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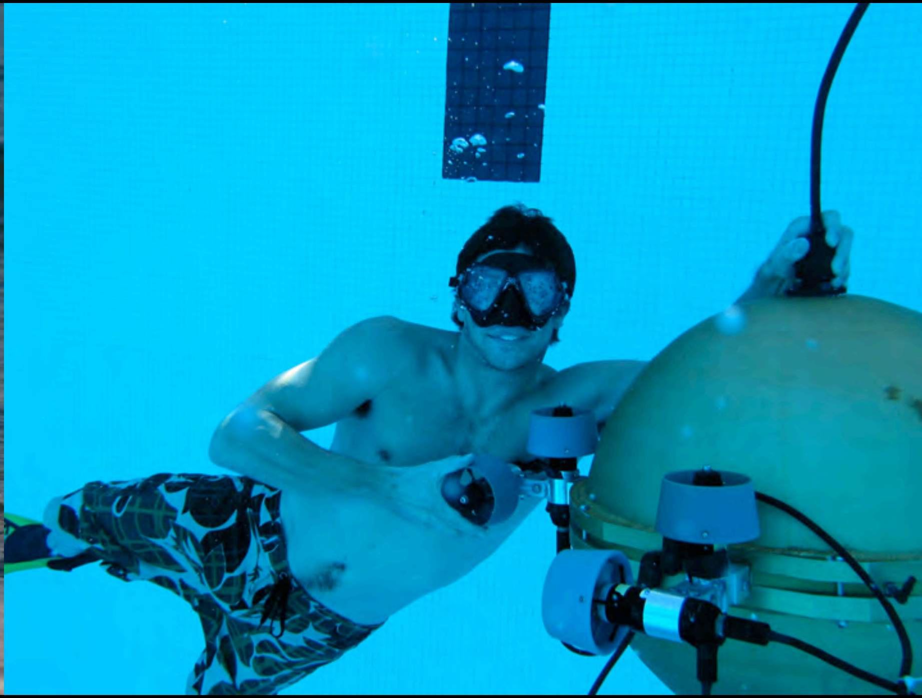
Marine Robotics Research Summer School

Surface Robot Planning

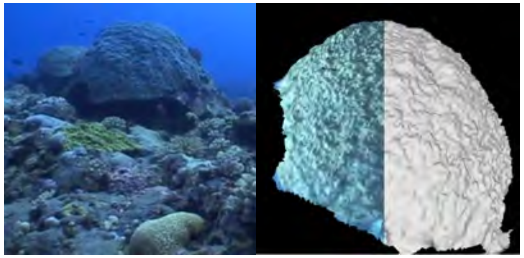


MRRSS – 2016

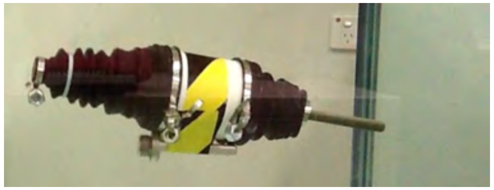
Ryan N. Smith

Robotic **GNOME** Lab - Fort Lewis College

- Robotic **G**uidance and **N**avigation for **O**bservation and **M**onitoring the **E**nvironment (Robotic **GNOME**)
  - Nexus of Robotics, Sensor Networks and Environmental Monitoring
    - Research areas in robotic perception, conceptualization, planning and long-term navigation.
  - Creating robotic systems that operate for long periods, without human intervention in dynamic and complex, real-world environments.



Fort Lewis College



Background

- Types of robots
- Robot Locomotion
- Remotely operated
  - Tele-operated
  - Piloted
- Autonomous
  - Fixed plan/course
  - Autonomous/Deliberation

Background

- Constraints
  - Local
  - Operational
- Logistics
- Types of Plans

Surface Vehicles

- Multiple shapes, sizes, applications, etc.
- Kinematics and Dynamics similar to ground robots
  - Configuration Space is R^2
  - X , Y, θ
- GPS available
- Communication over air
- Applications
  - Survey, support, monitoring, etc.

Standard Surface Vehicles

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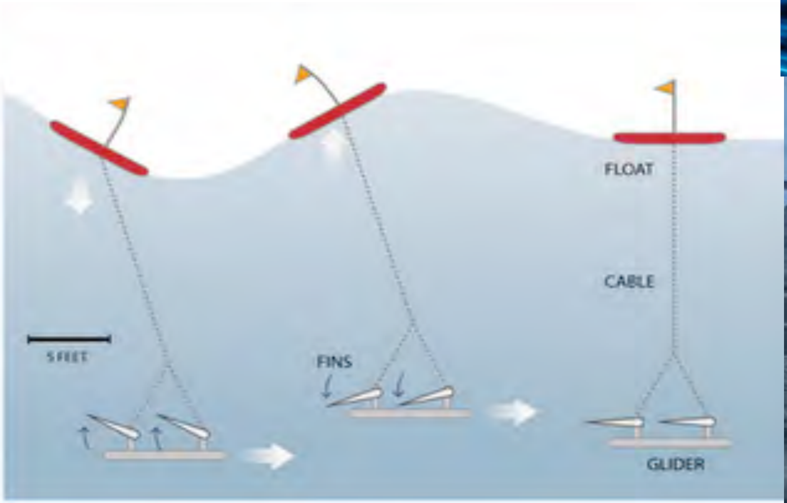
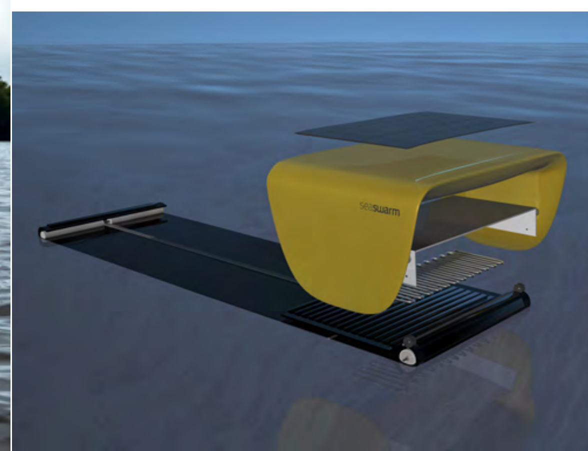
Wave Glider

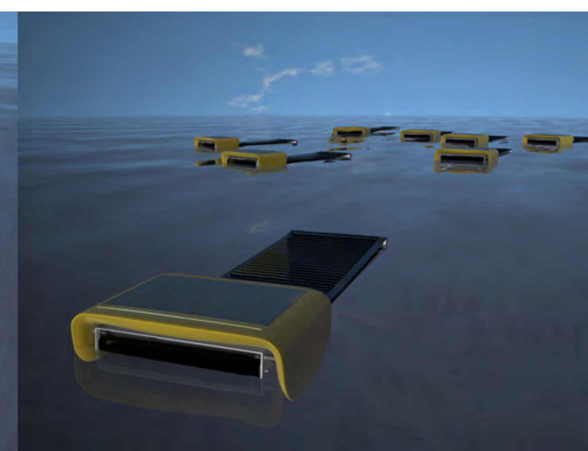
- Persistent presence
- >> 1 year
- Robust platform
- Multiple Applications
- Integration of many sensors



MIT SeaSwarm

- Conveyor belt for locomotion
- Nanowire mesh absorbs oil
- Deployed as fleet to clean petroleum spills





National Oceanography Centre Autonomous Surface Vehicle

- Research vessel
  - Ocean Conditions
  - Water quality
  - Marine life
- Generally accompanied by underwater glider
- Long endurance (solar)
- Data Muling applications

Bluebird Marine Systems' SeaVax

- Intended to clean garbage, plastic waste
- Autonomous / Remotely Operable
- Large-scale applications
- Long-term deployments

Robot X Competition

- Annual Competition
- Queensland University of Technology Vehicle

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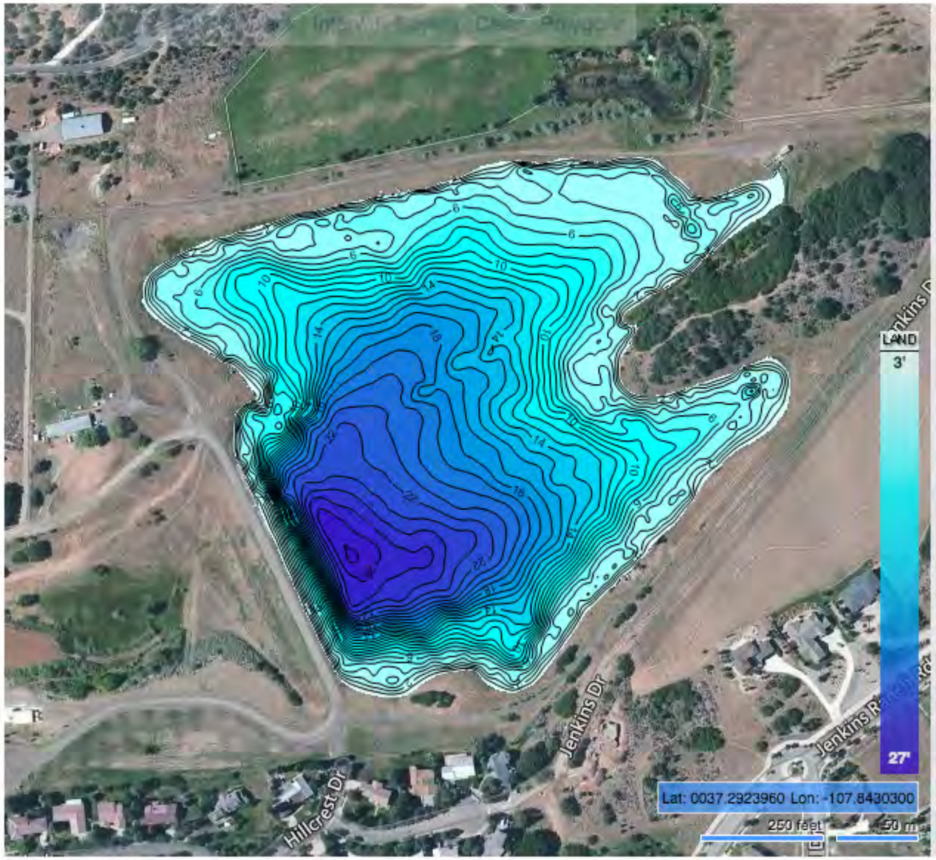
Platypus – Lutra Airboat

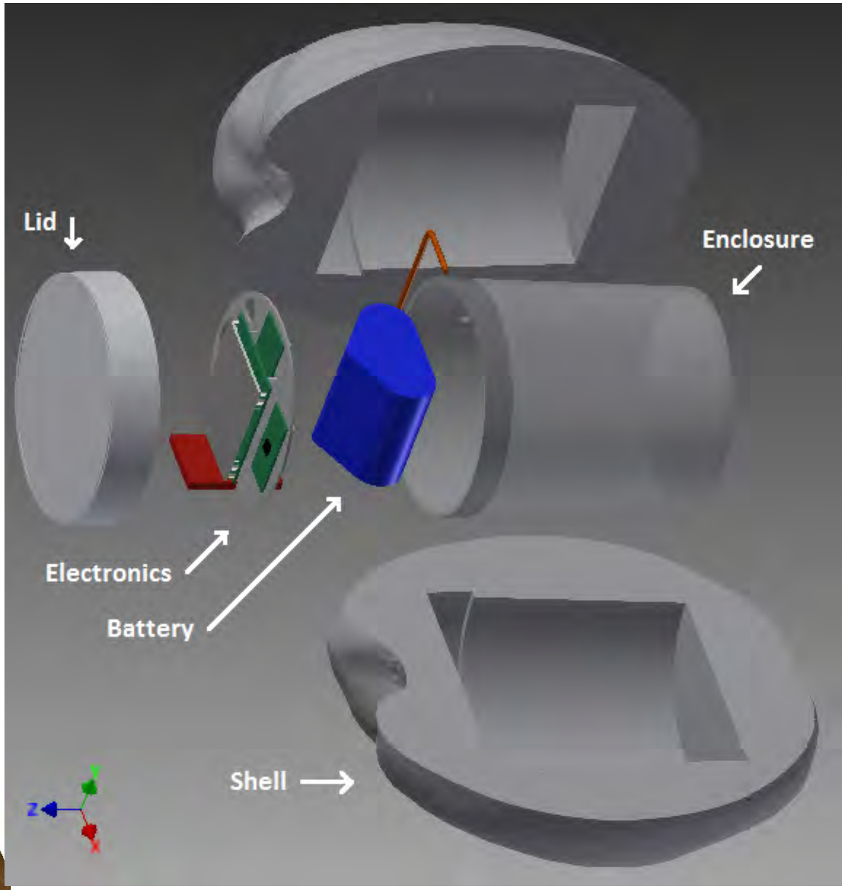
- Small and lightweight
- Deployable in shallow water
- Minimizes environment disruption
- Bathymetric mapping
- Water Quality sensors



Custom Builds

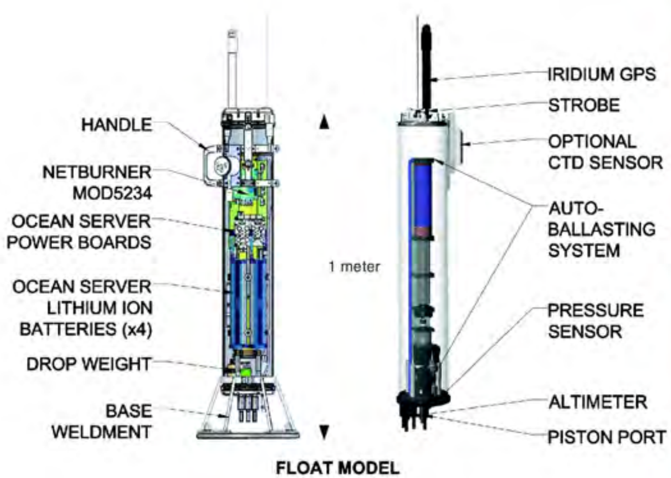
Drifting Vehicle

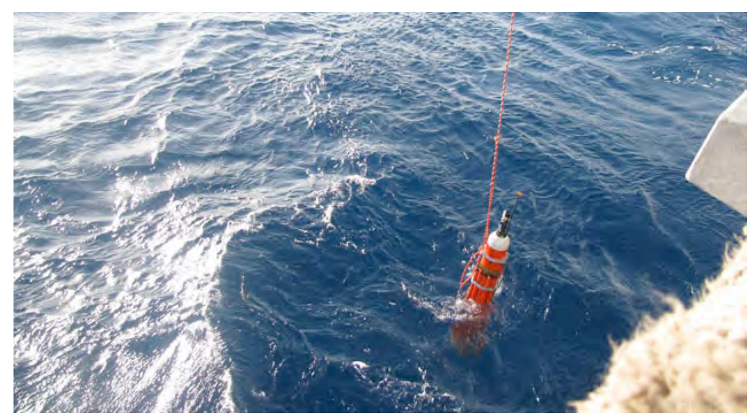
- Pseudoseeds
  - Long-term monitoring
  - Move with currents and wind



