Cooperative Navigation for Autonomous Underwater Vehicles

Navigare 2011, 4 May 2011, Bern

Distributed Intelligent Systems and Algorithms Laboratory

disal.epfl.ch

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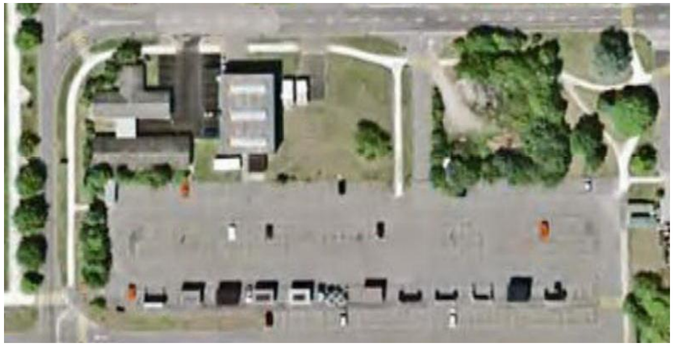
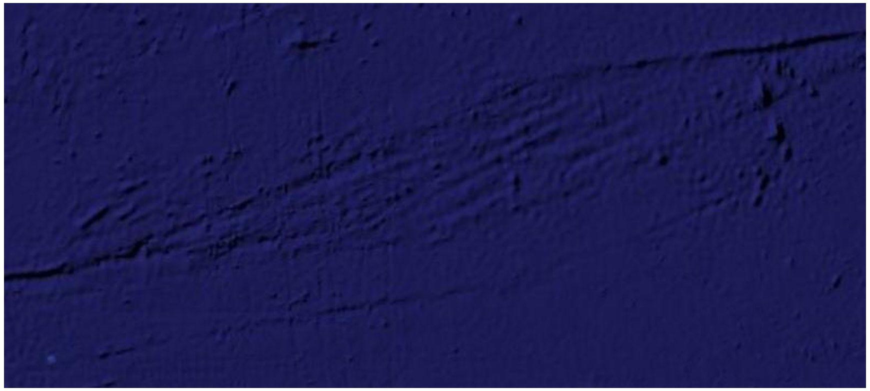
Why go under water ?

- Land, atmosphere and sea surface maps:
  - Many parameters obtainable through remote sensing
  - High-resolution
  - (Almost) complete coverage
  - Up to date
  - Cheap to obtain
- Subsurface maps:
  - **In situ** measurements required !
  - Low resolution
  - Sparse
  - Out-of-date (often by decades)
  - Expensive to obtain



46°31' N 6°34' E (60 m * 150 m)



38°12' N 155° 03' W (700 km * 1500 km)

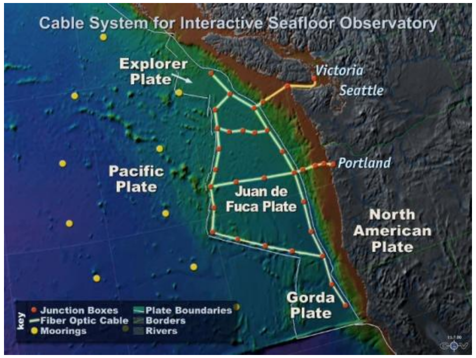
Outline

- What is an AUV?
- Types of AUVs
- Payloads (sensing/scientific and navigation)
- Challenges in underwater robotics (Communication, **Navigation**)
- Cooperative Navigation
- Applications

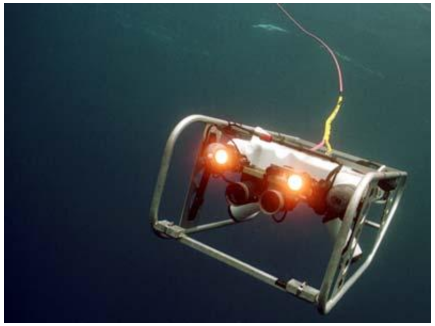
What is an AUV? – and what not

- **V**ehicle
  - Mobile
  - Resource-constrained
- **U**nderwater
  - Hostile environment
    - Pressure
    - Corrosion
    - Fouling
  - Potential loss of vehicle
- **A**utonomous
  - Not remote controlled
  - On board decision making
  - Limited intervention capabilities







