Distributed intelligence in mobile multi-agent networks

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Who am I

- Usman A. Khan
  - Assistant Professor, Tufts

- Postdoc
  - U-Penn

- Education
  - PhD, Carnegie Mellon
  - MS, UW-Madison
  - BS, Pakistan
My Research Lab: Projects and demos

Research Team

PhD Students

Current
- Fakhita Saadatniai, Sep. 2014 to date
- Sam Salavi, Jan. 2013 to date
- Chengxiang Xi, Sep. 2012 to date

Alumni
- Mohammadreza Doostmohammadi, graduated May 2015

MS Students

Current
- Christopher Sacco, Sep. 2015 to date
- Dong Park, Sep. 2015 to date

Alumni
- Alexander Henry, graduated Aug. 2015, Adaptive methods for robotic path planning
- Michael Tran, graduated Aug. 2015, Distributed target tracking in a sensor network
- Obeyedee Das, graduated Aug. 2015, Consensus with non-participating agents
- Luko Grymek, graduated Aug. 2013, Coverage and surveillance with autonomous agents
- Gerald Solimini, graduated May 2012, Distributed path planning algorithms for UAVs
- Syed S. Akbar, graduated Dec. 2011, Object recognition on AR-Drone (UAV) platform
- Qing Wu (Applied Mathematics), Summer 2012, Stochastic modeling of wind turbines

Undergraduates

Current
- Ryan Kortziewy, ECE Freshman, Fall 2015 onwards
- Anuththari Ramanag, ECE Sophomore, Fall 2015 onwards
- Syed M. Bukhari, ECE Junior, Summer 2015 onwards
- Terrance Tufenk, ECE Junior, Summer 2016 onwards

Alumni
- Dong Park, ECE Junior, Apr. 2014 to May 2015
- Ogbenogho Ahi, ECE Freshman, Summer 2014
- Pretik Chaitrath, ECE Junior, visiting student from SVNIT, Gujarat, India, Summer 2014
- John Kelly, CS Senior, Jan. 2013 to May 2014
- Cornell Wilson, ECE Junior, May 2013 to Sep. 2013, Aerial robot navigation
- Josh Ploip, ECE Sophomore, Jan. 2013 to Aug. 2013, Robotic networks

- Senior Design Project, 2014-2015
- Senior Design Project, 2012-2013
  - M. Tran, R. Singh, A. Simpson-Wolf, and S. Stannekicz: Low-power aerial surveillance for engineering infrastructures
  - Best project in ECE
- Senior Design Projects, 2011-2012
  - 3rd Place Winners, IBM/IEEE Smarter Planet Challenge: Student Projects Changing the World
  - Robust hardware and software redesign for AR-Drone platform

- ME undergrads (graduated), Spring 2012: N. Stone, C. N. Berger, J. Arena, W. Langford
- Kevin Morrissey (graduated), Distributed control of wind-farms, Spring 2012
- Hassan Oukacha, GPS-based autonomous navigation, Summer 2012
- Michael Tran, Decentralized target tracking, May 2011 to May 2013
- June Weik, Operational attributes and obstacle avoidance, Summer 2011 to August 2012
- Tyler Heck (Junior), Feasibility of object recognition algorithm, Summer 2011
<table>
<thead>
<tr>
<th>My Research Lab: Projects and demos</th>
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<tbody>
<tr>
<td><strong>Inspecting leaks in NASA’s lunar habitat</strong></td>
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<tr>
<td><img src="image1" alt="Image of a lunar habitat with people standing inside" /></td>
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<tr>
<td><strong>Inference in Social Networks</strong></td>
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<tr>
<td><img src="image3" alt="Graph showing social network" /></td>
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My Research Lab: Theory

Reza (2011-15):
Graph-theoretic estimation

Xi (2012-16):
Optimization over directed graphs

Sam (2013-17):
Fusion in non-deterministic graphs

Fakhteh (2014-):
Distributed estimation cont...d

Best paper, Journal cover

2 Best papers
My Research: In depth

- Distributed Intelligence in **multi-agent systems**
  - Estimation, optimization, and control over **graphs (networks)**

- **Mobile** → **Dynamic**

- **Heterogeneous** → **Directed**

- **Autonomous** → **Non-deterministic**

**Applications:**
- Cyber-physical systems, IoTs, Big Data
- Aerial SHM, Power grid, Personal exposome
- Indoor navigation (this talk)
How do we think about intelligence?
Intelligence: Conventional notion

- Individual
- Droids
- Cyborg
- Cyborg with skin grafts
  - Terminator, T-800
- Todays robots/UAVs
Intelligence: Conventional notion

- **System**
- **SkyNet Central Core**
  - Guarded by T1000000
- **Cylon BaseStar**
  - BSG
- **Other examples**
  - SCADA
  - Fusion centers in WSNs
  - Dispatch centers
What can go wrong?

- Single point of failure
- Infiltration
- Cyber/terrorist threats
- Blackouts
How can we think about intelligence?

- Individual level
- T1000
- (something I am interested in)
How can we think about intelligence?

