Distributed motion coordination of robotic networks

"Towards Swarms of Ocean Robots That Can Monitor Oil Spills"

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The main idea

e-puck, EPFL

Control of individual robots versus control of group

Challenge is in making overall group act as a coherent whole

Approach behind movie is **centralized**

- center with global knowledge,
  preplan trajectories in known scenario,
  individual robots receive plans to execute
- not robust to failures of center,
  scales poorly with number of robots,
  slow adaptation, communication intensive

We want **distributed, robust, scalable, adaptive** coordination algorithms

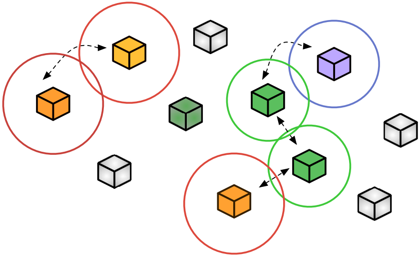
Cooperative robotic sensor networks

Each individual

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

Multiple robots provide

- inherent robustness
- adaptive behavior
- enable tasks beyond individuals' capabilities

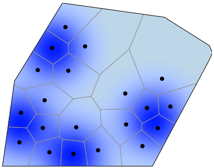
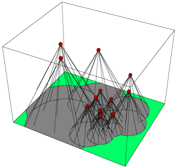
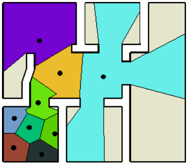
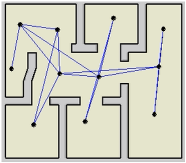


Tasks: mapping, localization, detection, surveillance,...

Snapshot on research program

Research challenges for sensor networks technologies

Feedback/adaptive	rather than open-loop computation for known/static setup
Information flow	who knows what, when, why, how, dynamically changing, no omniscient leader
Uncertainty	unknown environment, events happening evolving tasks
Reliability	robust, predictable behavior

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

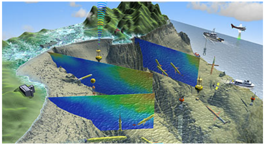
(Couzin et al, Nature 05; Conradt et al, Nature 03)

Sample applications of robotic sensor networks

- 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., habitat monitoring, 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

UCSD Scripps



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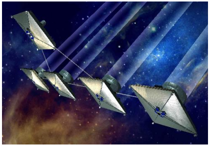
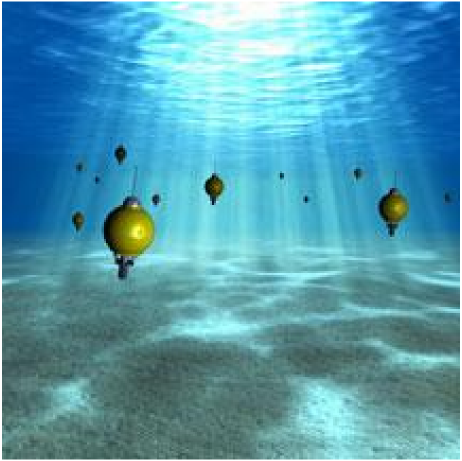


NASA

Ocean monitoring via coordinated buoyancy drogues



Distributed ocean monitoring via integrated data analysis of coordinated buoyancy drogues

Project funded by National Science Foundation
Cyber-Enabled Discovery and Innovation initiative
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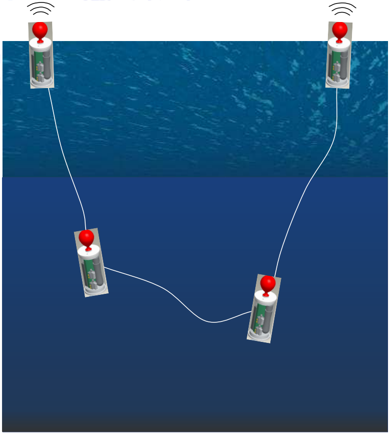
Next generation of ocean sensing and exploration

Objective: Reconstruct 3-dimensional time-varying flow field and basic physical features (temperature, salinity, chlorophyll, oxygen concentration)



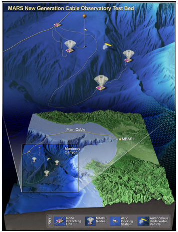
Swarm of small buoyancy drogues

- capable of arbitrary vertical migration behaviors
- can only get accurate geographic fixes when at surface
- when underwater, stores time record of depth and sensed variables
- at surface, transmits data to central location for analysis and receives position, updated local flow models, depth trajectories with timing information, etc.

