Workshop Introduction
Distributed Control of Robotic Networks

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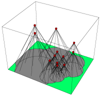
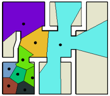
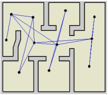
Cooperative multi-agent systems

What kind of systems?
Groups of agents with control, sensing, communication and computing

Each individual

- **senses** its immediate environment
- **communicates** with others
- **processes** information gathered
- **takes local action** in response

Self-organized behaviors in biological groups

Decision making in animals

Able to

- deploy over a given region
- assume specified pattern
- rendezvous at a common point
- jointly initiate motion/change direction in a synchronized way

Species achieve synchronized behavior

- with limited sensing/communication between individuals
- without apparently following group leader

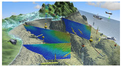
(Couzin et al, Nature 05; Conradt et al, Nature 03)

Engineered multi-agent systems

Embedded robotic systems and sensor networks for

- high-stress, rapid deployment — e.g., disaster recovery networks
- distributed environmental monitoring — e.g., portable chemical and biological sensor arrays detecting toxic pollutants
- autonomous sampling for biological applications — e.g., monitoring of species in risk, validation of climate and oceanographic models
- science imaging — e.g., multispacecraft distributed interferometers flying in formation to enable imaging at microarcsecond resolution


Sandia National Labs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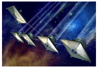

NASA Terrestrial Planet Finder

Research challenges

What useful engineering tasks can be performed with limited-sensing/communication agents?

Feedback	rather than open-loop computation for known/static setup
Information flow	who knows what, when, why, how, dynamically changing
Reliability/performance	robust, efficient, predictable behavior

How to coordinate individual agents into coherent whole?

Objective: *systematic methodologies to design and analyze cooperative strategies to control multi-agent systems*

Integration of control, communication, sensing, computing

Research program: what are we after?

Design of provably correct coordination algorithms for basic tasks

Formal model to rigorously formalize, analyze, and compare coordination algorithms

Mathematical tools to study convergence, stability, and robustness of coordination algorithms

Coordination tasks
exploration, map building, search and rescue,
surveillance, odor localization, monitoring, distributed sensing

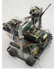
Technical approach

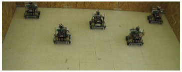
Optimization Methods
- resource allocation
- geometric optimization
- load balancing

Geometry & Analysis
- computational structures
- differential geometry
- nonsmooth analysis

Control & Robotics
- algorithm design
- cooperative control
- stability theory

Distributed Algorithms
- adhoc networks
- decentralized vs centralized
- emerging behaviors





What is the workshop about?

A little bit of all of the following

- Cooperative robotic networks
- **Distributed** motion coordination algorithms
- **Local agent interactions** giving rise to **global behavior**
- Limited information, **no omniscient leader**
- **Verifiably correct,** rigorous assessment of properties

What will we cover?

Models
: Robotic network, coordination algorithm, and task
Complexity notions that help quantify the performance and cost of execution of coordination algorithms

Analysis
: Tools that can be used to analyze the correctness, robustness, and optimality of coordination algorithms

Design
: Algorithm design for consensus, rendezvous, deployment, and boundary estimation

Three sample tasks

Consider **rendezvous/deployment/agreement** scenario

Consensus	=	reach common value for some variable
Rendezvous	=	get together at certain location
Deployment	=	deploy over a given region
Boundary estimation	=	monitor and estimate a boundary

From agent viewpoint,

- What should I process/compute/sense?
- What do I transmit? To whom?
- How do I take into account information that I acquire?
- Where do I move?

Overall, what do I do?

What will we not cover?

Plenty of things because of time constraints!

- formation control
- cooperative control over constant graphs
- quantization, asynchronism, delays
- distributed estimation, data fusion, and tracking
- ...

Literature is full of very interesting recent works in cooperative control

A short bibliography on cooperative control

- I. Suzuki and M. Yamashita. Distributed anonymous mobile robots: Formation of geometric patterns. *SIAM Journal on Computing*, 28(4):1347--1363, 1999
- E. W. Justh and P. S. Krishnaprasad. Equilibria and steering laws for planar formations. *Systems & Control Letters*, 52(1):25--38, 2004
- A. Jadbabaie, J. Lin, and A. S. Morse. Coordination of groups of mobile autonomous agents using nearest neighbor rules. *IEEE Transactions on Automatic Control*, 48(6):988--1001, 2003
- R. Olfati-Saber and R. M. Murray. Consensus problems in networks of agents with switching topology and time-delays. *IEEE Transactions on Automatic Control*, 49(9):1520--1533, 2004
- V. Gazi and K. M. Passino. Stability analysis of swarms. *IEEE Transactions on Automatic Control*, 48(4):692--697, 2003
- W. Ren, R. W. Beard, and E. M. Atkins. Information consensus in multivehicle cooperative control: Collective group behavior through local interaction. *IEEE Control Systems Magazine*, 27(2):71--82, 2007

A short bibliography on cooperative control – cont

- J. A. Marshall, M. E. Broucke, and B. A. Francis. Formations of vehicles in cyclic pursuit. *IEEE Transactions on Automatic Control*, 49(11):1963--1974, 2004
- V. Sharma, M. Savchenko, E. Frazzoli, and P. Voulgaris. Transfer time complexity of conflict-free vehicle routing with no communications. *International Journal of Robotics Research*, 26(3):255--272, 2007
- L. Moreau. Stability of multiagent systems with time-dependent communication links. *IEEE Transactions on Automatic Control*, 50(2):169--182, 2005
- P. Ögren, E. Fiorelli, and N. E. Leonard. Cooperative control of mobile sensor networks: Adaptive gradient climbing in a distributed environment. *IEEE Transactions on Automatic Control*, 49(8):1292--1302, 2004
- M. Mesbahi. On state-dependent dynamic graphs and their controllability properties. *IEEE Transactions on Automatic Control*, 50(3):387--392, 2005

What is the general plan?

Today's schedule

30 mins		**Workshop introduction and preface**
2 hrs	Lect#1	**Distributed algos: graph theory, averaging**
1 hr	Lect#2	**Robotic networks: models, complexity**
1 hr		lunch break
1 hr	Lect#3	**Rendezvous and connectivity-maintenance**
1 hr	Lect#4	**Deployment via geometric optimization**
1 hr	Lect#5	**Boundary estimation**

Workshop Objectives

Ideal goal: you can associate scientific concepts to following words

Network modeling, algorithm design and validation

- **Network modeling**

  network, ctrl+comm algorithm, task, complexity
- **Coordination algorithms**

  rendezvous, deployment, consensus
- **Systematic algorithm design**
  1. geometric structures
  2. aggregate objective functions
  3. class of (gradient) algorithms **local, distributed**
  4. invariance principles and stability