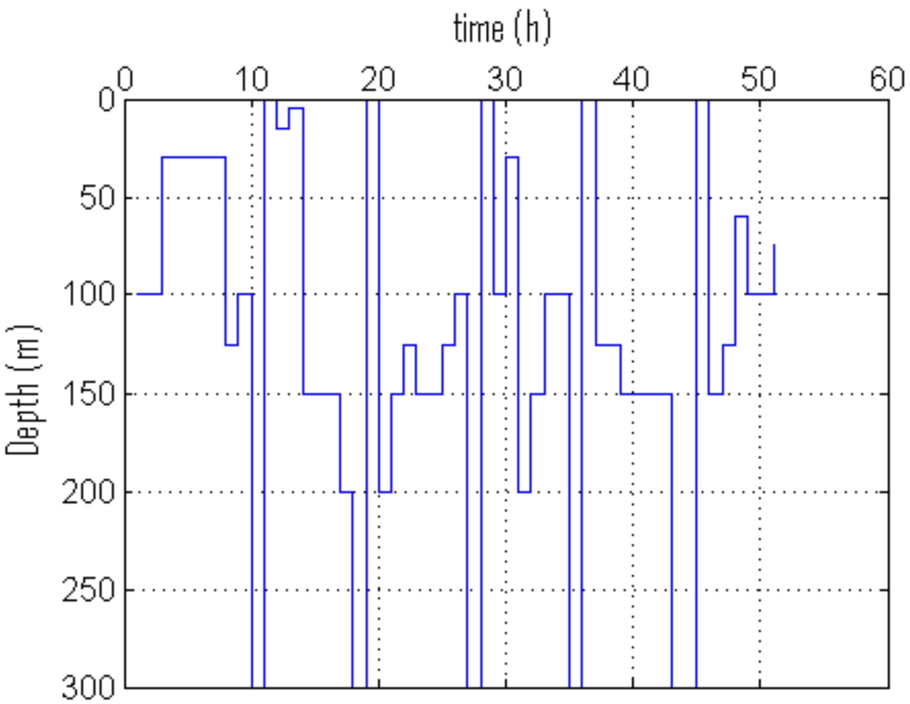
Lagrangian Profilers

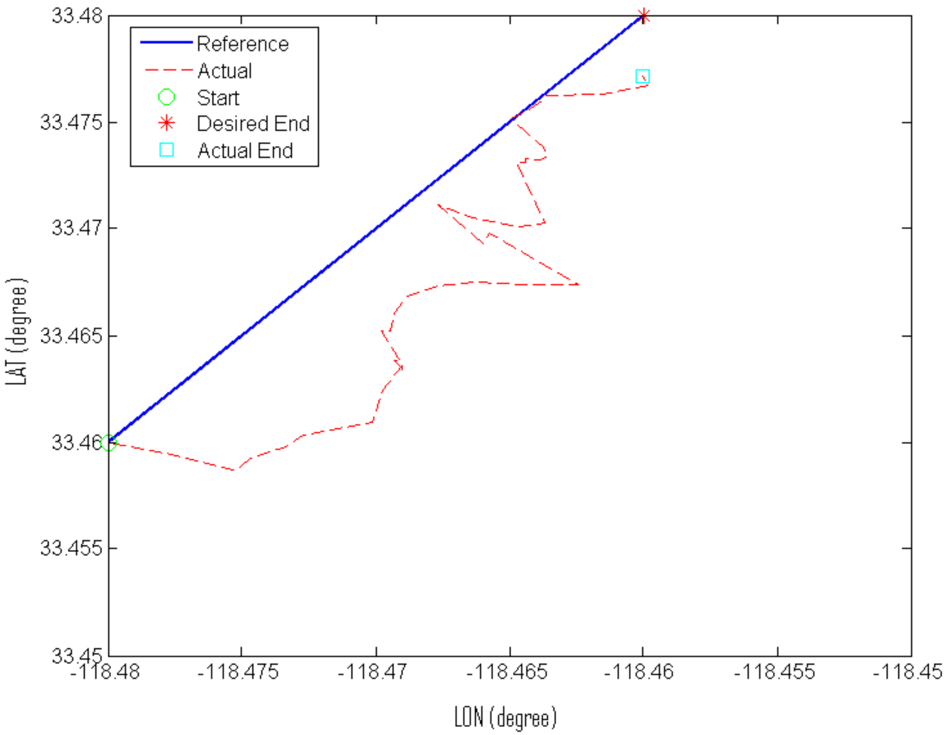
- Vertical actuation ONLY
- Horizontal motion from currents
- Multiple deployment duration models



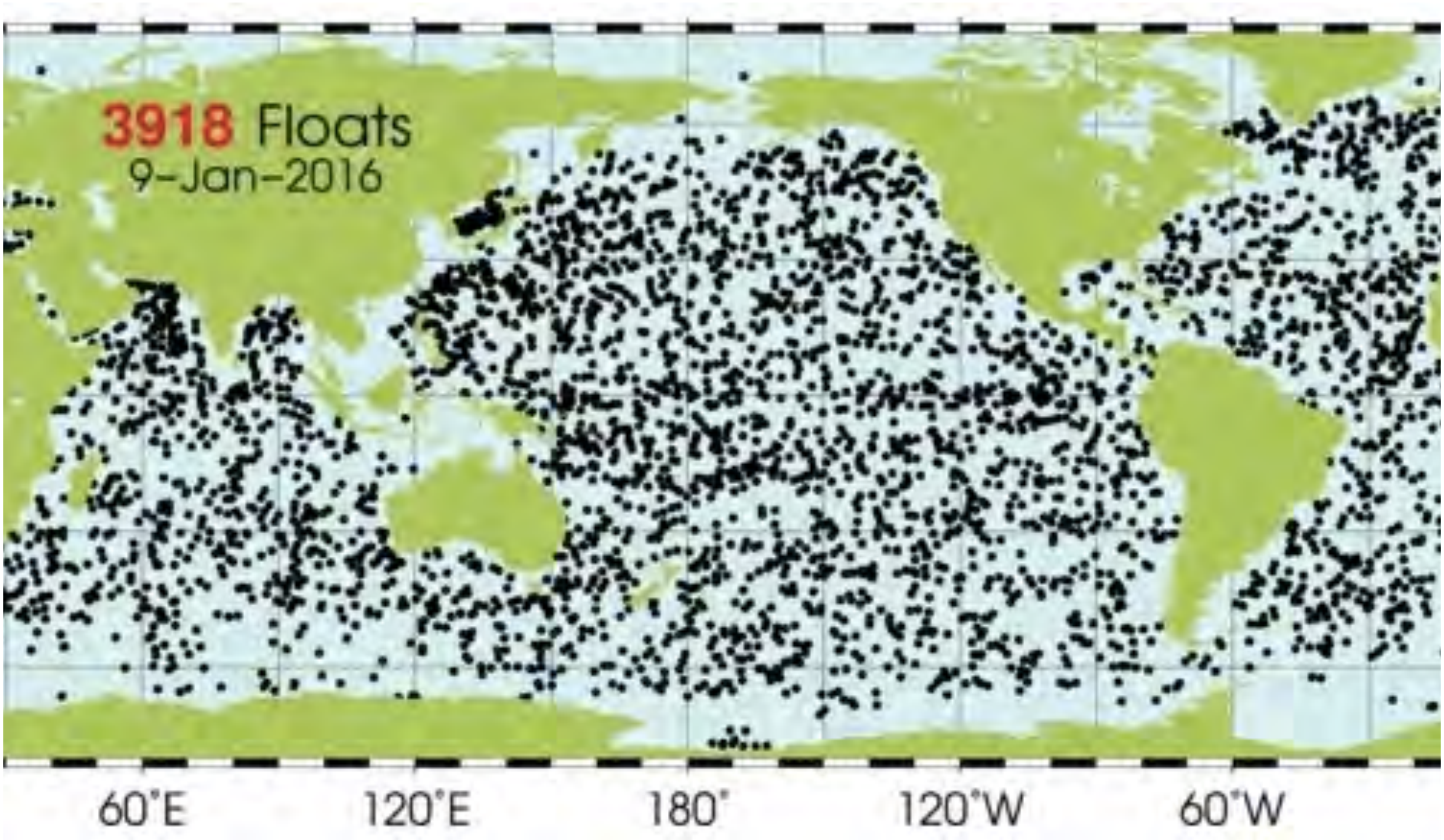


Lagrangian Profilers





Argo Floats

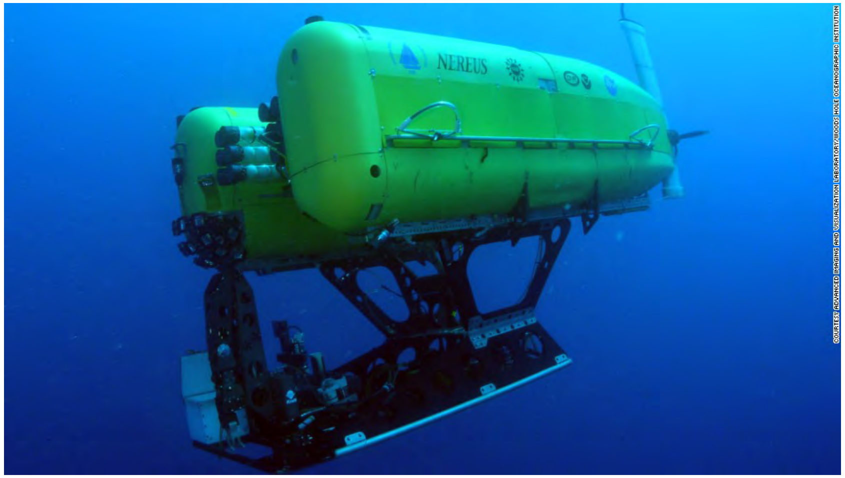


Underwater Vehicles

- Included for completeness
  - Notice the differences in
    - Shape
    - Control
    - Operational Space

Nereus AUV

- Deep sea research vessel
- "Hybrid" ROV/AUV
  - Micro-thin fiber-optic cable for a tether



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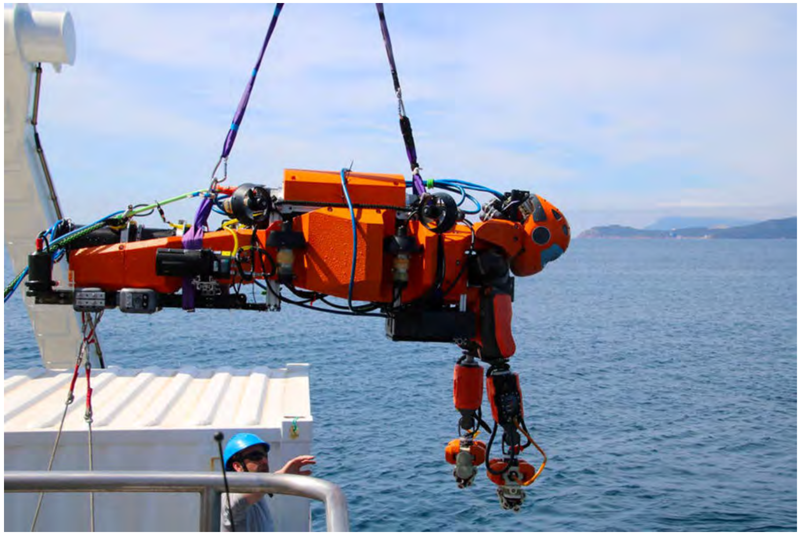
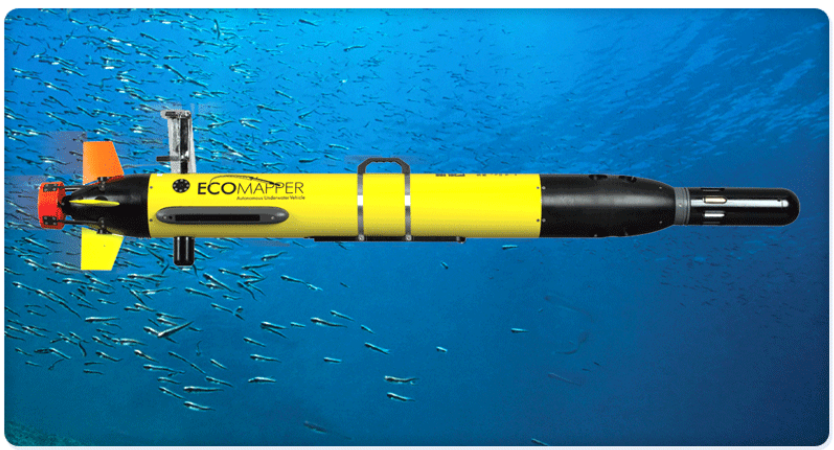
OceanOne - Stanford