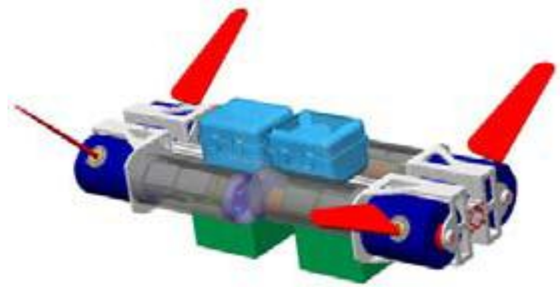
Types of AUVs – active propulsion

Pictures courtesy of University of Hydroid, Ocean Server

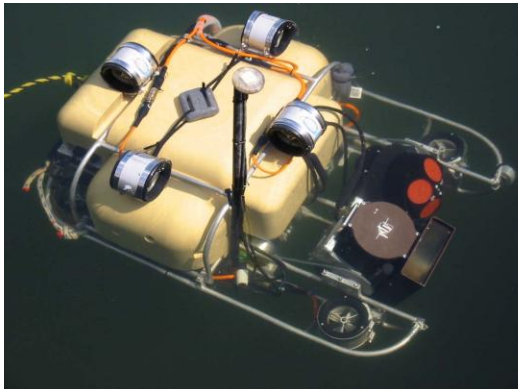
	Low end AUV	Top end AUV
Dimensions	0.7 m length * 0.1 m diameter	5 m length * 0.7 m diameter
Price	$15’000	$2’000’000
Top speed	1 m/s	3 m/s (15 m/s ?)
Max depth	100 m	11’000m
Endurance	2h	24h (72h)

Types of AUVs – active propulsion

Cetus (Lockheed Martin, USA)



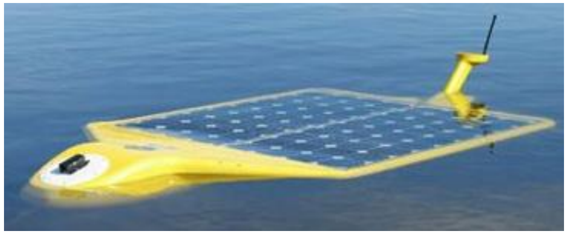
Flapping foil AUV (MIT)



Hovering **AUV** (MIT/Bluefin)

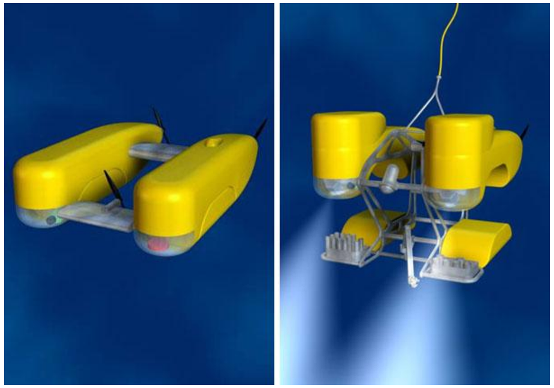
Gavia (Hafmynd, Iceland)

SAPPHIRES (Saab, Sweden)



Solar AUV (AUVSI, USA)

SeaBed (WHOI, USA)

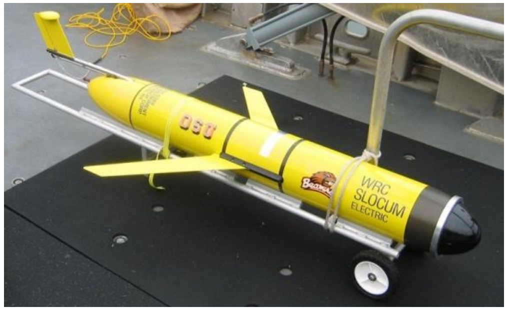


Nereus, hybrid AUV/ROV (WHOI)