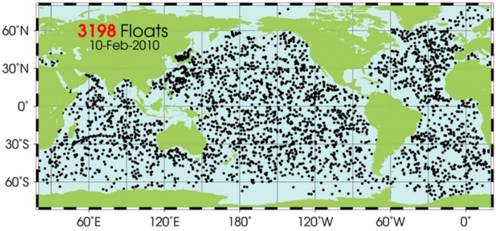
Current ocean technologies

NSF Ocean Observatories Initiative calls for the exploitation of two tools:

- ocean observatories that provide power and communication to operate real-time sensors located at fixed sites
- small, low-cost autonomous underwater vehicles that function as mobile ocean observing systems and provide broad spatial coverage



MARS



ARGO program


ARGO float

Provides broader coverage at global scale

Our project

Current technologies only sample oceanic features at very large scale

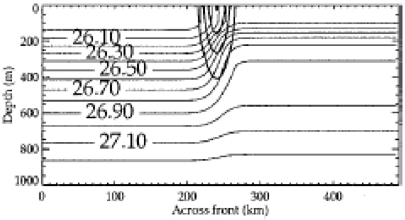
Small-scale phenomena aliased because of undersampling in space and time

Drogue-based system

1. smaller scale relevant for physical, chemical and biological processes (volumes 5 km x 5 km x a few hundred m deep)
2. higher spatial and temporal resolution for sub-mesoscale features
3. generation of three-dimensional maps of time-dependent flow fields
4. many small, inexpensive drogues (100m depth, 1l in volume, $1K cost)
5. leverage knowledge of flow field to sample ocean
6. flexible tool for opportunistic sampling, no permanent installation

Sampling of along-isopycnal flows of nutrients

Most flows occur along **isopycnals** – density surfaces in the ocean



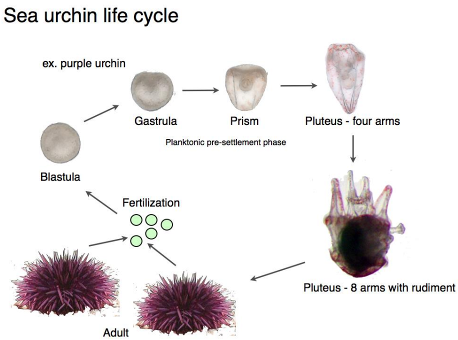
Presently we can only infer these flows from models

- Rudimentary understanding of how deflections of isopycnals influence nutrient transport into upper well-lit waters of the ocean
- Drives phytoplankton growth, hence organic carbon & oxygen production

Coastal circulation analysis

Many species that live as adults on the sea floor spend early life in open ocean

Larval are extremely small and cannot swim against even weak ocean currents



How do these animals migrate out to sea and then return to shore?

Claim: they use buoyancy to "hitch" a ride on depth-dependent currents

Marine protected area (MPA) connectivity

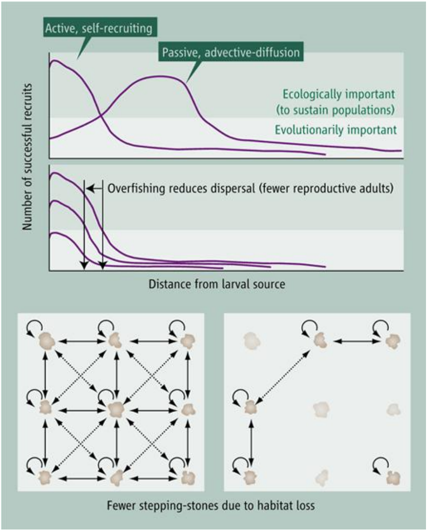
MPA's are areas with significant restrictions on fishing and recreation

Philosophy: species protected within MPA boundaries will serve as seed stocks for other regions

Objective is determine MPA size and spacing to ensure connectivity

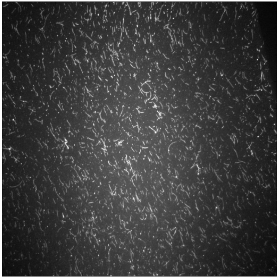
Key factors:

- coastal circulation
- behaviors of the organisms within three-dimensional, time-dependent flow field



Environmental response

Ability to track down interesting environmental feature, e.g, water parcel, harmful algal blooms and monitor release of episodic pollutants, oil spill



San Diegans are especially vulnerable to shifting currents that can send effluents from the Tijuana estuary up the coast instead of out to sea

Concentration of contaminants can vary greatly over small distances

The drogue

Desired features:

- small
- inexpensive
- adaptive

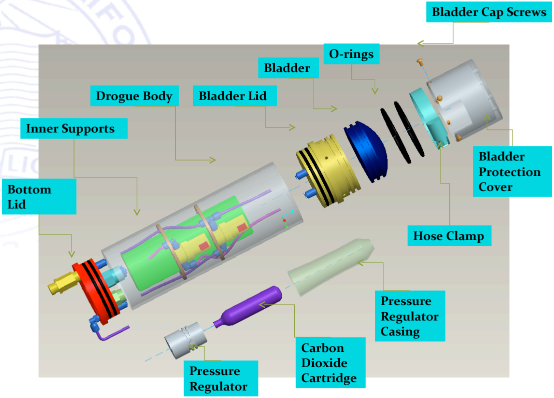
SIO

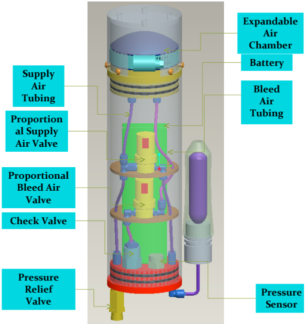
MAE 1st

MAE 2nd

MAE 3rd

Drogue component schematics



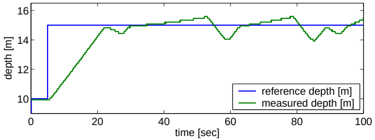


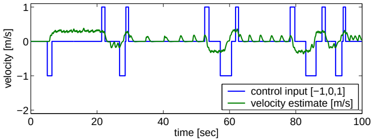
- onboard processor, battery, buoyancy control via pneumatical bladder
- optical communication for close ranges
- globally referenced via cell phones
- onboard sensors (CTD, nitrate, phosphate, fluor, oxygen, pH,...)

Buoyancy control

Buoyancy control via CO_2-pressurized neoprene bladder

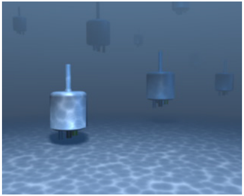
- non-linear (depth dependent) unstable dynamics: beneficial for low energy consumption
- stabilization of depth via feedback: servo-motor for small changes in buoyancy volume and compression/bleed valve for large changes





Capable of repeatable intermittent surfacing control for data transfer and position location via cellular communication

Research needed



Networked drogue system requires solution to **multiple challenges**

- How can we reconstruct the shear layers of ocean circulation from the displacements reported by drogues in successive submersions?

  3D kinematic and dynamic models, ensemble Kalman filter

- How can individual drogues take advantage of knowledge of flow to move between points or track the dispersion of pollutant?

  inverse kinematics, geometric control

- Are there drogue formations that help improve field estimation?

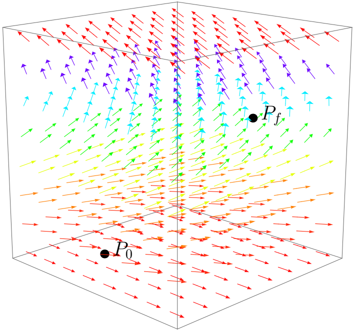
  cooperative control, convex optimization

- How should data be assimilated to predict and validate ocean circulation model and execute coordinated control algorithms?