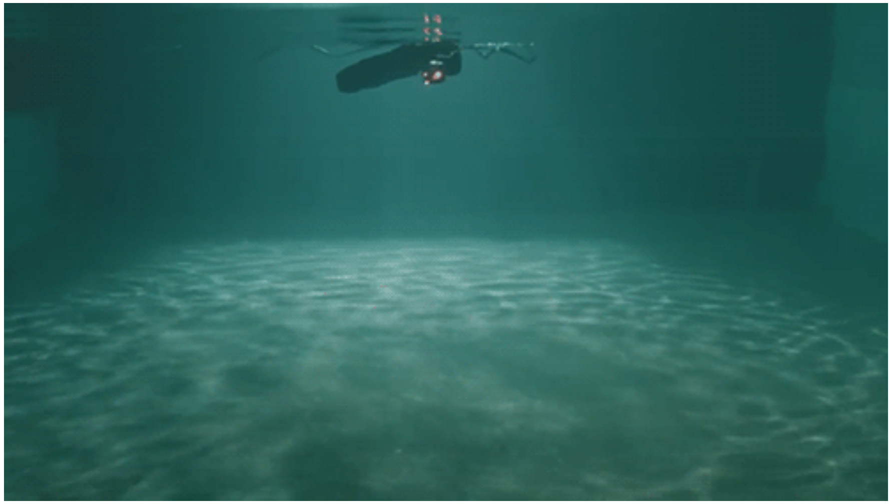


- Assists divers in recovery
- Utilizes human vision, haptic force feedback

IVER or EcoMapper



Eelume ROV

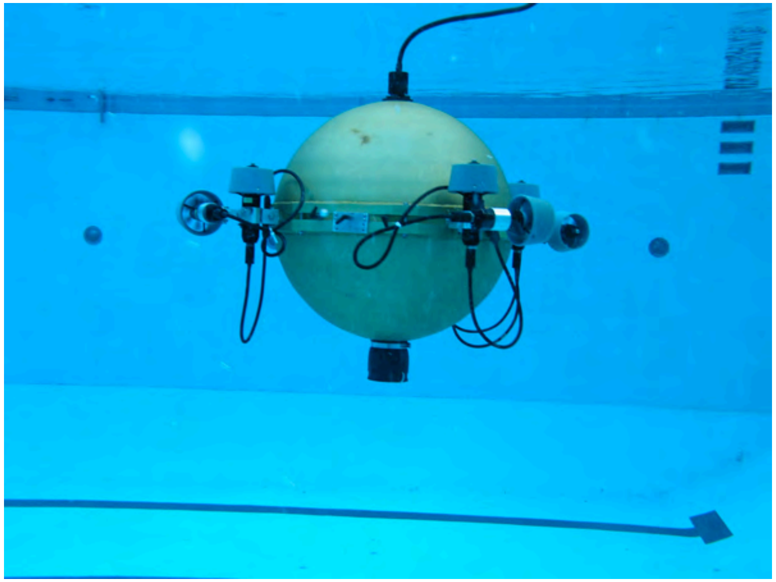


Eelume ROV

- Manipulator to perform maintenance tasks
- Can access confined spaces

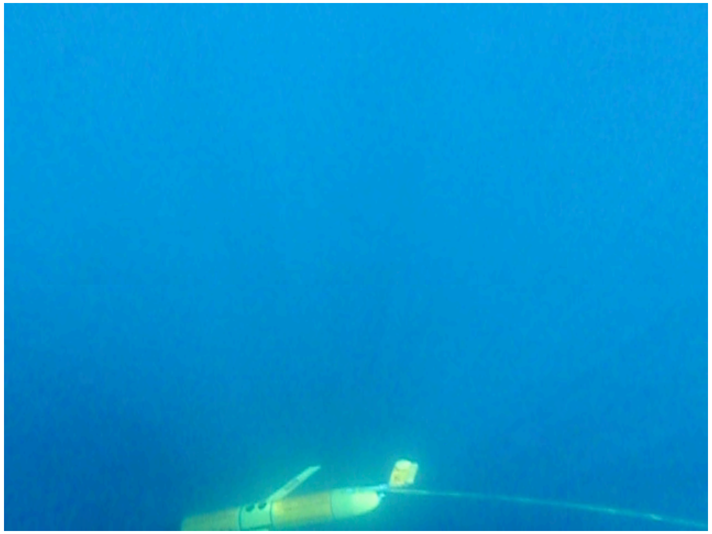
Omni-Directional Intelligent Navigator (ODIN)

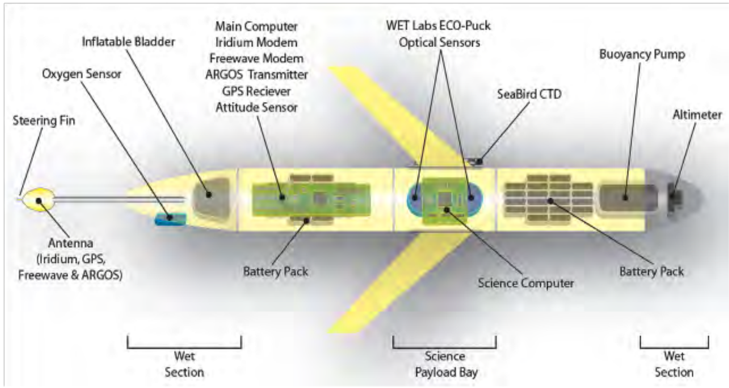
- 63 cm spherical body
- 8 thrusters
  - 4 horizontal and 4 vertical
- Mass = 123.8 kg
- + buoyant by 1.3 N
- Full 6 DOF motion
- Max. depth = 100 m
- Max. speed = 3 m/s
- Controlled testing environment



Webb Slocum Glider

- Passive actuation
- Long-term deployments (~1 month)
- Slow moving vehicle (~1 km/hr)
- Waypoint-based trajectory plan
- Robust low-level controller
- Depth-rated to 200 m
- Dead-reckoning navigation
- Saw-tooth trajectory pattern
- Surface every 4 – 8 hours





Robot Locomotion

- Propellers/Thrusters
- Buoyancy-driven
- Wave Power (LR Wave Glider)
- Ocean Currents
- Wind Powered

Robot Operation

- Remotely Operated
- Semi-Autonomous
- Autonomous

Remotely Operated

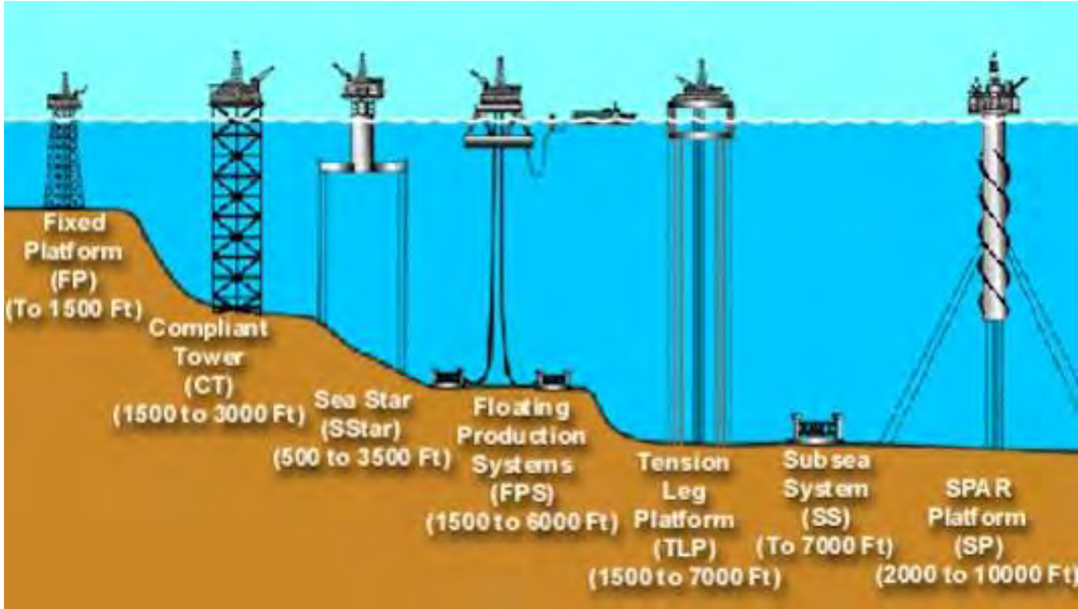
- Tele-operating
  - Wi-Fi
  - Radio
  - Hardwire
  - Acoustic
- Piloted
  - Line-of-sight
  - Tether length limits deployment range

Tele-operating Scenarios

- Line of sight
  - Known environment
  - Unknown environment (build maps)
- On-board Camera
  - Data sent on wire/cable
  - Visualization of environment at controller workstation

Example: Oil Rig Anchor

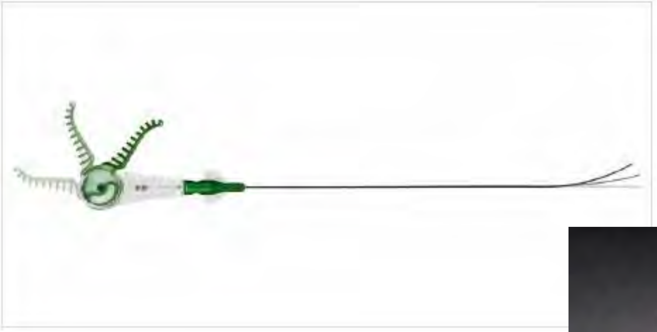
Depending on the type of platform, oil platforms drill in waters as deep as 3700 meters (~12,000 feet) [1]. While some drilling units use submersibles to access the seafloor, others are anchored. All equipment must be maintained, especially the drilling apparatus and anchors. It is common practice to use ROVs in environments divers cannot access [2].

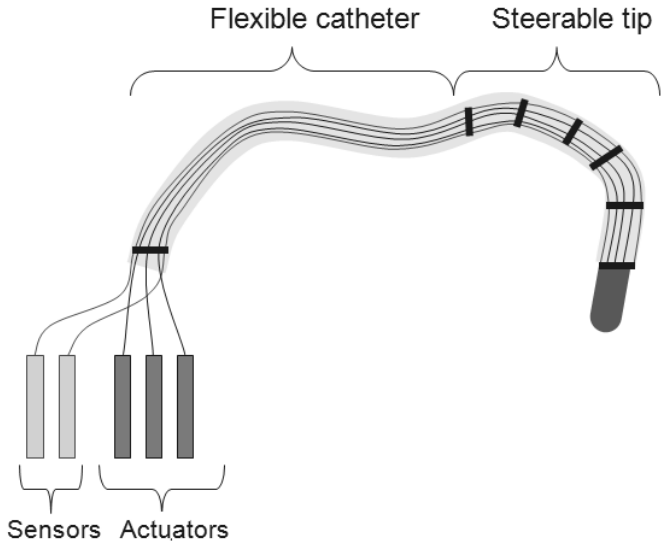


[1] https://en.wikipedia.org/wiki/Oil_platform
[2] http://eelume.com/

Example: Endoscopic Surgery

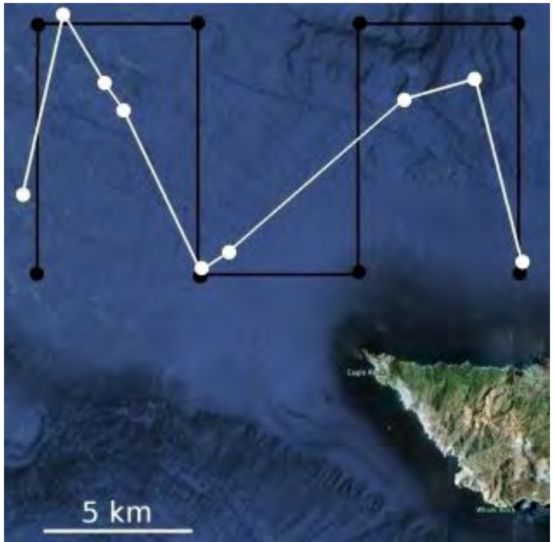
- Endoscopic surgery is a minimally invasive form of surgery. Small cameras and manipulators are used through incisions smaller than those of traditional operations. This significantly reduces recovery times.
- Tele-operated systems may be used to perform surgeries long distance.

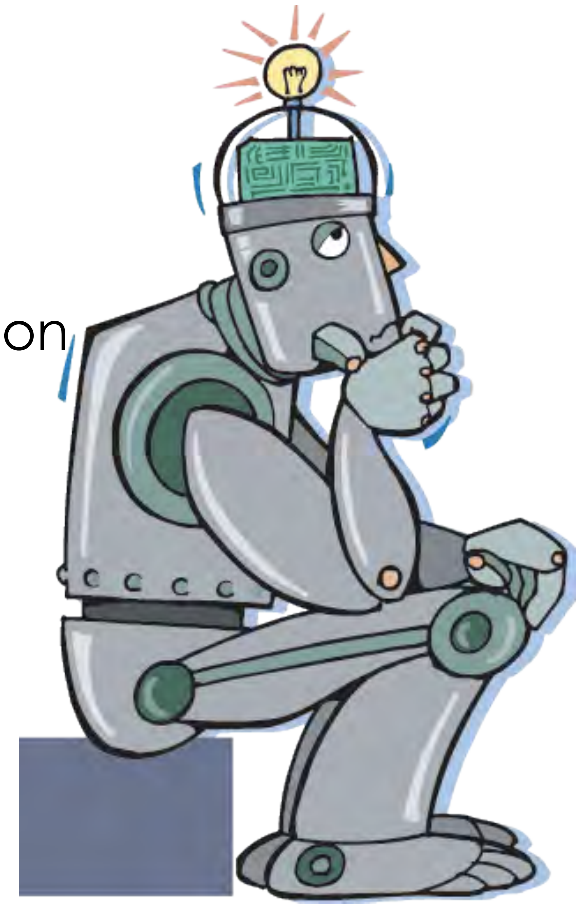




Autonomous Operation

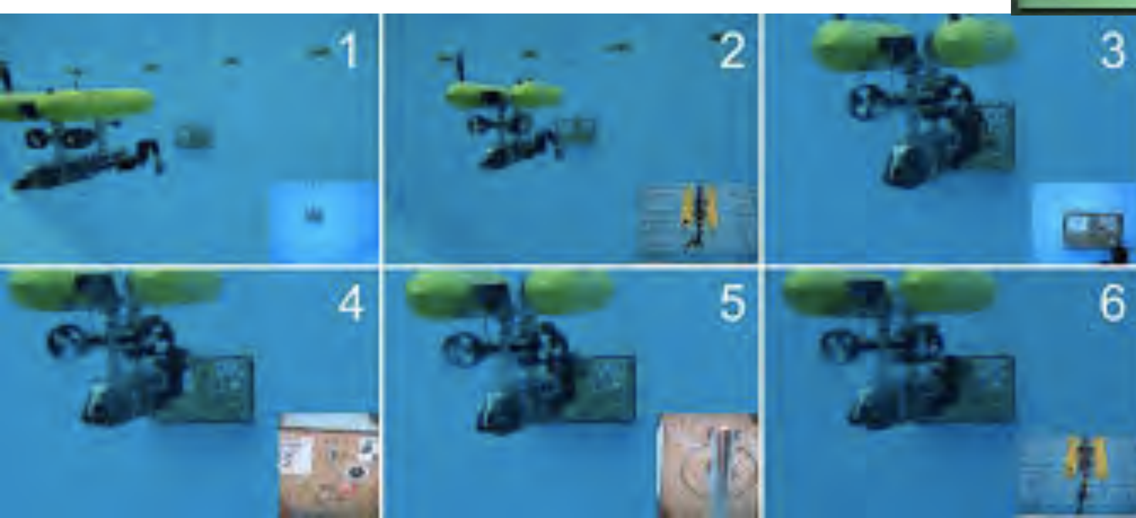
- Fixed Plan/Course
  - Waypoints
  - Similar to land-based navigation
- Autonomy/Deliberation
  - Feedback-based environmental exploration