- **System level**
  - Driving directions in *Finding Nemo*
    - *(I wonder if Finding Dori is particularly harder than Finding Nemo)*

- *(Majority of) this talk*
  - GPS-free navigation in mobile and autonomous systems
An Example Project: Individual Intelligence

- Indoor GPS-free Aerial Navigation

https://www.youtube.com/watch?v=0AuF_Xj_Xms

- General Problem with multiple robots
Distributed sensor localization
Distributed sensor localization

- Localize $M$ sensors with unknown locations in $\mathbb{R}^m$

- Sensors can only communicate in a neighborhood

- Only local distances in the neighborhood are available

- What is the minimal number of known locations required?
  - Called anchors, QR codes

- Where do we place them?

$m = 2$, plane
Sensor localization

- Traditional (non-linear) multilateration scheme
  - (only distances to known locations are given)
  - Nonlinear
  - Coupled in coordinates

- Minimal anchors: $m+1$

- Placement: arbitrary
Distributed sensor localization

- Can we iteratively build on the nonlinear approach?
  - each sensor iteratively updates its location
  - several sensors may not be able to talk to any anchor
  - no sensor may be able to talk to all of the $m+1$ anchors

- No, the iterations do not converge in general

$m = 2$, plane
Distributed sensor localization

- The non-linear problem has a linear iterative solution
- Convexity arguments
  - Sensors lie in the convex hull of at least $m+1$ anchors
  - This condition can be relaxed
- Barycentric coordinates
  - August Ferdinand Möbius (1790 – 1868)
- Cayley-Menger determinants
  - Joseph-Louis Lagrange (1736 – 1813)
  - Arthur Cayley (1821 – 1895)
  - Karl Menger (1902 – 1985)
Barycentric coordinates: Main idea

- Linear-convex combination on a line (m=1)
- Need m+1 = 2 anchors
- Unknown location is within the convex hull of knowns
- Barycentric coordinates: Sum to 1 and are positive
- The idea is extendible to arbitrary dimensions
- What should replace distances?

\[
x = \frac{5}{5+3} \cdot 1 + \frac{3}{5+3} \cdot 9
\]
Barycentric coordinates: Definition

- Linear representation of coordinates

\[ a_{c1} = \frac{A_{c23}}{A_{123}} \]

\[ \mathbf{c} = a_{c1} \mathbf{c_1} + a_{c2} \mathbf{c_2} + a_{c3} \mathbf{c_3} \]

- Decoupled in coordinates
  - Unique and between 0—1 (if within the convex hull)
  - Sum to 1

- How do we compute the areas or generalized volumes in \( \mathbb{R}^m \)?
Cayley-Menger determinant

- Computes the generalized volumes of an m-simplex
  - Computation from local distances alone (six distances)

\[
A_{\Theta t}^2 = \frac{1}{s_{m+1}} \begin{vmatrix}
0 & 1^T_{m+1} \\
1_{m+1} & Y \\
\end{vmatrix}
\]

\[
s_m = \frac{2^m(m!)^2}{(-1)^{m+1}}
\]

- Y is a 3x3 matrix containing pairwise squared distances
Distributed Sensor Localization

- **Recipe:**
  - Each sensor finds three neighbors such that it lies in their convex hull
- **How?**
  - Finds BC from CM determinants and local distances
  - Update its coordinates using the linear equation and coordinates from (appropriate) neighbors
**Triangulation**

- Test to find a triangulation set
- Convex hull inclusion test based on the following observation

\[ A_{l12} + A_{l13} + A_{l23} = A_{123} \]
\[ A_{l12} + A_{l13} + A_{l23} > A_{123} \]

- The test becomes
- Node \( l \) is inside if the sum = total
- Node \( l \) is outside if the sum > total
Distributed sensor localization

- Let $u_k$ and $x_l$ be the coordinates of $k$th anchor and $l$th sensor, respectively.

- We have the following update:

  Anchors: $u_k(t+1) = u_k(t) = u_k^*$,

  Sensors: $x_l(t+1) = \sum_{j \in \Theta_l} v_{lj} x_j(t)$,
Convergence Analysis

- The update converges to exact sensor locations regardless of the initial conditions.
- Under strongly-connected sensor to sensor graph and when each anchor can communicate to at least one different sensor.
- The proof sketch is as follows:
  - (each row sums to 1 and has +ve elements)

\[
\begin{align*}
    u^{k+1} & = \begin{bmatrix} I_{m+1} & 0 \end{bmatrix} \begin{bmatrix} B & P \end{bmatrix} \begin{bmatrix} x^{k+1} \\ x^k \end{bmatrix}
\end{align*}
\]
Convergence Analysis

- Comment on Absorbing Markov chains
- The iteration matrix is a stochastic matrix

\[(m+1) \times (m+1) \text{ identity matrix, the anchors do not update}\]

\[
\begin{bmatrix}
I_{m+1} & 0 \\
B & P
\end{bmatrix}
\]