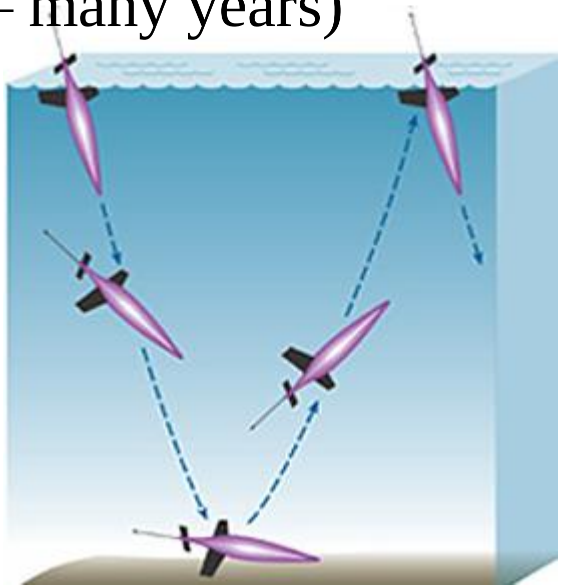
http://auvac.org/resources/browse/configuration/

Types of AUVs – buoyancy driven

- Vehicle changes buoyancy from positive to negative and back
- Attached wings cause forward motion
  - Maximum depth (2000 m)
  - Forward speed (0.3 m/s)
  - Range: 5000 km (and more)

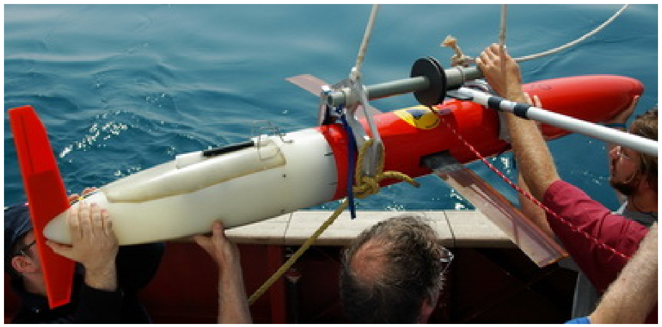


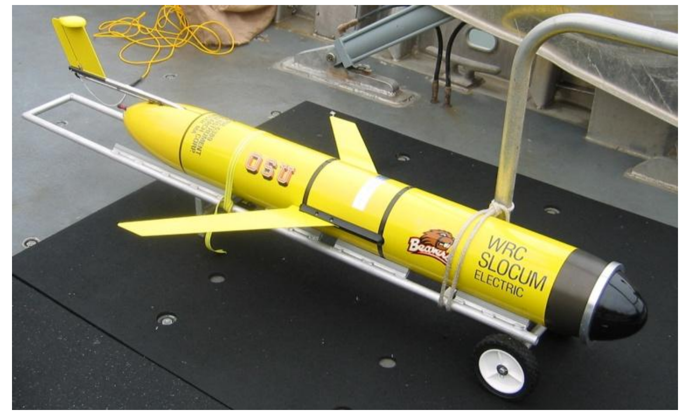
- Very long endurance vehicle (6 months – many years)
  - Very low power consumption
  - Limited sensing capabilities
  - Limited navigation sensors
  - Limited controllability
  - Bio fouling becomes relevant
- Price: $100’000



Pictures courtesy of University of Washington/APL, Webb Research

Types of AUVs – buoyancy driven





Pictures courtesy of University of Washington/APL, Webb Research

External sensing payloads

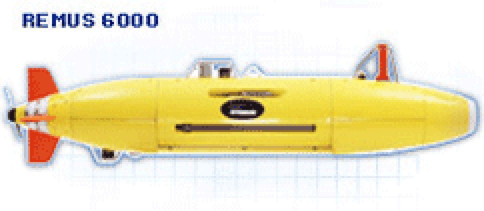
- Video Camera
- Sophisticated sonar (multi-beam, SAS)
- Active acoustics (sub-bottom profiler)
- Sampler
- Manipulator
- Large chemical sensors (CO_2)
- Computationally expensive sensors

- Camera (still)
- Simple sonar (side-scan, pencil beam)
- Magnetometer
- Small chemical sensors (O_2, chlorophyll)