Semi-Autonomous Operation

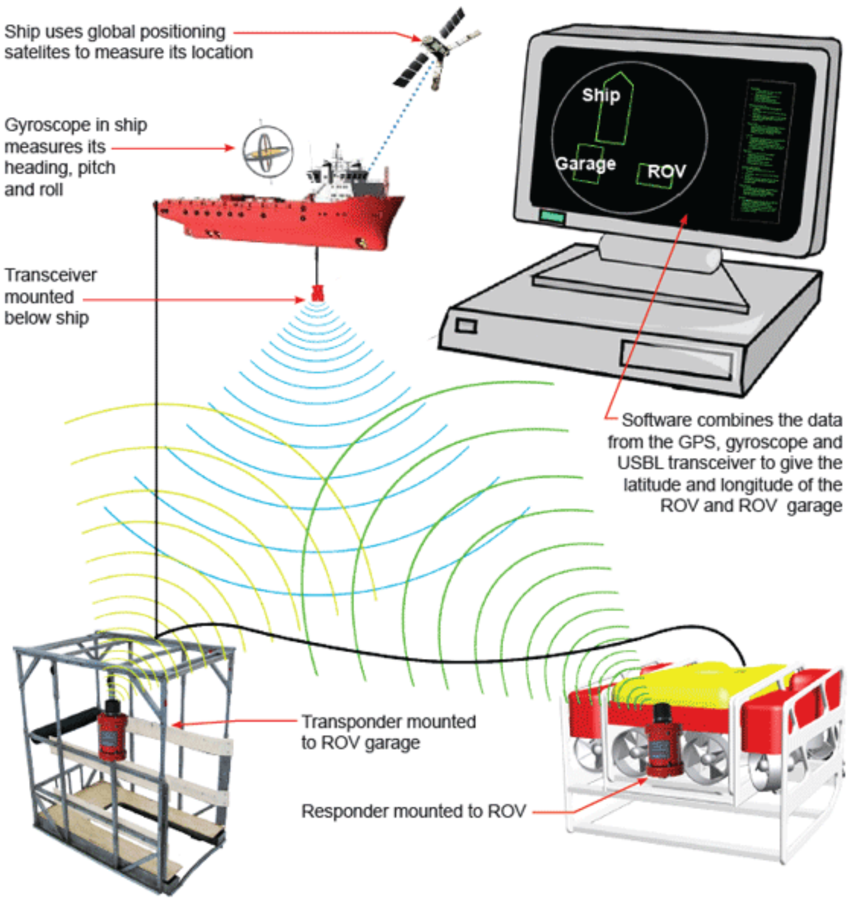
- Generally a vehicle with a gripper or manipulator
- Autonomous stabilization
- Remotely operated manipulation



Underwater Communication

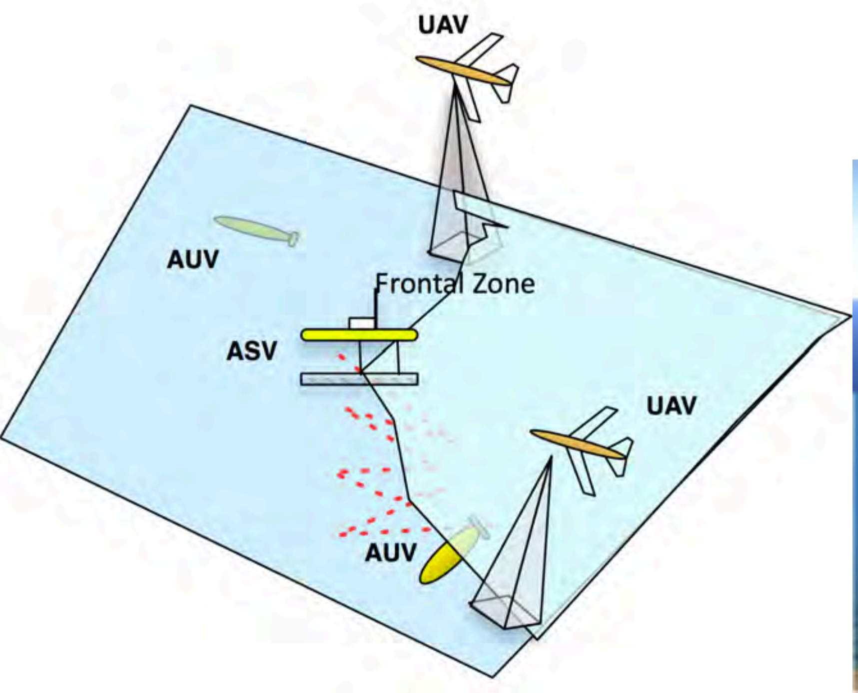
Underwater communication is difficult. Some options are available for acoustic communication and localization. Acoustic communication has a limited range and bandwidth.

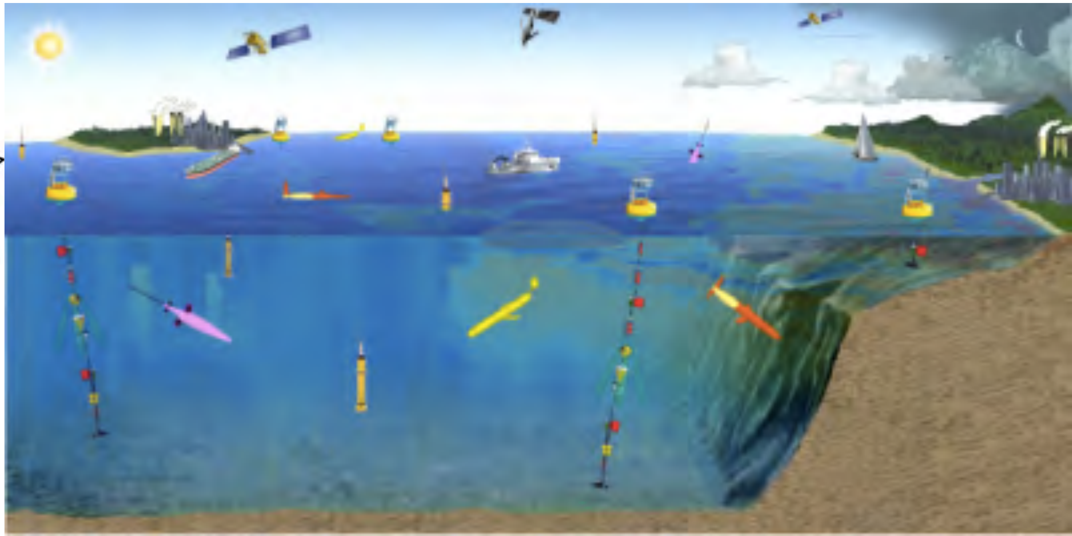
- USBL
- LBL
- Pingers



Example: Environmental Monitoring

- Environmental monitoring is of growing interest with the looming prospects of global climate change and water scarcity.





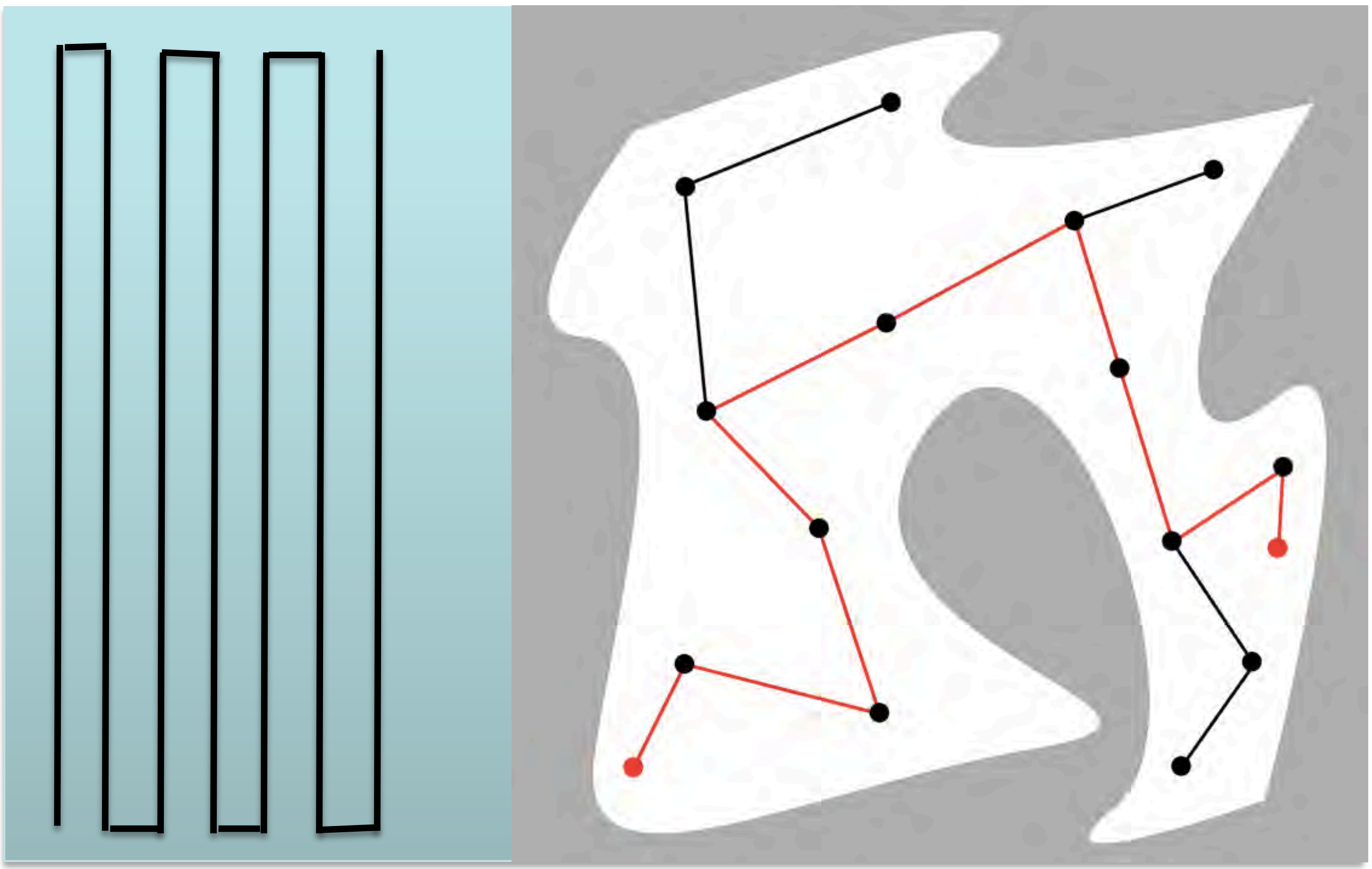
Mission Planning

- Location
- Objective(s)
- Time
- Energy
- Logistics
- Regulations
- Data

Objectives

- Exploration
- Patrol/Monitor
- Change Detection
- Information Gain
- Data Muling
- Testing
- Operational Demonstration

Coverage vs. Sampling



Common Sensors in Aquatic Robots

- Vision (camera)
- GPS
- Water quality sensors
- Radio beacon
- Inertial Measurement Unit (IMU)
- Compass
- Magnetometer
- Gyro
- LiDAR
- Radar
- Doppler Velocity Log (DVL)
- Sonar
- Acoustic Pingers
- Pressure transducers
- Water sampler

Mission Logistics

- How many vehicles?
- Communication?
- Deployment Methods?
- Access to water?
- Data Collection and Dissemination?
- Repercussions?

Data

- What are the data?
- What format?
- Processing
- Dissemination
- Comparison

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General Science Goals

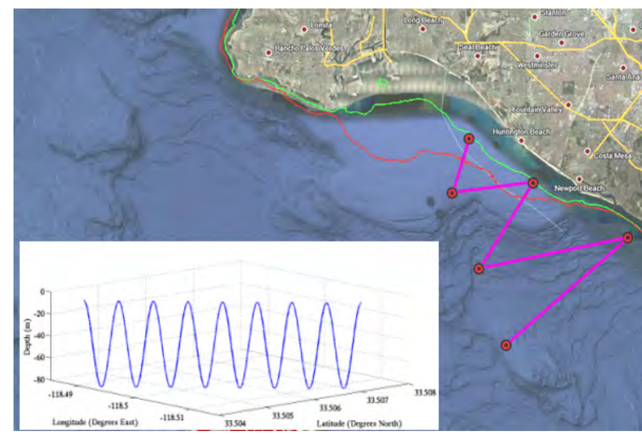
Regional/Local constraints

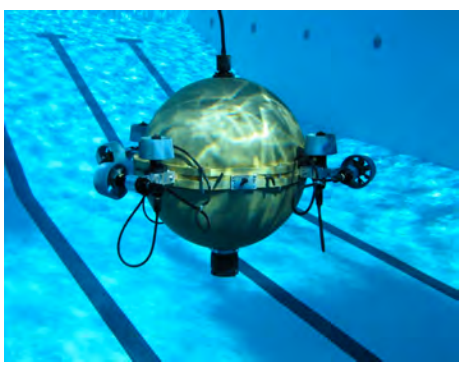
Vehicle fleet

Supervisory Control
-Define survey area and type
-Vehicle selection

Specific science goals
Vehicle dynamics and kinematics
Model predictions
Survey type
Feasibility

Executive Control
-Path planning





Actuation

Trajectory

Vehicle Model

Low-level control
-Aboard the vehicle

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Ocean (under)Sampling, Automation and Planning

"Most of the previous century could be called a century of undersampling."

-- *Walter Munk*

Secretary of the Navy/Chief of Naval Operations Oceanography Chair at [Scripps Institution of Oceanography]

We can deal with *undersampling, as long as it is in the "**right place** at the **right time**."*

Ocean (under)Sampling, Automation and Planning

"In preparing for battle I have always found that plans are useless, but planning is indispensable. Failing to plan is planning to fail."

