally have different supports in distributed tracking
  - Sensors observe different areas
  - Often model birth only in FoV/FoR
  - Even with global birth model, unsupported information is often truncated out
- AMD/GMD fusion cause loss of information outside shared support





GMD fusion



AMD fusion

Challenge: Bandwidth Constraints

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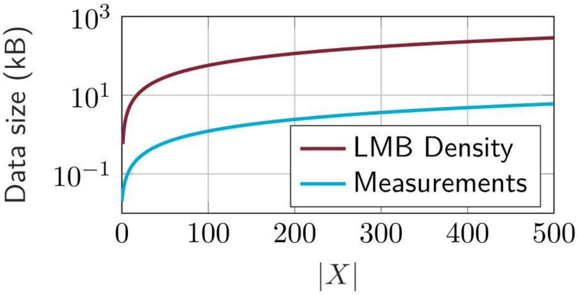
- Measurement information for one frame is often more compact than a full posterior
  - Is measurement fusion more efficient than posterior fusion?

$$N^{(\mathsf{LMB})} = 4|\mathbb{L}|\left(3 + n_{\mathsf{GM}}\left(1 + n_x + \frac{n_x^2 + n_x}{2}\right)\right)$$

$$N^{(\mathsf{meas})} = 4(2 + n_z + n_z|Z|)$$



Fusion Type Trade-off

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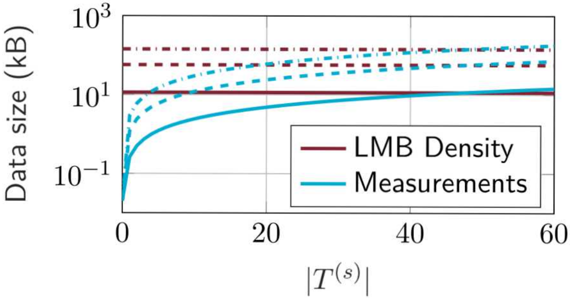
- How long does it take for accumulated measurement data to exceed posterior size?
  - **Information propagates through the network by successive fusion**

$$N^{(\text{meas})} = 4 \sum_{s \in \mathcal{S}} \left(2 + n_z + \sum_{k \in T^{(s)}} \left(1 + n_z |Z_k^{(s)}| \right) \right)$$



Challenge: Track Management

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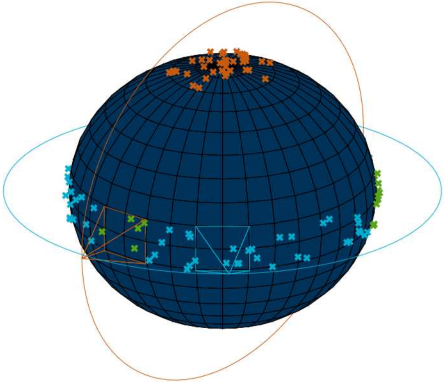
- Competing objectives
    1. Limited number of manageable tracks
    2. State knowledge needed for decision making
        - Discard tracks that aren't deemed important
- How to make this decision?
- Discarding tracks exacerbates support diversity



Challenge: Sensor Trust Bottlenecking

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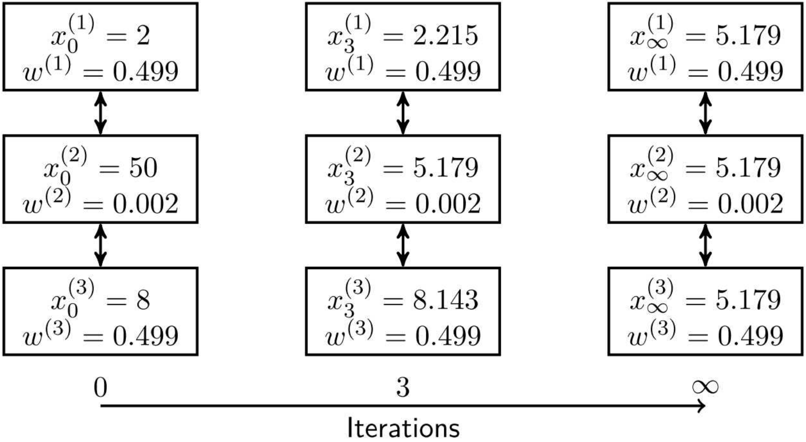
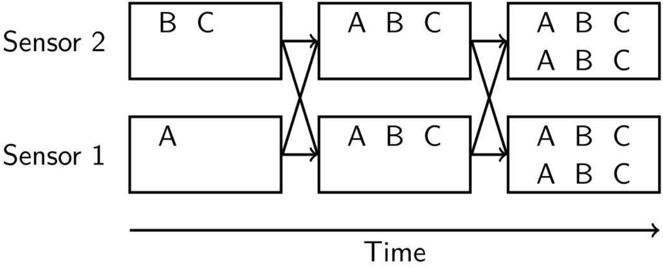


$$x_i^{(s)} = \sum_{\varsigma \in \mathcal{N}^{(s)}} w^{(\varsigma)} x_{i-1}^{(\varsigma)}$$

Challenge: Double-Counting



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Acknowledgment

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.