CS-417 INTRODUCTION TO ROBOTICS AND INTELLIGENT SYSTEMS

Underwater Robotics

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What are robots best suited for?

- Environments that are dangerous.
- Environments that are inaccessible.
- Environments that are taxing.
- Environments are expensive to access.
- Environments that are inhospitable.

- **Undersea: inaccessible, dangerous, costly, demanding.** As we all know, most of the world is undersea, yet it's the environment on earth we understand the least well!

Coral Reefs

Oceans: 70% of earth's surface.

Reefs: Greatest diversity / area of any marine ecosystem

- 4-5% of all species (91 000) found on coral reefs

Significant to the health of the planet:

- 1/2 of the calcium that enters the world's oceans /year is taken up and bound into Coral Reefs as Calcium Bicarbonate

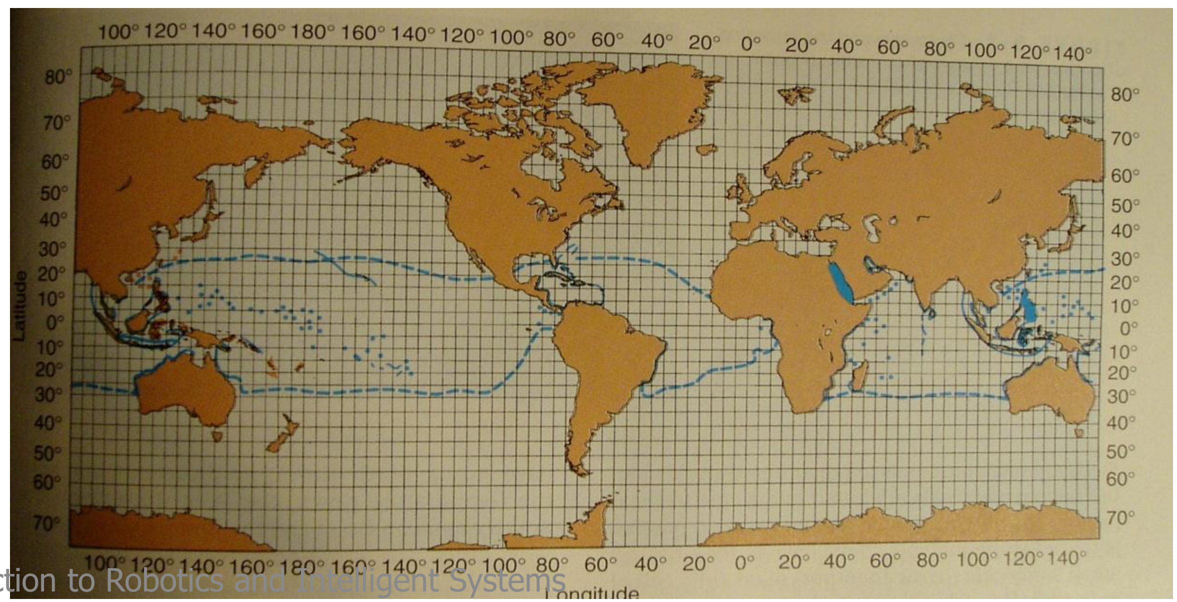
World Distribution

Coral reefs are found in polar, temperate and tropical waters

Highest diversity of species in tropics

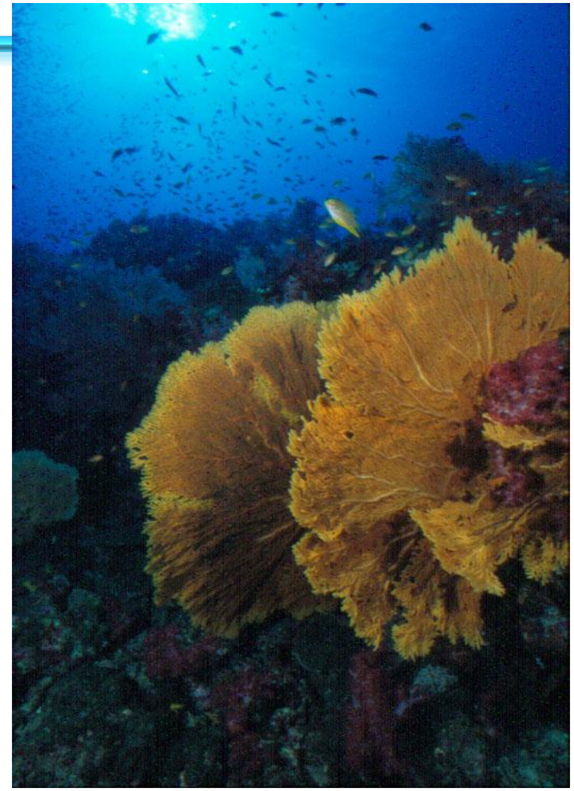
Found in 20 degree C surface isotherm

Optimal temperature for coral is 23-25 degrees C.