- Passive acoustics

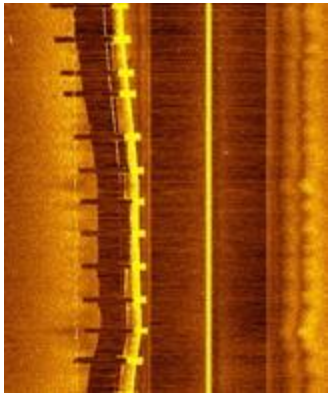
- **C**onductivity, **T**emperature, **D**epth
- Fluorescence
- Backscatter

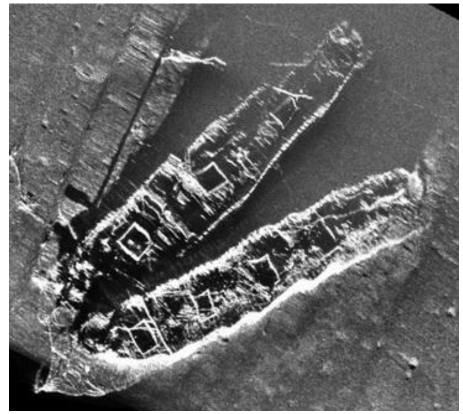
Size and power requirements



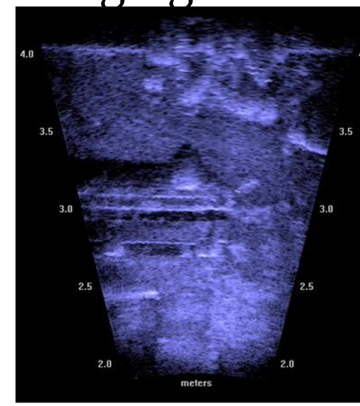
External sensing payloads

- Side-scan sonar



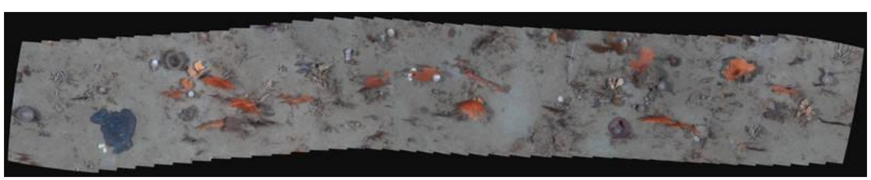


- Imaging sonar



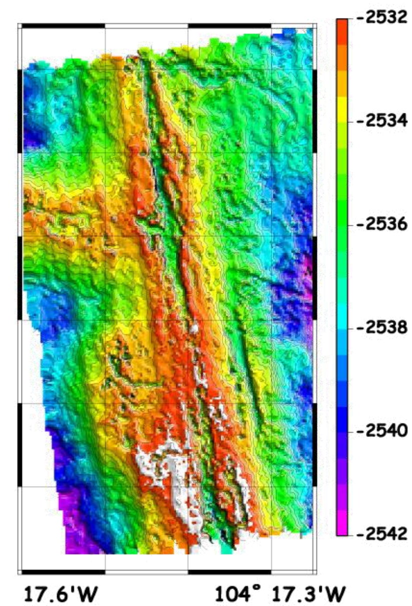
- Photos





Pictures courtesy of Dana Yoerger, Hanu Singh, Hafmynd, Bluefin, IMOS Australia

- Multi-beam sonar:



Navigation payloads

- Fiber-optic north seeking gyro
- Sophisticated INS

- **D**oppler **V**elocity **L**ogger (DVL)
- Simple **I**nertial **N**avigation **S**ystem (INS)
- **L**ong / **U**ltra-**s**hort **B**ase **L**ine

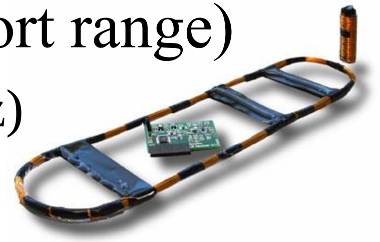
Size and power requirements

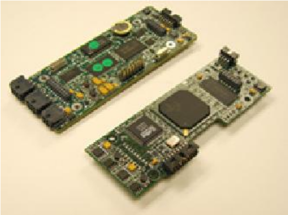
- GPS
- Depth
- Simple accelerometer (orientation)
- 3 axis magnetic compass