-- *General David Dwight G. Eisenhower Supreme Commander Allied Forces, WWII and 34th President of the United States*

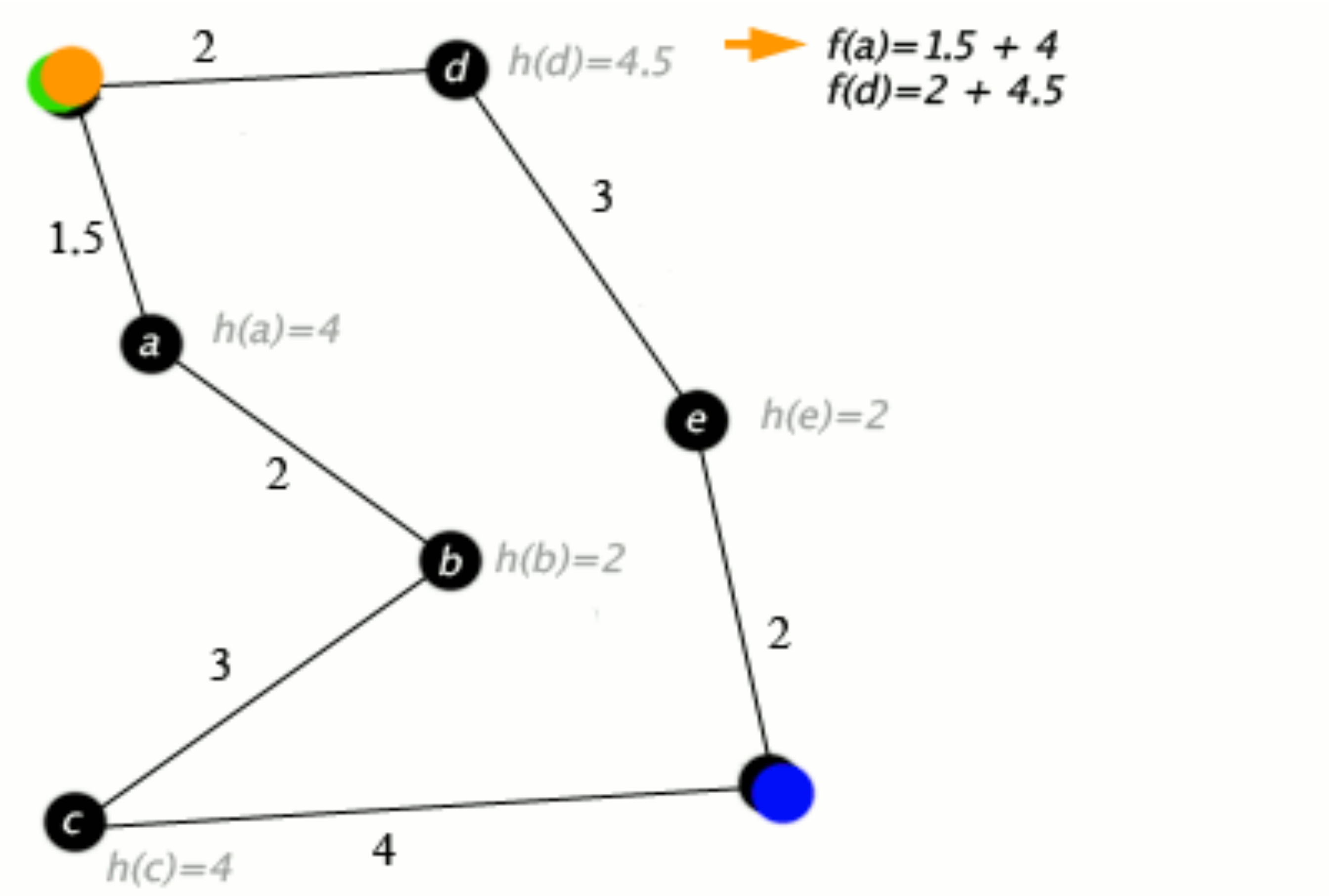
Common Planners

- Total Coverage
- A*
- D*
- Field D*
- RRTs
- Probabilistic Road Map
- Uncertainty/Entropy Reduction

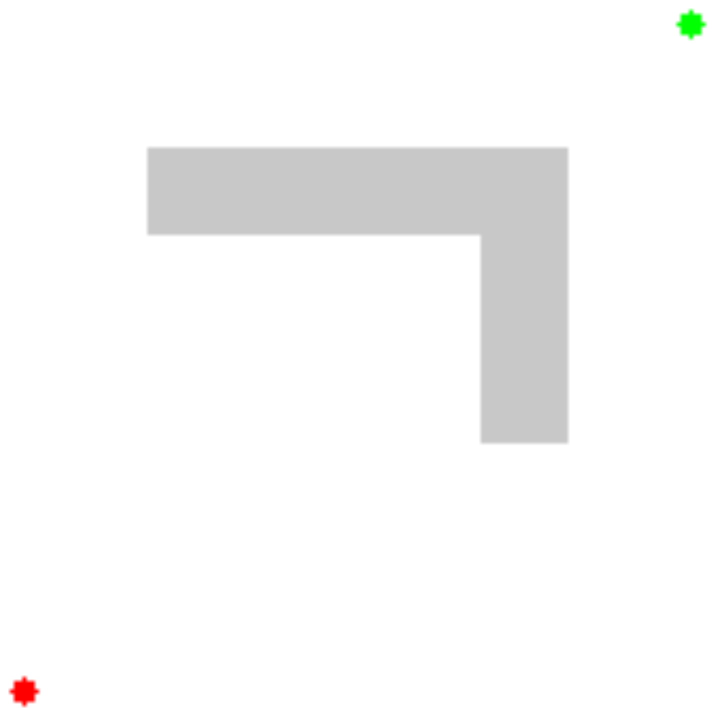
A* Planner

- Graphical, grid-based planner
- Optimizes path for a known environment
- Based on mission criteria
  - Time
  - Fuel
  - Power
- Weighs points (nodes) on defined cost
- Optimal path is minimum cost
- Calculation time is number of nodes squared

A* Path Planning Algorithm



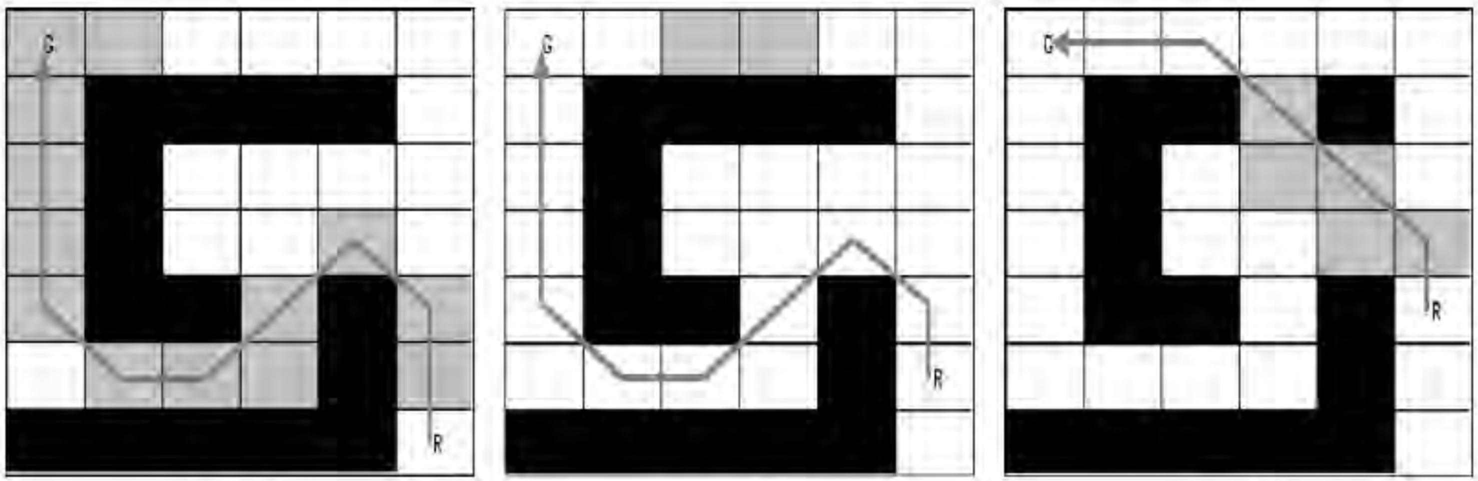
A* Path Planning Algorithm



D* Planner

- Based on A*
  - Grid-based planner
  - Based on mission criteria
  - Weighs points (nodes) on defined cost
  - Optimal path is minimum cost
  - Calculation time is number of nodes squared
  - Informed incremental search algorithm
- Mostly-known environment
- Can re-asses optimal path when new obstacles arise

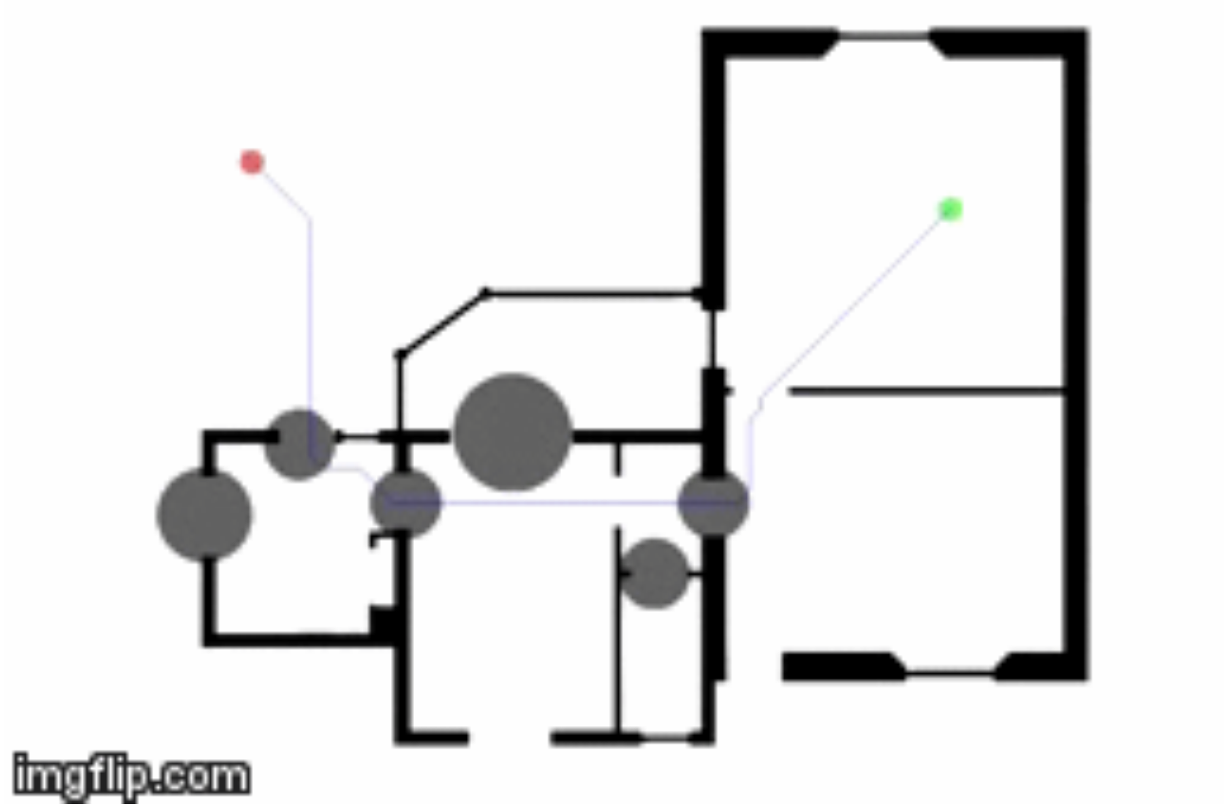
D* Path Planning Algorithm



$\epsilon = 2.5$ $\epsilon = 1.5$ $\epsilon = 1.0$

A simple robot navigation example. The robot starts in the bottom right cell and uses Anytime Dynamic A* to quickly plan a suboptimal path to the upper left cell. It then takes one step along this path, improving the bound on its solution, denoted by ε, as it moves. After it has moved two steps along its path, it observes a gap in the top wall. Anytime Dynamic A* is able to efficiently improve its current solution while incorporating this new information. The states expanded by Anytime Dynamic A* at each of the first three stages of the traverse are shown shaded.

D* Path Planning Algorithm

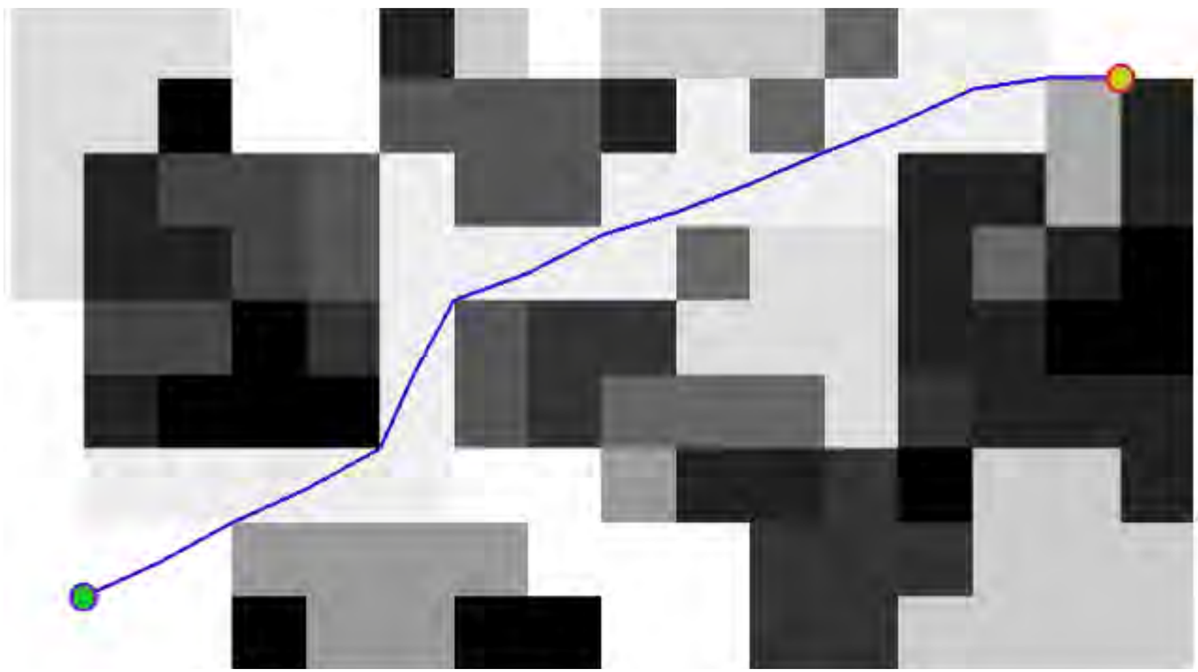


Courtesy of S. Koenig and M. Likhachev.