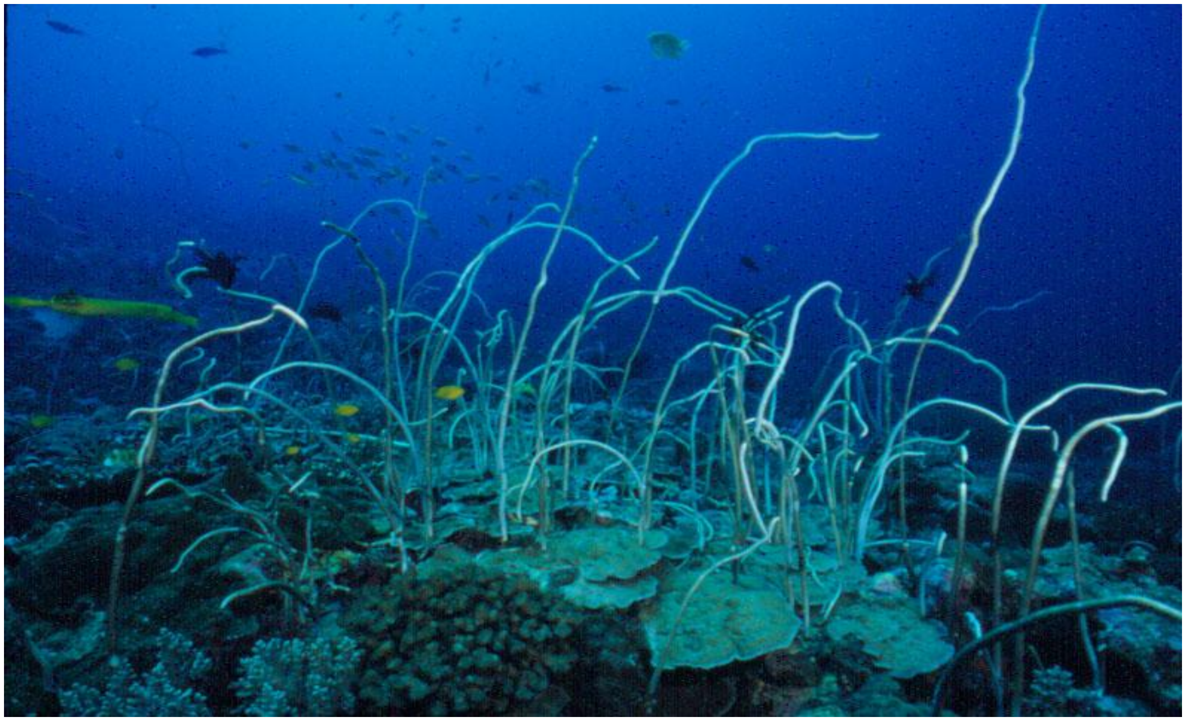


Atlantic

Sea fan



More common in Atlantic:



Sea Whip

Dominant coral types:
Branching coral (3 sp)
Fire Coral

Why Study Coral Reefs?

- Most biologically diverse and sensitive marine ecosystem
- Dramatically altered by humans
- By 1998, 27% of reefs were destroyed
  - 16% was from coral bleaching event (El Nino)

Coral Reefs

- Reefs are regions of *exceptional* biodiversity.
- 20% of the world's reefs have been destroyed.
- 24% of reefs are under imminent threat of collapse due to human pressure, 26% under longer term threat of collapse!