Pictures courtesy of University of Hydroid, Ocean Server, Webb Research

Challenges - communication

- What does not work
  - Very High Frequency, Ultra High Frequency radio (MHz) (Wifi, Bluetooth, etc.)
  - Extremly High Frequency radio (GHz) (GSM, Satellite)
  - Infrared
- What "sort-of" works (short range)
  - Very Low Frequency radio (kHz)
  - Green/blue LEDs
  - Directed laser
  - Return current
- What works
  - Extremly Low Frequency (Hz)
  - Acoustic



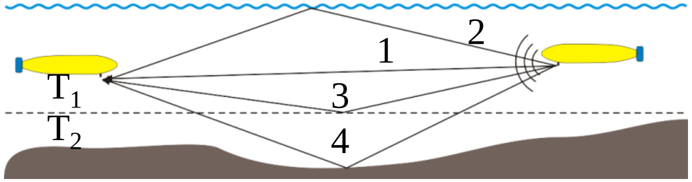


Pictures courtesy of WHOI, MIT, Grumman, ANU, US Navy

Acoustic communication

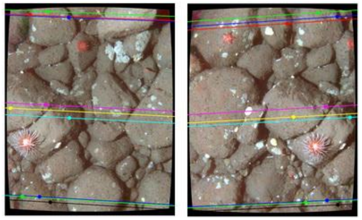
- Acoustic modem (WHOI, Benthos, MIT, …)
- Range: O(100 m) – O(1-10 km)
- Data rate: O(bytes/s) – O(kbytes/s)
- Energy expensive O(1 Joule/byte)
- Small channel capacity (one modem at a time)
- Strong temporal and local variations of channel
- Interference with navigation equipment (LBL, DVL)
- Strong acoustic signature
- Multipath
  - Direct (1)
  - Surface bounce (2)
  - Thermocline Bounce (3)
  - Bottom bounce (4)

32 bytes every 10s !

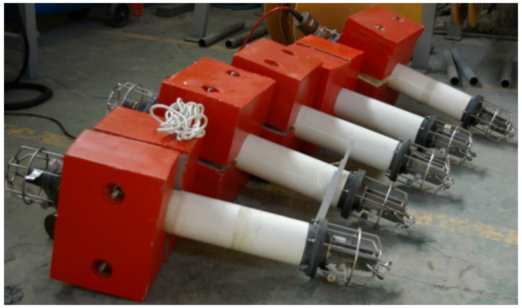


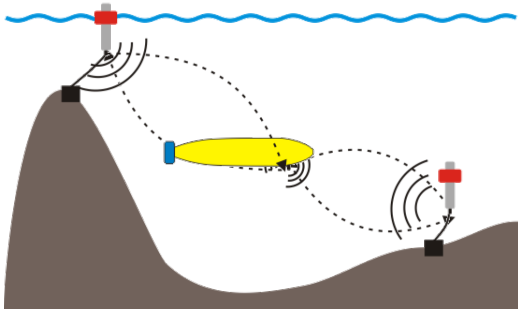
Underwater navigation

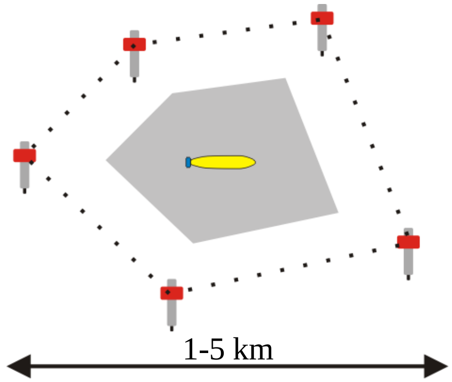
- Absolute positioning
  - GPS (only when surfacing)
  - LBL:
    1. AUV send query ping to all beacons
    2. Beacon 1 responds
    3. Beacon 2 responds
    4. Vehicle computes position
    - Beacon field needs to be predeployed
    - Operating area is limited by to a few km^2
  - Vision-aided navigation