  Kepler workflow

Motion planning in the flow field
for optimal collective motion, estimation and drogue retrieval

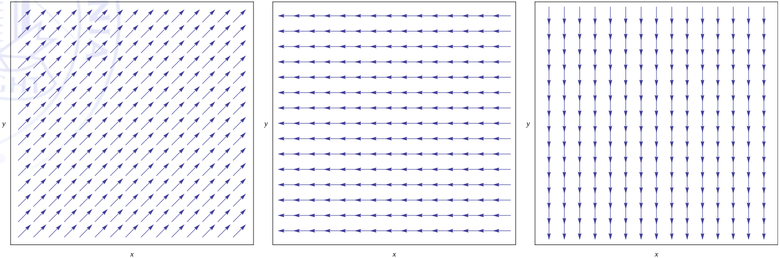
Point-to-point reconfiguration problem: find control that takes drogue from initial $P_0 = (x_0, y_0, z_0) \in \mathbb{R}^3$ to final $P_f = (x_f, y_f, z_f) \in \mathbb{R}^3$



Smart planning of sequence of depth changes $c_1, \ldots, c_m$ and coasting times $t_1, \ldots, t_m$ to take advantage of ocean flow (get drogue from (x_0, y_0) to (x_f, y_f))

What are the right depths to flow at?

How to identify depth-dependent flows to go from P_0 to P_f?



$\text{flow}_1 = (1, 1)$ $\text{flow}_2 = (-1, 0)$ $\text{flow}_3 = (0, -1)$

3 flows positively span $\mathbb{R}^2$, i.e., for any $v \in \mathbb{R}^2$, there exist $a_1, a_2, a_3 > 0$ with

$$v = a_1 \text{flow}_1 + a_2 \text{flow}_2 + a_3 \text{flow}_3$$

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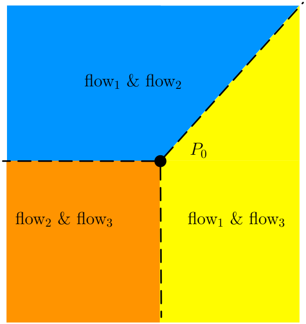

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$$v = a_1 \text{flow}_1 + a_2 \text{flow}_2 + a_3 \text{flow}_3$$

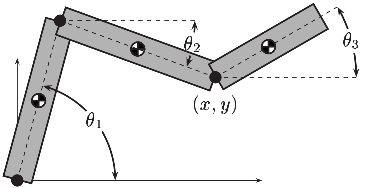
For how long should the drogue coast at each depth?

Connection with kinematics problems in robotics

Forward kinematics: find final configuration of end link resulting from set of joint motions

Inverse kinematics: find joint angle motions that make end link attain desired final configuration

In general, no closed-form solution



Iterative shooting approach: choose $t_1, \dots, t_m$ and compute error

$$\mathrm{Err}(t_1, \dots, t_m) = \Phi^{t_m}_{\mathrm{flow}_{c_m}}(\Phi^{t_{m-1}}_{\mathrm{flow}_{c_{m-1}}} \dots (\Phi^{t_1}_{\mathrm{flow}_{c_1}}(x_0, y_0)) \dots) - (x_f, y_f)$$

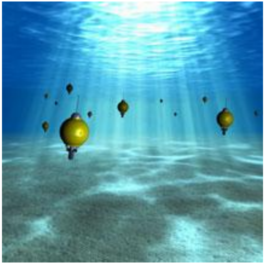
Numerically solved via quasi-Newton method

Conclusions

Ocean sensing and observation through swarms of buoyancy-controlled drogues

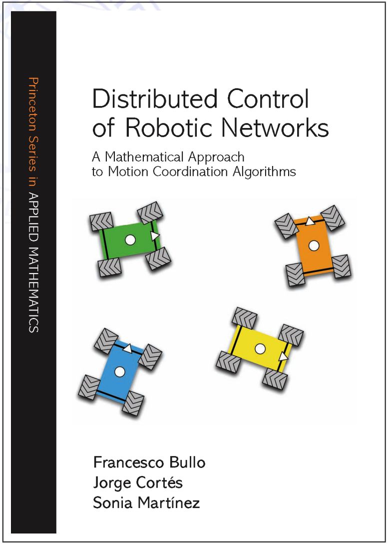
Networked drogue system requires integration of

- ocean flow circulation models
- flow estimation algorithms
- motion planning algorithms
- data assimilation and analysis



Flexible, inexpensive infrastructure for opportunistic sampling of physical features

Book: Distributed Control of Robotic Networks



1. intro to distributed algorithms (graph theory, dynamical systems, synchronous networks, averaging algos)
2. geometric models and geometric optimization problems
3. model for robotic, relative sensing networks, and complexity
4. algorithms for rendezvous, deployment, boundary estimation, connectivity maintenance

Freely downloadable at
http://coordinationbook.info
with tutorial slides & software libraries

Available from Princeton Univ Press