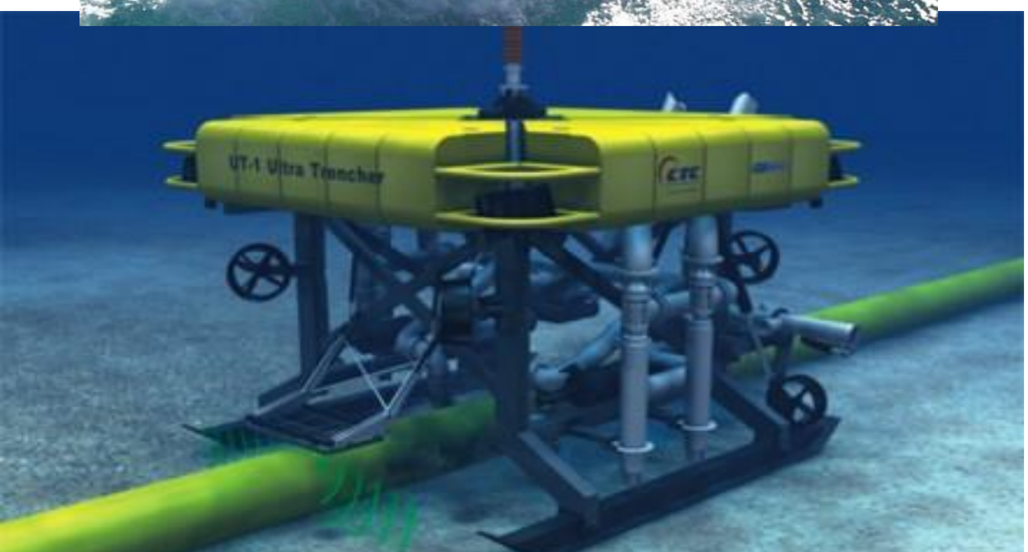
  Dec. 2005 there was a terrible coral bleaching (and destruction) in the Caribbean.

  95% of Jamaica's reefs are dead or dying.
- If we want to make things better, we need to be able to measure the changes!
- This is taxing, error-prone, tiring and dangerous.

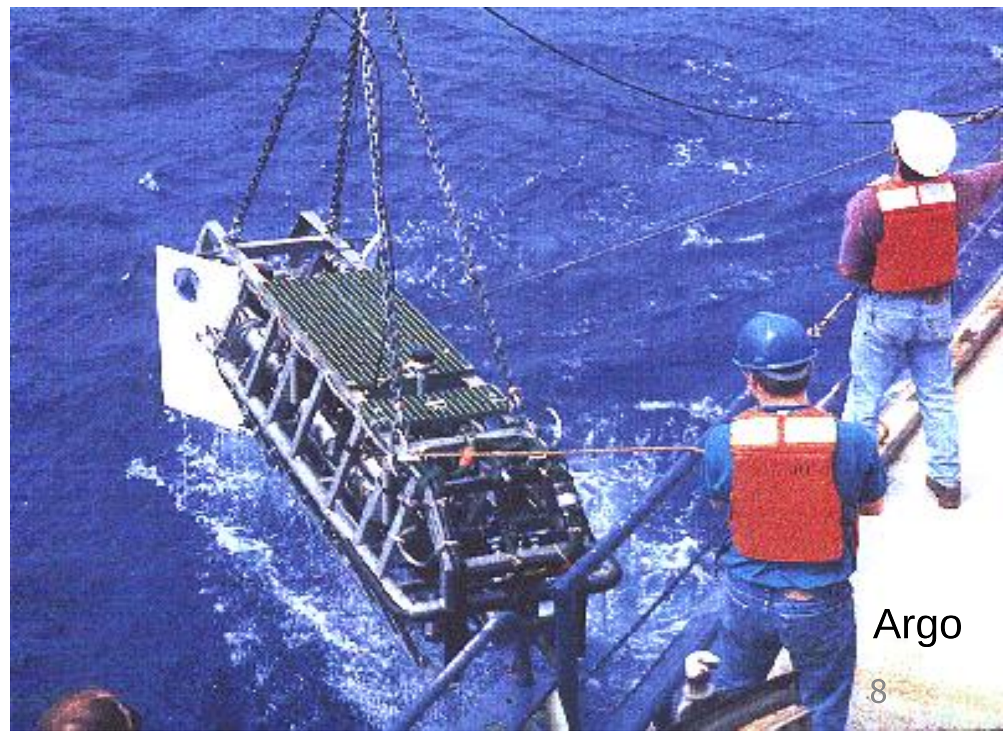
Underwater vehicles

Autonomous Benthic Explorer (ABE)

1200 pounds and a little over 2 meters long.