Field D*

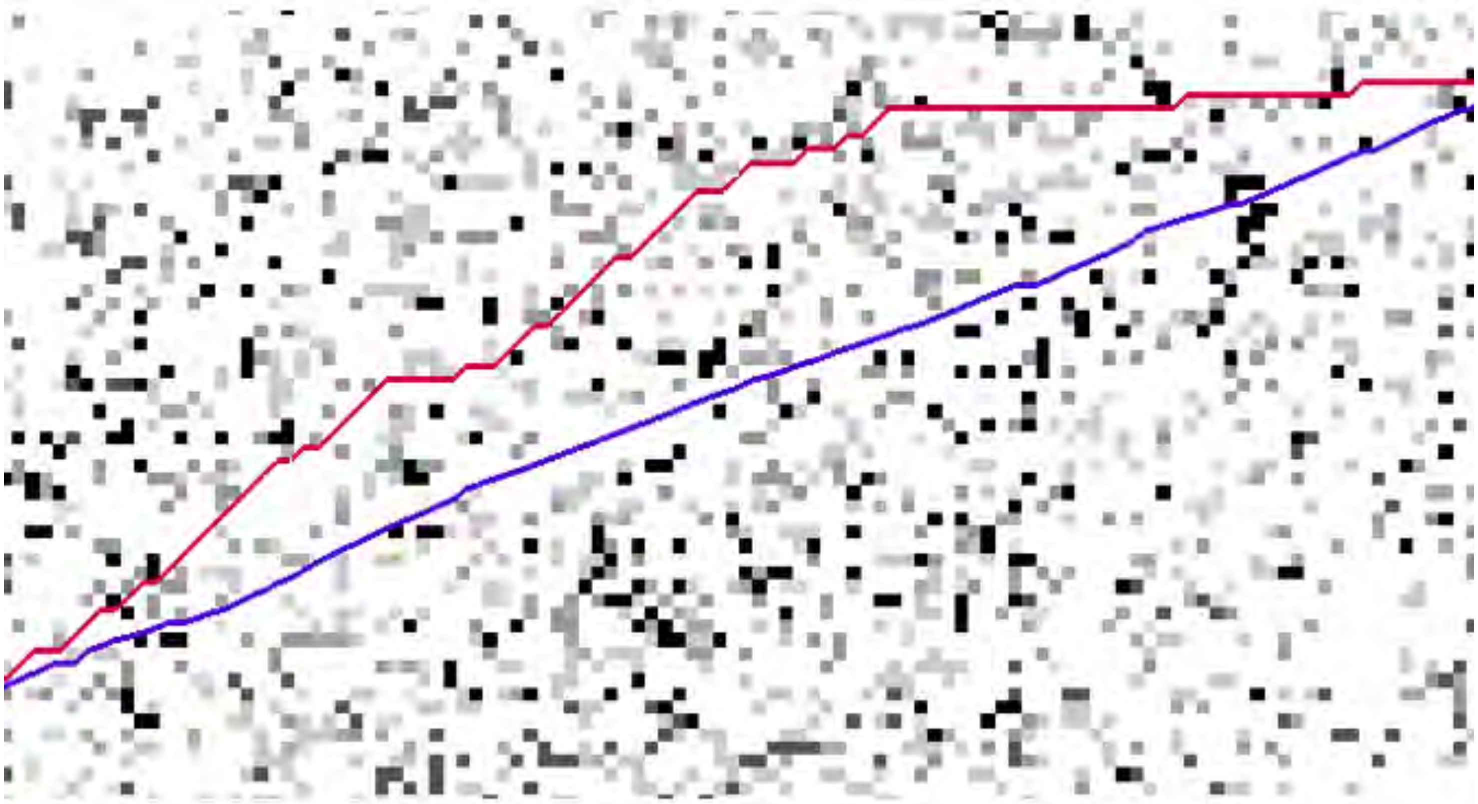
- Optimized D*
- Smooth paths in non-gridded environments
- Linear interpolation based (not grid based)
- Mostly-known environment
- Can re-asses optimal path when new obstacles arise

Field D* Algorithm



- A close-up of a path planned using Field D* showing individual grid cells. Notice that the path is not limited to entering and exiting cells at corner points.
- Photo courtesy of Dave Ferguson, Anthony Stentz.

Field D* Algorithm



- **D* Lite**
- **Field D***

Photo courtesy of Dave Ferguson, Anthony Stentz.

Field D* Algorithm

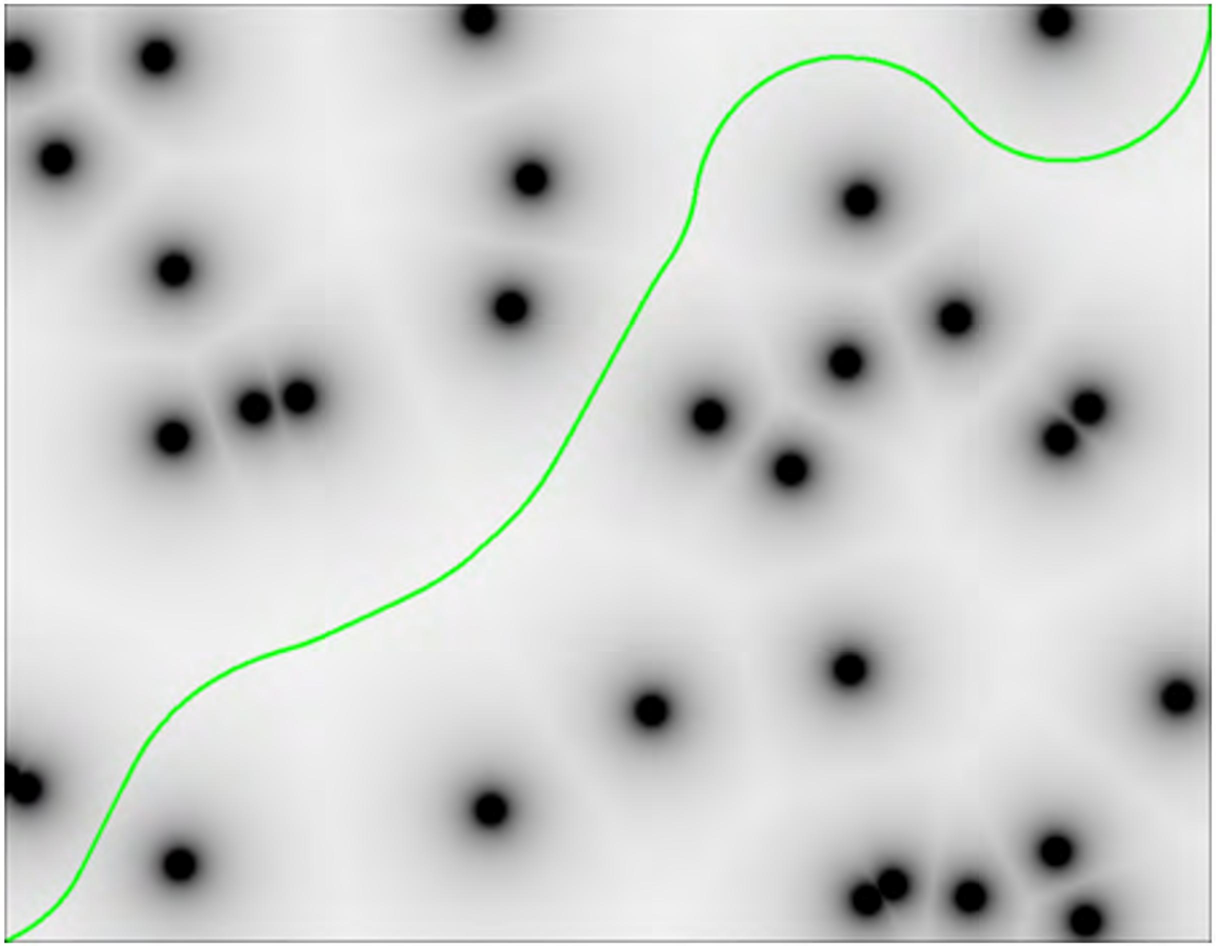


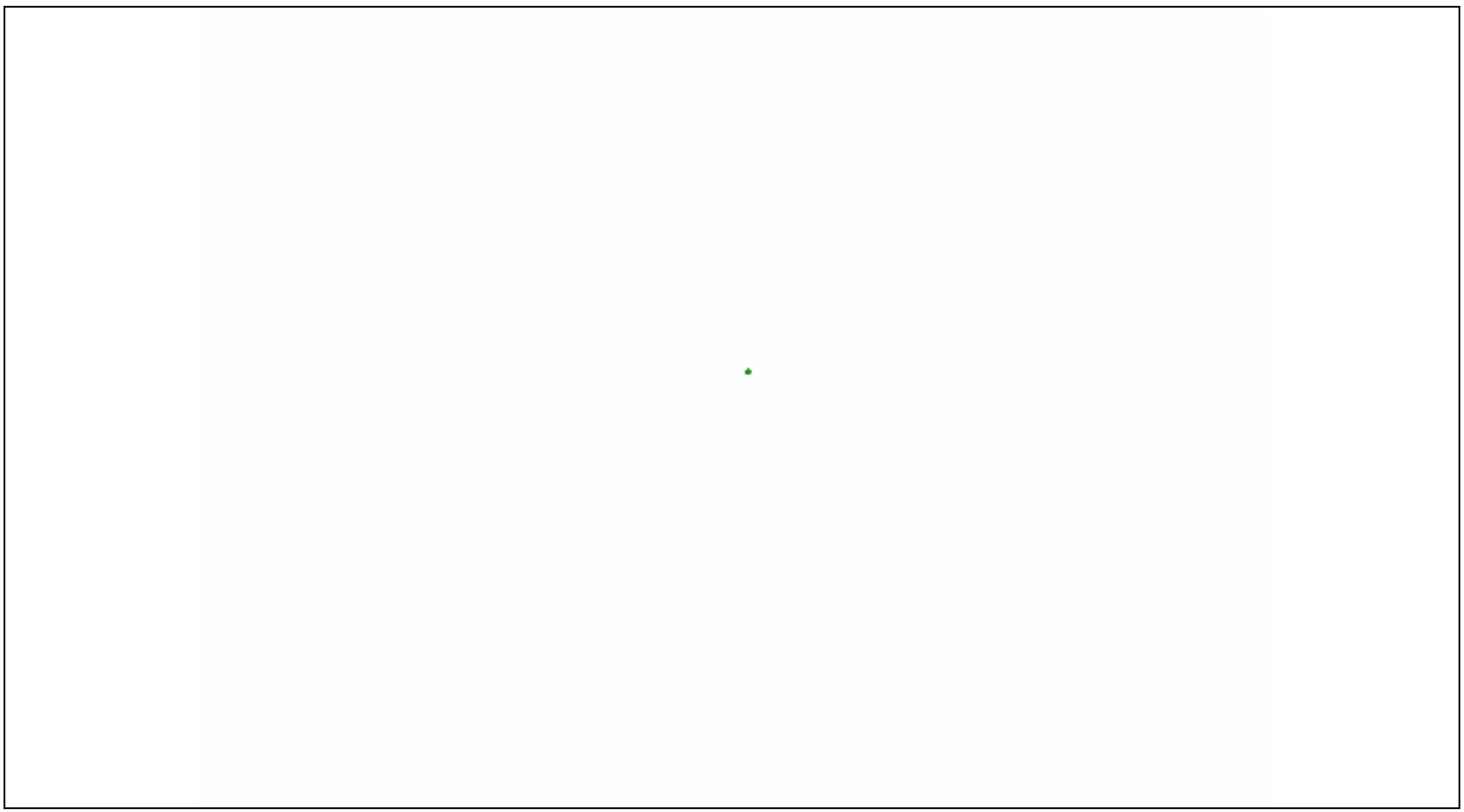
Figure shows planning through a potential field of obstacles. At high grid resolutions, Field D* produces smooth curves through both uniform and non-uniform cost environments; this is not generally true of standard grid based planners.

Photo courtesy of Dave Ferguson, Anthony Stentz.

RRT Planner

- Generates graphical, open-loop trajectories for nonlinear systems with state constraints
- Efficiently searches nonconvex, high-dimensional spaces by building space-filling trees or curves
- Mostly-known environment
- Good for handling differential constraints
- Utilizes Voronoi Regions
    - Larger regions are primary objectives, guide tree expansion
    - Probability of branch expansion is proportional to size of its Voronoi Region

Rapidly-expanding Random Trees (RRT)

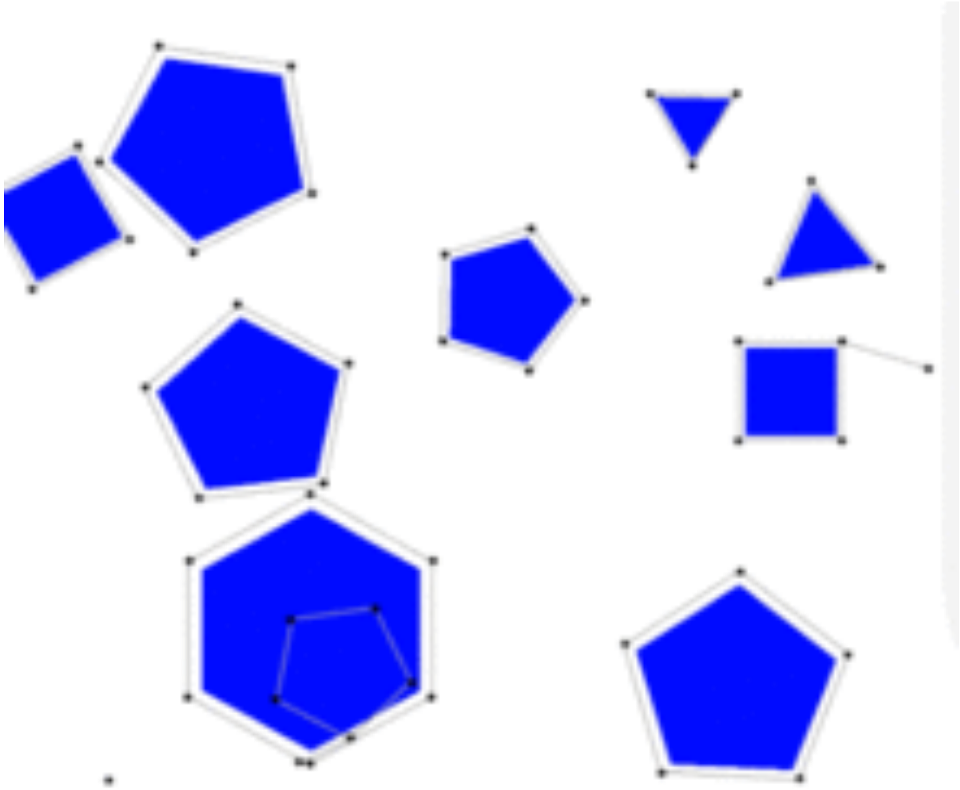


Iterations: 0 to 10,000.