Picture courtesy of Ryan Eustice





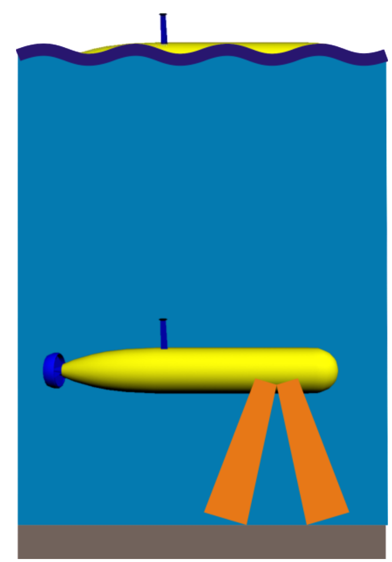


Underwater navigation

- Relative positioning:
  - Depth sensor → underwater navigation is a 2D problem
  - Magnetic compass ($1k; accuracy: 1-3 degrees)
  - Fiber Optical Gyro (FOG) ($40k; accuracy: 0.1 degree)
  - Inertial Navigation System
  - Doppler Velocity Logger (DVL)
    - Provides 2D speed over ground
    - Maximum distance to seafloor: 30 m – 200 m

Best case AUV navigation accuracies
    - Surface: GPS
    - Near seafloor: 0.1% distance traveled
    - Mid-water column: 1.5 km/h drift

Pictures courtesy of RDI, IXSEA

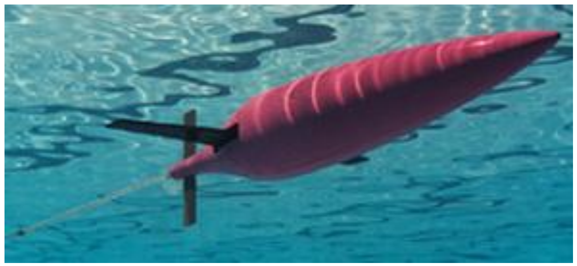


Cooperative navigation

Different vehicles have different navigation sensors with different accuracies

Navigation error [%/distance travelled]

10%



Glider
(compass + speed estimate)

1%

AUV
(DVL/compass based navigation)

0.1%

AUV deluxe
(INS with fiber- optic gyro)

0%

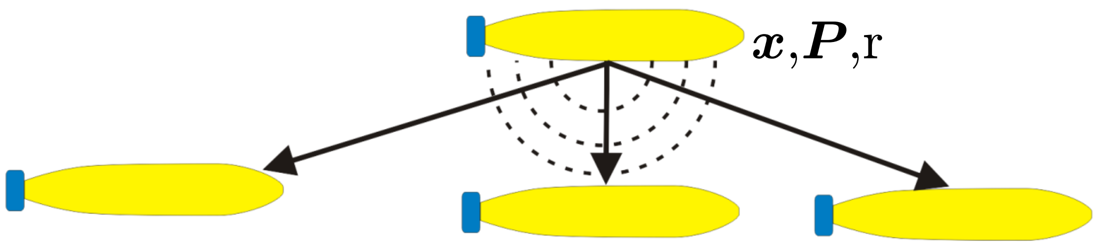
Surface vehicle
(GPS)

Pictures courtesy of University of Washington/APL, Hydroid, Kongsberg

Cooperative navigation

In heterogeneous teams:

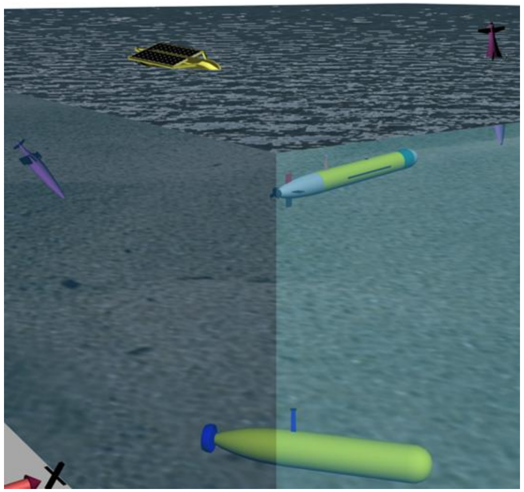
"Use other vehicles' position estimate to update my own"