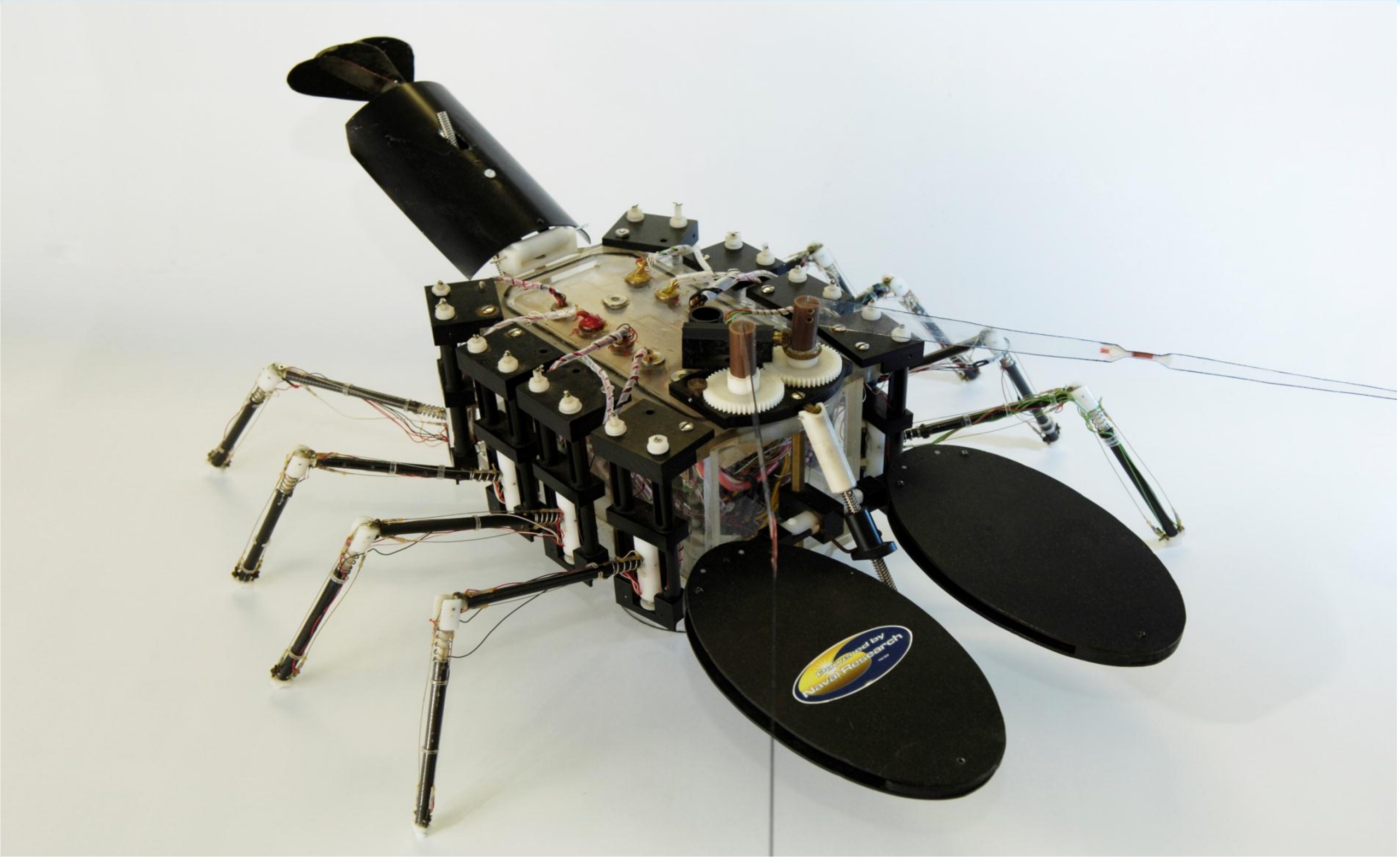
UT-1 Ultra Trencher 7.8 x 7.8 x 5.6 meters