Probabilistic Road Map

- Connects random samples from the robot configuration space that are in the free space to each other
- Produces a path plan graphically
- Two phase
    - Construction: randomly produces possible paths
    - Query: optimizes shortest path

Probabilistic Roadmap



Silly Autonomy

- Semi-Autonomous
- Operates using defined tasks or procedures
- Has some decision-making capability
- “Hands-off” actuation

Deliberation

- Once a plan is made, execution is non-trivial
- Do we execute the path as planned, or do we alter in-situ?
  - Who makes the decisions?
- DELIBERATION ON-BOARD
  - Details to follow later…

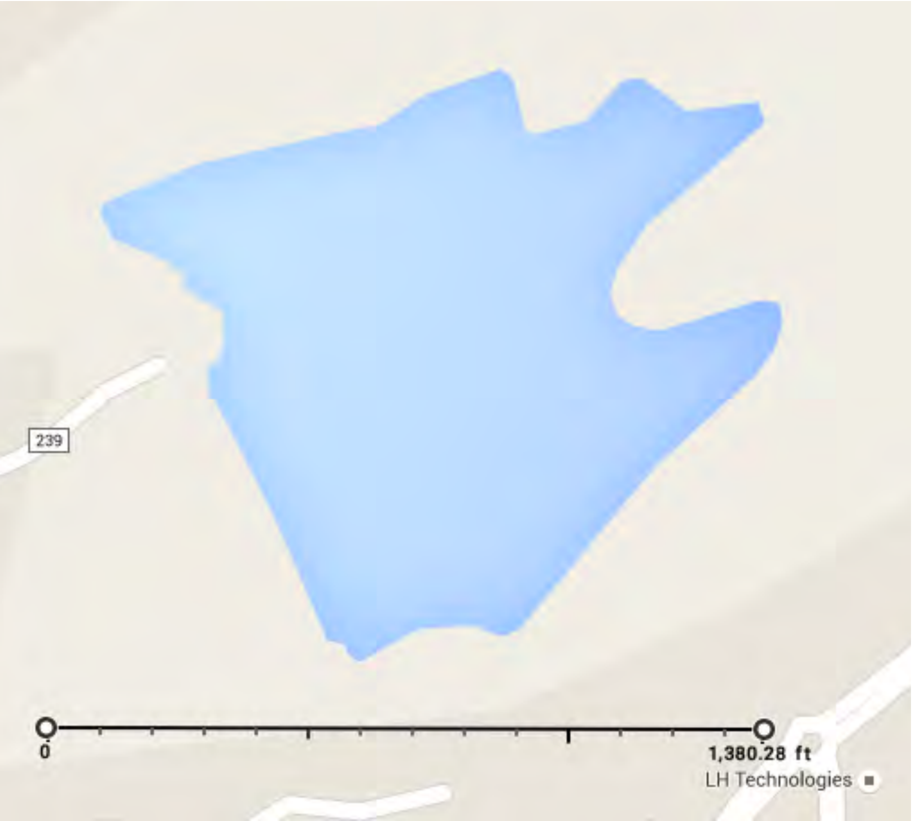
Repositories

- https://github.com/justinhj/astar-algorithm-cpp A*
- https://github.com/robEllenberg/stairclimbingRRT/blob/master/matlab/RRT.m RRT
- https://www.mathworks.com/matlabcentral/fileexchange/21443-multiple-rapidly-exploring-random-tree--rrt RRT
- https://github.com/nguyenchanhtruc2005/Path-Planning-Algorithm Field D*
- https://github.com/ArekSredzki/dstar-lite D* Lite
- http://www.mathworks.com/help/robotics/ref/robotics.prm-class.htm PRM
- https://github.com/apeeyush/motion-planning PRM

Exercises

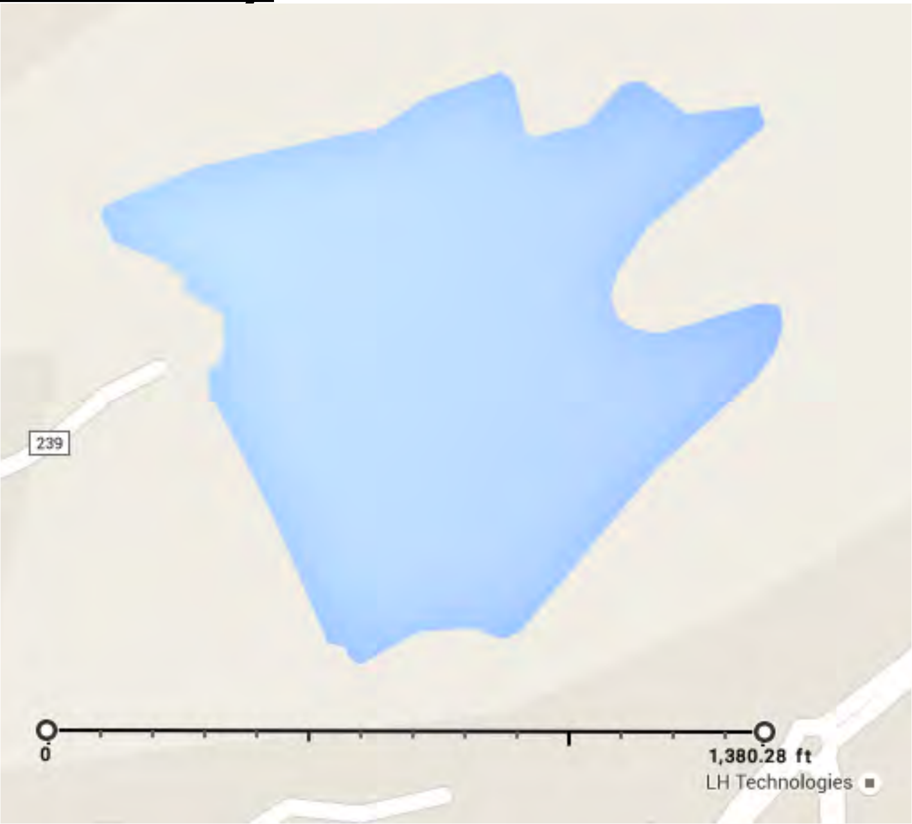
Example A: Rogers Reservoir, CO

An estimate of the volume of water is needed for city's drinking water reservoir. Devise a plan to gather data and compute the volume.



Scenario A: (cont.)

- What kind of vehicle should be used?
- What sensors are needed?
- Plan how the vehicle will accomplish the objective.



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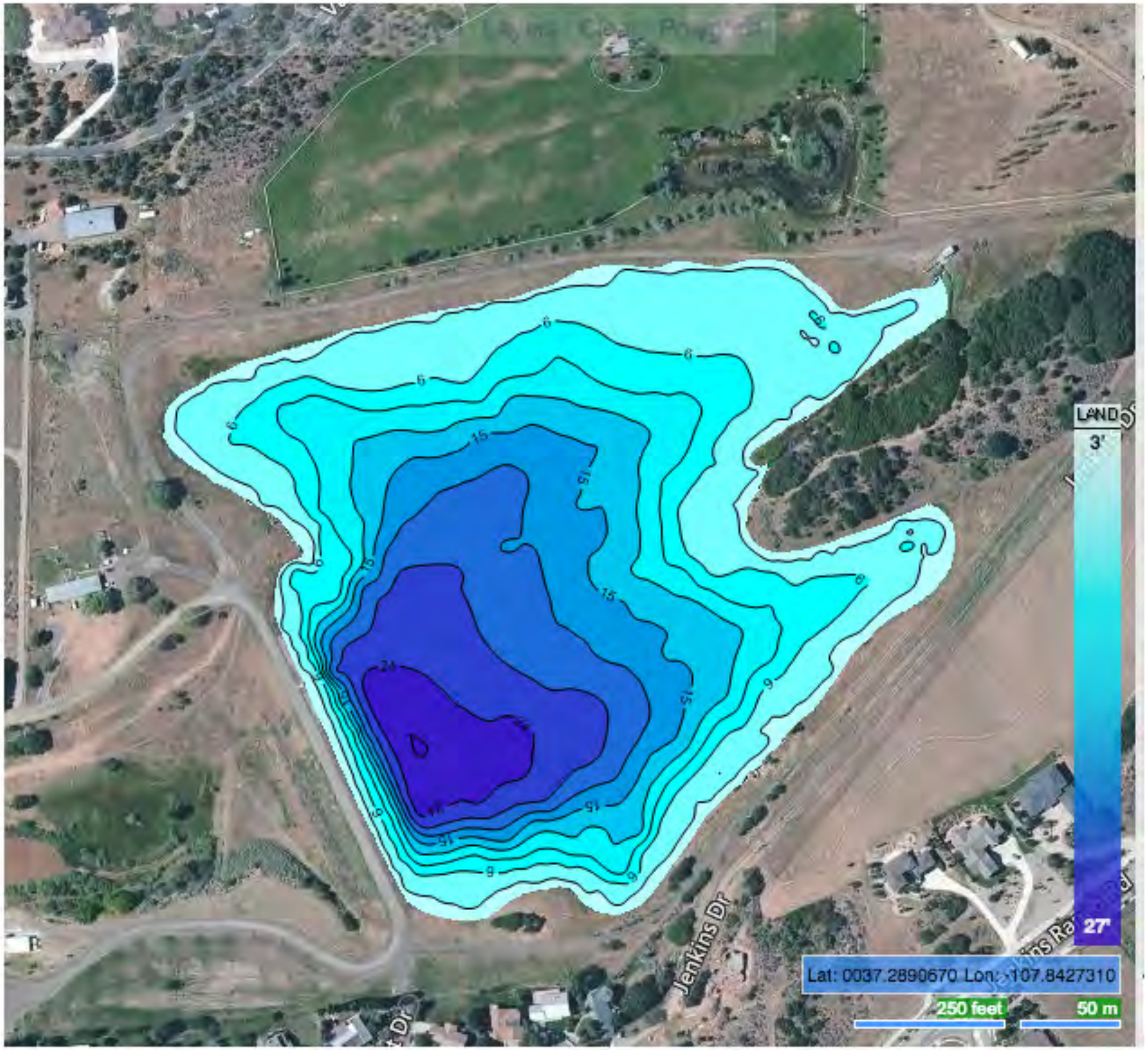

Scenario B: Live Oaks Reservoir, CA

Live oaks Reservoir nearby Harvey Mudd College (~2 miles) provides drinking water for the surrounding community. Estimate the volume of water within.

1. What kind of vehicle should be used?
2. Plan how the vehicle will accomplish the objective.

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Deployment Exercise

- We will use one of the vehicles to gather data this afternoon and compute the volume of water in Phake Lake in the Bernard Field Station.

Scenario 2: Taylor Reservoir, CO

- High mountain lake (~10,000 ft.)
- Cold temperatures
- Dam controlled

Survey water body for environment changes.

1. What kind of vehicle should be used?
2. Specify the type of control system.
3. Plan how the vehicle will accomplish the objective.


Taylor Park Reservoir
Taylor Park
Trading Post
742
742A
lor Park Reservoir
0
2.00 mi

Scenario C: Lake Tahoe, CA

Instable water availability has drastically affected Lake Tahoe. Find a way to estimate the volume of water. Examine the quality of its water. Design a system that would identify anomalies.

1. What kind of vehicle should be used?
2. Plan how the vehicle will accomplish the objective.
3. What are the logistical constraints that might exist?

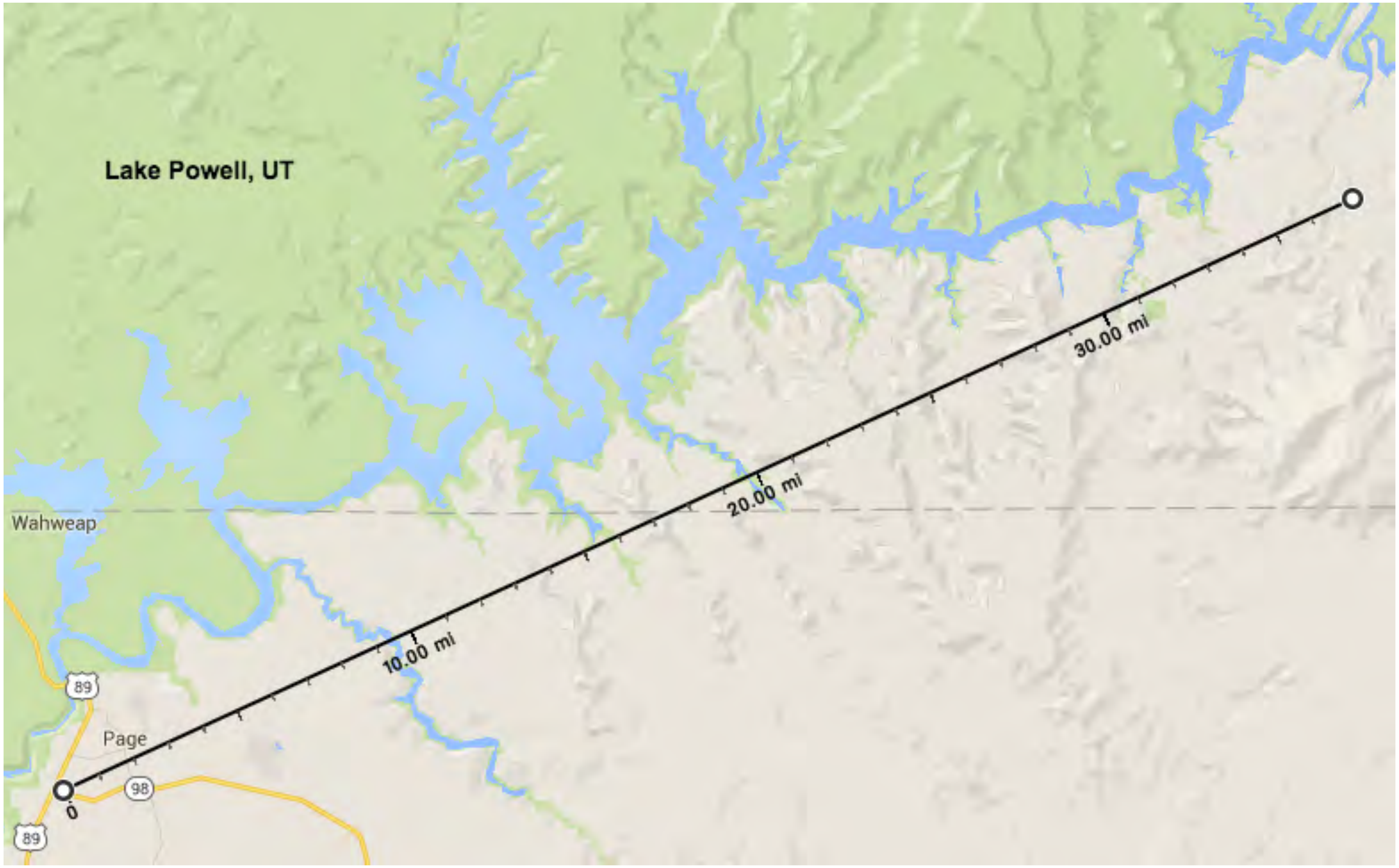

Incline Village
Kings Beach
28
89
Lake Tahoe
Nevada
State Park -
Sand Harbor
Olympic
Valley
28
Tahoe City
Lake Tahoe
89
Glenbrook
Homewood
Tahoma
50
Genoa
207
Stateline
89
South Lake
Tahoe
Camp
Richardson
206
0
10.00 mi
17.77 mi
Fallen Leaf

Scenario D: Lake Powell, UT

Built in 1963, Lake Powell is the second largest man-made reservoir in the U.S. (behind Lake Mead). It primarily serves as a supply for drinking and agricultural water. As a recreations site it receives visits from about 2 million people per year.