- Each vehicle is outfitted with an acoustic modem
- Vehicle broadcast
  - Position estimate $\boldsymbol{x}$(x,y, depth, course, speed)
  - Certainty estimate $\boldsymbol{P}$
  - (additional information)
- Inter-vehicle measurement (range r is available)

Cooperative navigation

- Ad-hoc:
  - Heterogeneous group of vehicles
  - Broadcast when position uncertainty low
- Hierarchical:
  - Task specific AUVs
  - Dedicated communication and navigation aids (CNA) (expensive navigation sensors, frequent surfacings, few vehicles) → **master**
  - Mission specific AUVs (cheap navigation sensors, no surfacing, many vehicles) → **slave**



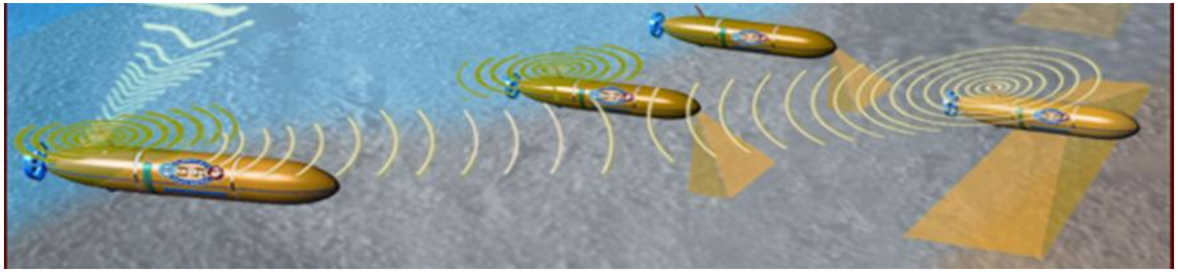
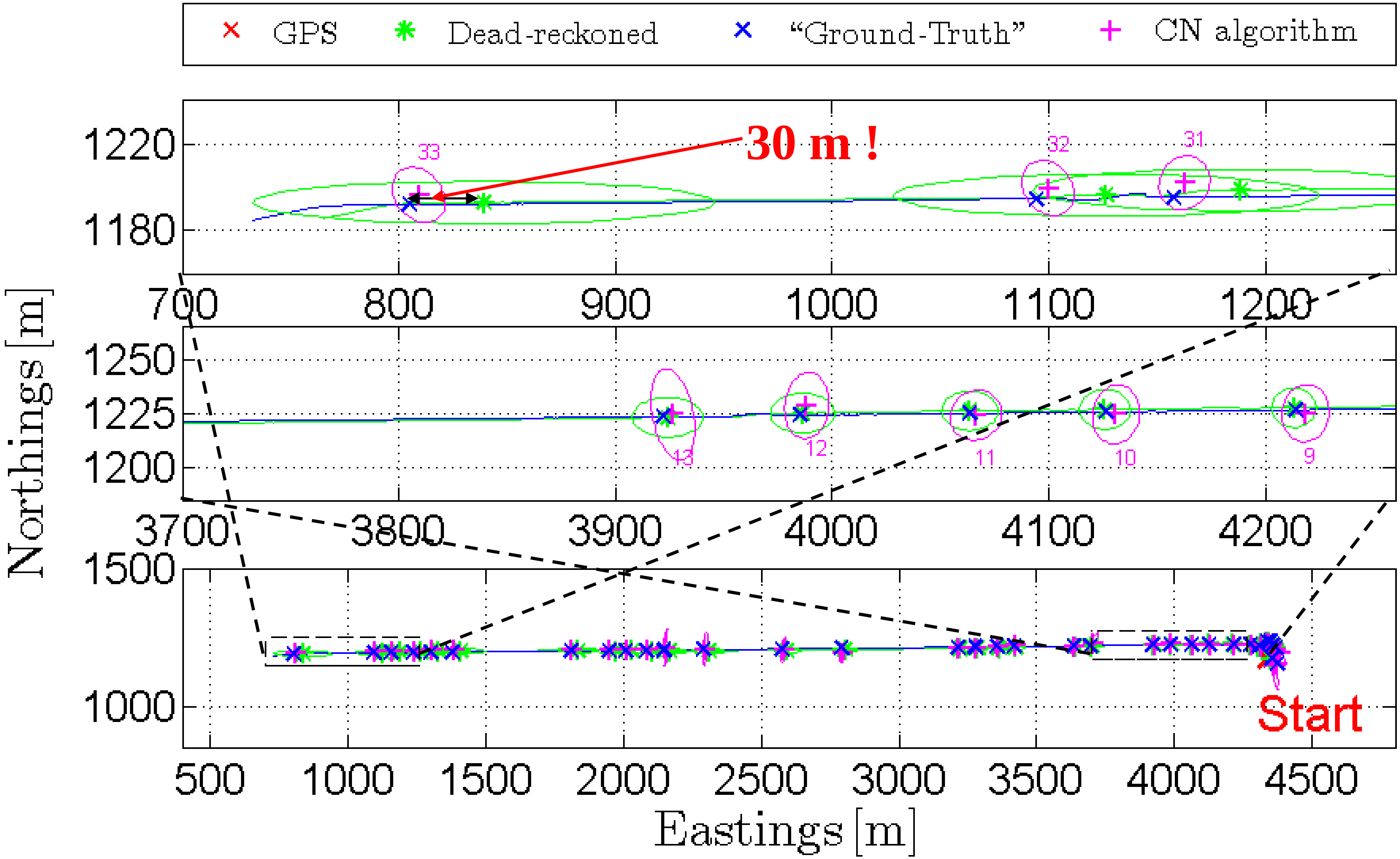