Argo

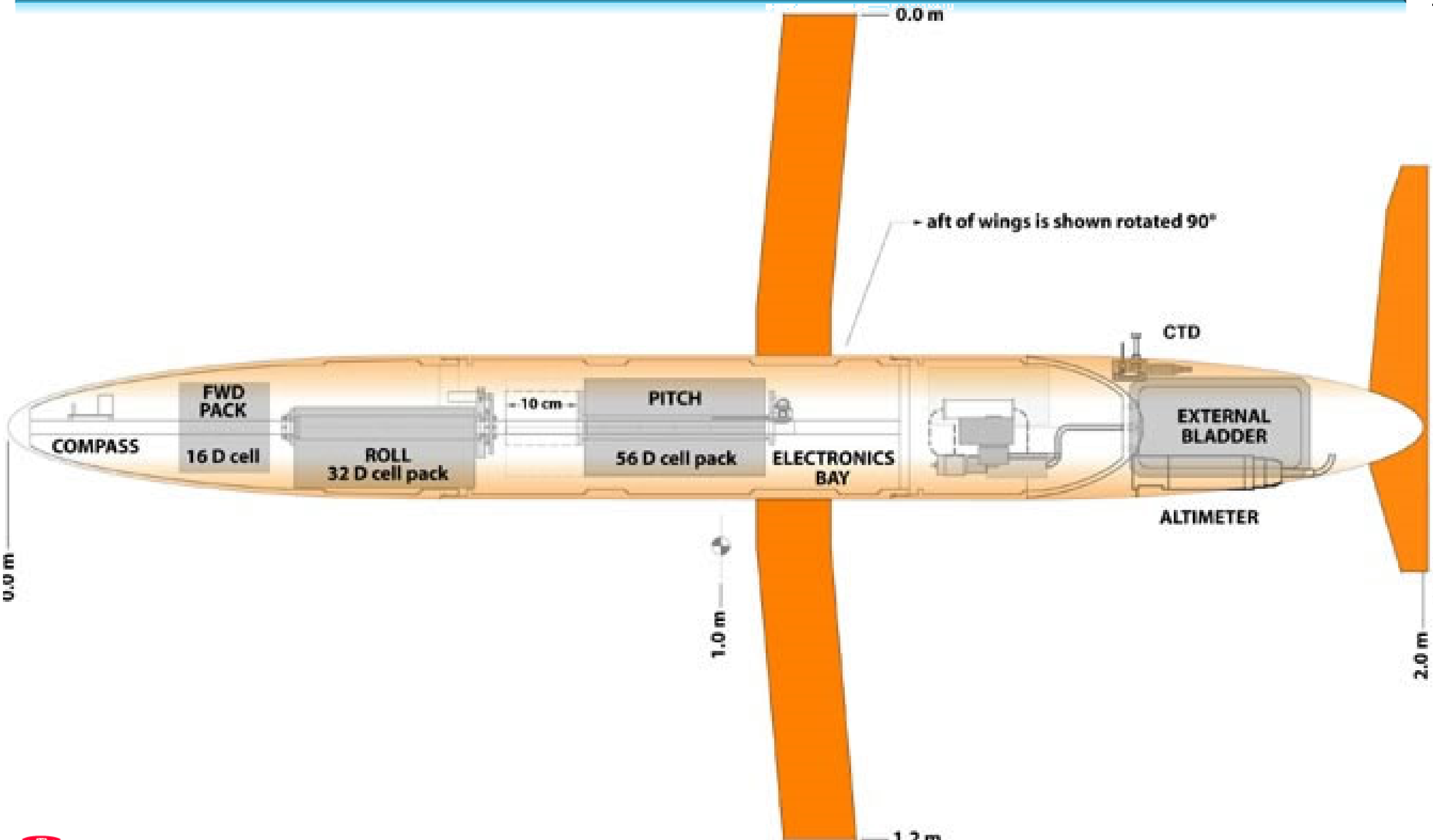
Turtle like Robot

Lobster like Robot



Glider UW Robot

Glider UW Robot



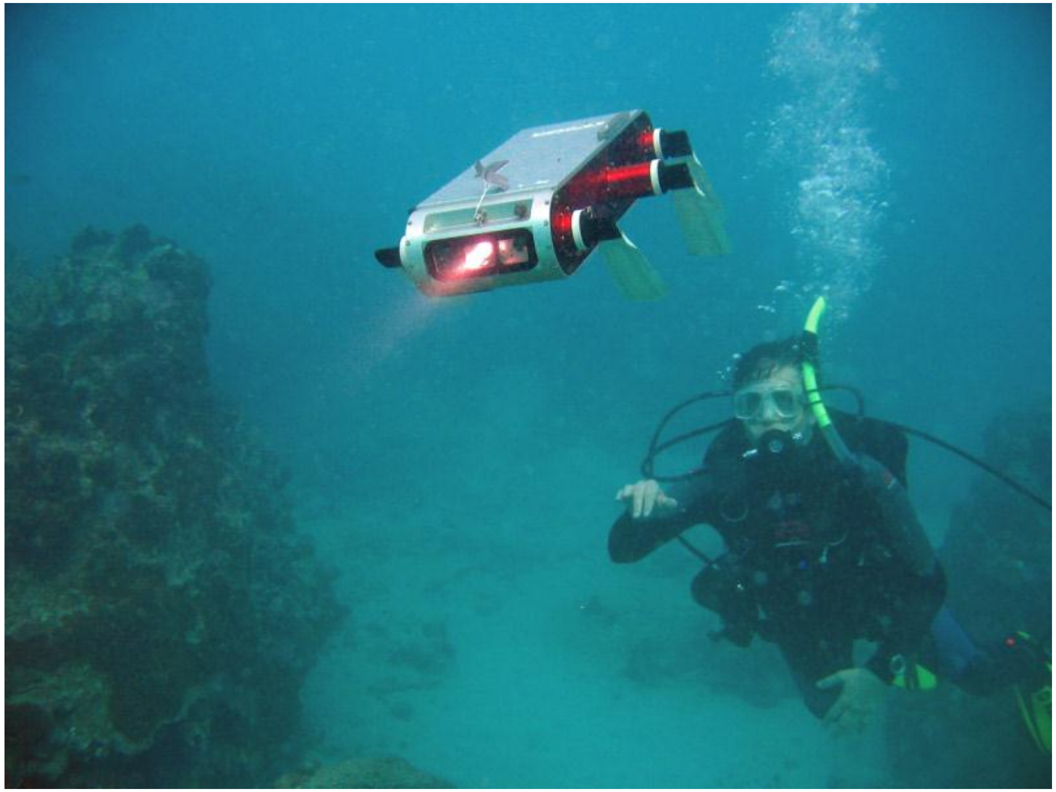
Enabling Autonomous Capabilities in Underwater Robotics

- This work was presented at the International Conference on Intelligent Robots and Systems (IROS), 2008, at Nice, France