- Each row sums to 1
- Has exactly \((m+1)\) non-zeros in [0, 1]

We can show that \(P\) is Hurwitz

\[
\rho(P) < 1,
\]
Convergence Analysis

\[
\begin{array}{c|c}
I_{m+1} & 0 \\
B & P
\end{array}
\quad
\begin{array}{c|c}
I_{m+1} & 0 \\
B & P
\end{array}
\quad
\begin{array}{c|c}
I_{m+1} & 0 \\
B & P
\end{array}
\quad\ldots
\]

\[
\Sigma P^k B = (I - P)^{-1} B
\]

\[
\begin{array}{c|c}
I_{m+1} & 0 \\
\Sigma P^k B & P^k
\end{array}
\quad
\begin{array}{c|c}
I_{m+1} & 0 \\
(I - P)^{-1} B & 0
\end{array}
\]
Finally, we can show that \((I-P)^{-1}Bu^0\) are the exact sensor locations.
Localization – Simulations

- $N=7$ node network in 2-d plane

- $M=4$ sensors, $K = m+1 = 3$ anchors
Simulations

Robustness under imperfections

\[ x(t+1) = \left[ 1 - \alpha(t) \right] x(t) + \alpha(t) \left\{ E_t \odot P (\bar{d}_t) \left[ x(t) + v(t) \right] + E_t \odot B (\bar{d}_t) \left[ u + v(t) \right] \right\} \]

- The above algorithm converges a.s. to the exact sensor locations under some persistence conditions on the weights
- Weights go to zero but not too fast
Distributed position tracking

- All of the nodes are mobile
- The agents are mobile and autonomous
- The graph is dynamic and non-deterministic

No update
All neighbors have unknown locations
At least one neighbor knows its location
Distributed position tracking

- New update:
- New Location = Old location + motion
  = Update with neighbors (if possible) + motion

- Recall the static update: Basically an LTI system

\[
\begin{align*}
x_{k+1} & = \begin{bmatrix} I_{m+1} & 0 \end{bmatrix} \begin{bmatrix} B & P \end{bmatrix} \begin{bmatrix} u_k \end{bmatrix} \\
u_{k+1} & \end{align*}
\]
Now we have an LTV system where the corresponding matrices are random.

\[
\begin{bmatrix}
  u_{k+1} \\
  x_{k+1}
\end{bmatrix}
= \begin{bmatrix}
  I \theta & 0 \\
  B_k & P_k
\end{bmatrix}
\begin{bmatrix}
  u_k \\
  x_k
\end{bmatrix}
+ \text{motion}
\]
Distributed position tracking

- New update:

\[ \begin{bmatrix} u_{k+1} \\ x_{k+1} \end{bmatrix} = \begin{bmatrix} \mathbf{I} & 0 \\ \mathbf{B}_k & \mathbf{P}_k \end{bmatrix} \begin{bmatrix} u_k \\ x_k \end{bmatrix} + \text{motion} \]

- Perfect locations follow: \( x_{k+1}^* = P_k x_k^* + B_k u_k + \text{motion} \)

- Error: \( e_{k+1} = P_k e_k \)

- where \( P_k \) is asymmetric, dynamic, non-deterministic
Distributed position tracking

- Matrix form: $e(k+1) = P(k) e(k)$
- $P_k$ randomly switches between no update, update with agents, update with anchors
- Consider the sequence: All agents update in, e.g., 6 steps
  - with the anchor, or
  - with an agent that has updated with the anchor

- The information cycle completes in 6 steps
- The next cycle starts at, e.g., time 13 (what happens between 6 and 13?)
- Slice: P12, P11, P10, P9, P8, P7, P6, P5, P4, P3, P2, P1, P0
Distributed position tracking

- Each slice contains
  - the system matrices such that one information cycle is completed, and
  - continues until the next cycle starts

- We have an alternate view: \( e(\infty) = ... P_3 P_2 P_1 P_0 e(0) = ... M_3 M_2 M_1 M_0 e(0) \)
- Instead of the product of system matrices, we study the product of slices
Distributed position tracking

- We have an alternate view: \( e(\infty) = \ldots M_3 M_2 M_1 M_0 e(0) \)

- Result 1: As the slice length goes to infinity, the two-norm goes to 1

- Result 2: If a slice completes in a finite time, then its two-norm is less than 1

- Result 3: If each slice completes in a fixed finite-time, then error goes to 0
  - (If an infinite subsequence completes in finite-time)

- Main Result 1: If the slice lengths grow at a certain rate, then the error goes to 0
- Main Result 2: The procedure works as long there is at least one anchor
Distributed position tracking: Experiments
SPARTN—Signal Processing and RoboTic Networks Lab at Tufts
https://www.youtube.com/watch?v=k6fOLbYj-5E
Structural Health Monitoring

- Dowling Hall footbridge
More Information

- My webpage: http://www.eecs.tufts.edu/~khan/

- My email: khan@ece.tufts.edu

- My Lab’s YouTube channel: https://www.youtube.com/user/SPARTNATtufts/videos/