Illustration courtesy of Bluefin Robotics

Cooperative Navigation experiment

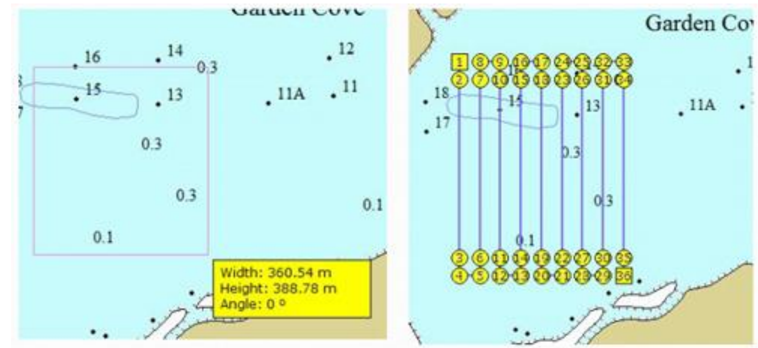
- Panama City, FL, December 2006
- Mine Counter Measure (MCM)
- 2 Autonomous Surface Crafts
- 1 AUV:
  - Bluefin 12’’
  - Navigation: depth gauge, DVL, INS, compass
  - Acoustic modem
- ASCs followed AUV
- ASCs broadcast GPS position, AUV got range to ASC

Cooperative Navigation experiment

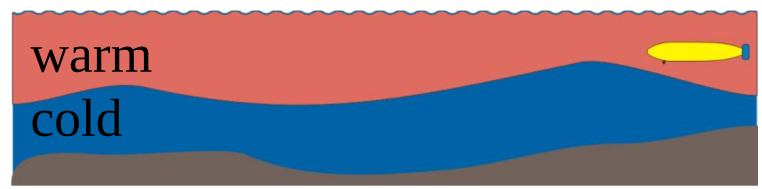


Applications

- Static missions
  - Pre-programmed
  - List of waypoints
  - Non-adaptive
- Adaptive missions
  - Partially pre-programmed
  - List of behaviors
  - Vehicle adapts depending on sensor reading
- Multi-vehicle missions
  - Pre-programmed or adaptive



Pictures courtesy of Ocean Server



Conclusions

- AUVs face difficulties not encountered in other environments
- Expensive hardware, but cheaper alternatives are underway
- Experiments require careful planning and execution

- Most difficult terrain to navigate in
- Drift will always get you
- Absolute position update requires extensive infrastructure **OR**
- **Cooperative navigation**

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FÉDÉRALE DE LAUSANNE

Thank you !