Estimate the volume of water within.

1. What kind of vehicle should be used?
2. Plan how the vehicle will accomplish the objective.
   a. Should a whole-body survey be taken?
   b. How would one account for traffic?


Lake Powell, UT
Wahweap
Page
89
98
89
0
10.00 mi
20.00 mi
30.00 mi

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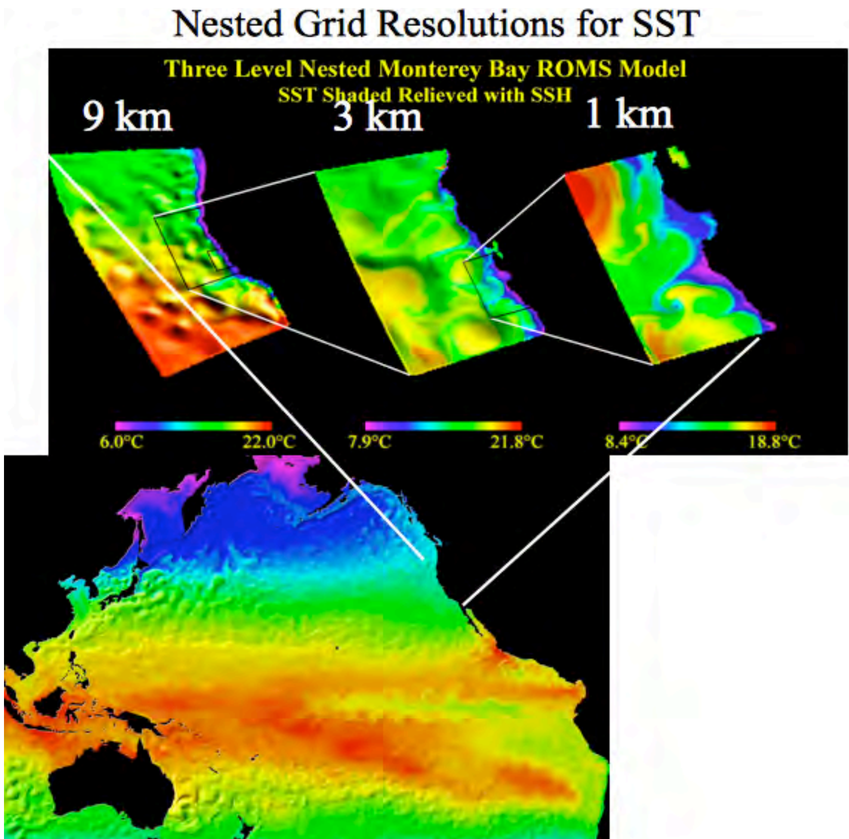
Dynamic Scenarios

- Previous examples examined/sampled a static feature with dynamic constraints.
- How do you examine a dynamic feature with dynamic constraints?
- What tools are available?
  - Ocean models
  - Sea surface currents



Scenario E: Open Ocean

- Track and collect daily information at a specific location within an evolving ocean process or feature
  - Two primary objectives:
    - Utilize ocean model predictions as a component in an end-to-end autonomous prediction and tasking system
    - Provide in situ measurements to a regional ocean model for assessment and to increase the skill of future predictions
  - Design daily missions of 12 - 20 hours
  - Iteratively track features over many days or weeks
  - Increase knowledge regarding the onset, life-cycle and ultimate mortality of HABs

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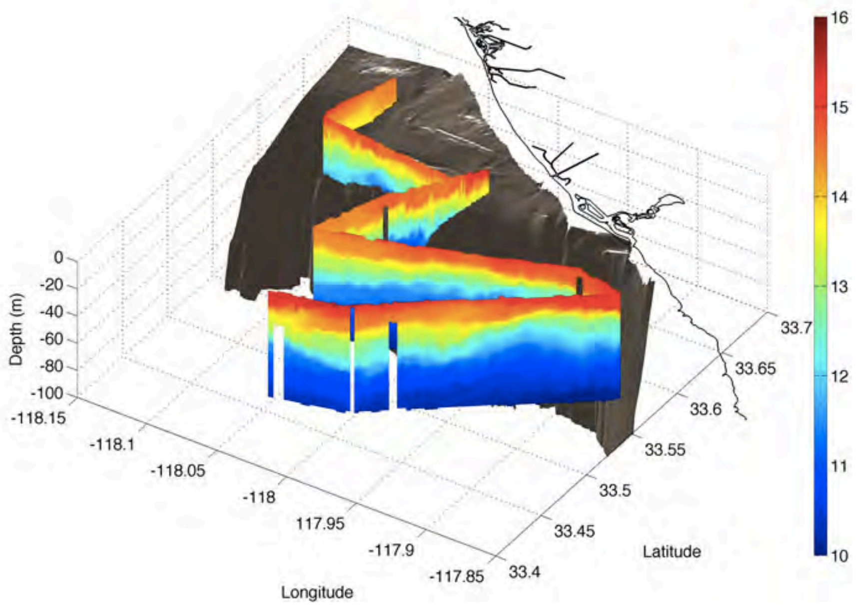
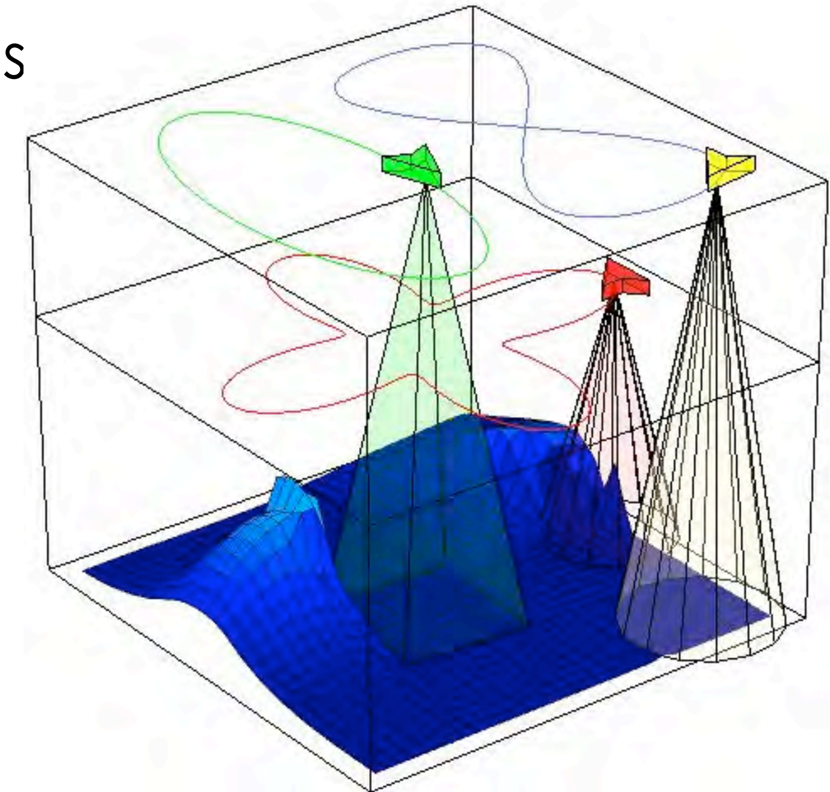
Scenario E: Open Ocean

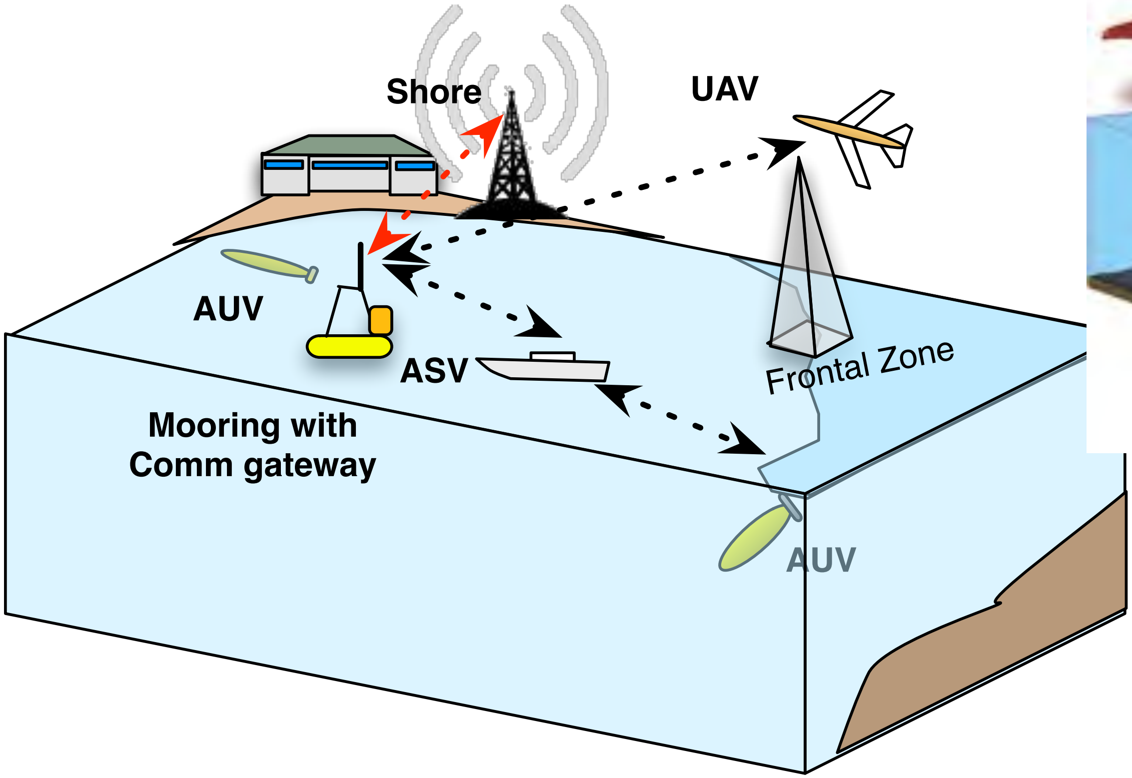
- What vehicle would you use?
- What control and planning is necessary?
- Describe some logistical issues

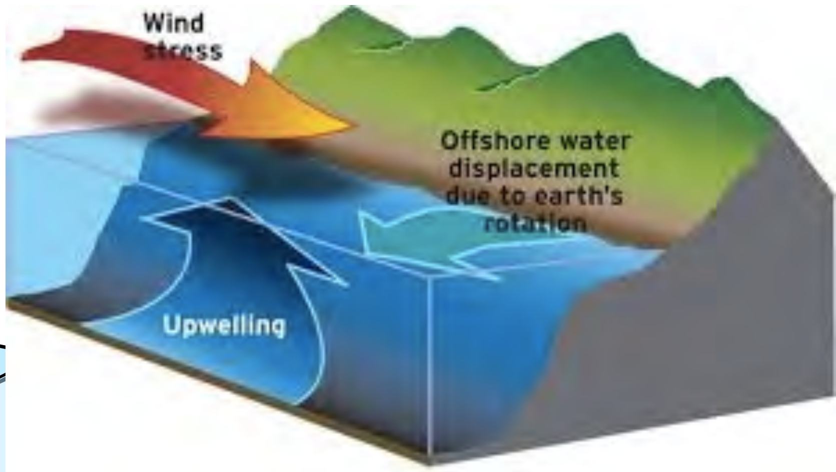


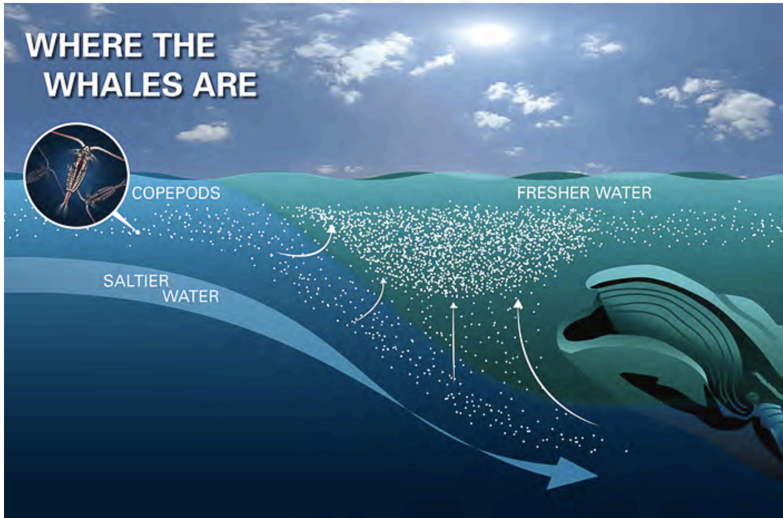


Ocean Location of Algal Blooms

Scenario F: Ocean Front Tracking







Scenario F: Ocean Front Tracking

- What vehicle would you choose?
- What control/planning is necessary?
- What logistical constraints might exist?