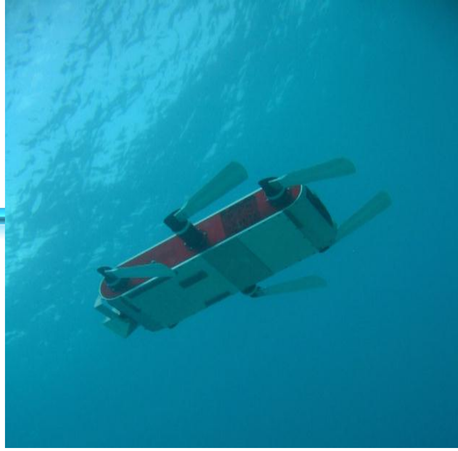
Overview

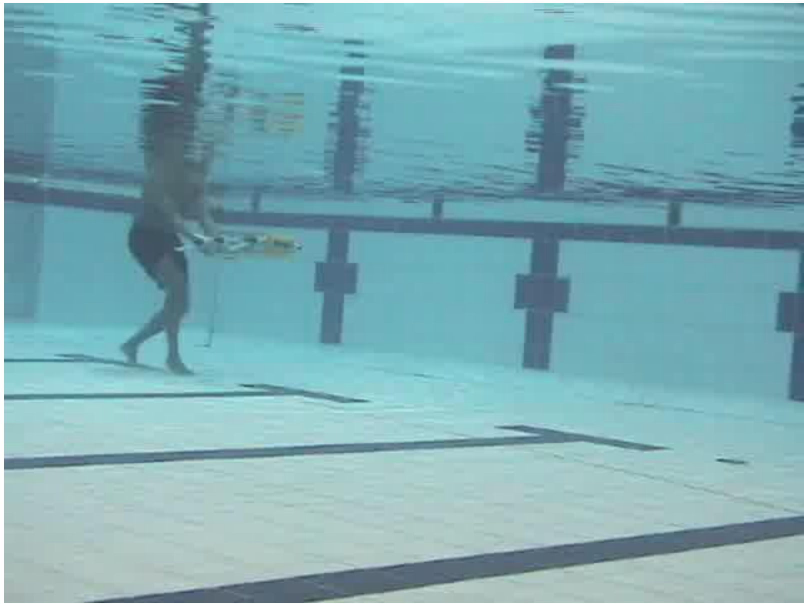
Technologies to increase the level of autonomy

- AQUA description
- Guidance and Control
  - Hovering
- Terrain Classification
- HRI
- Underwater Sensor Nodes
  - Video Mosaics



About Aqua



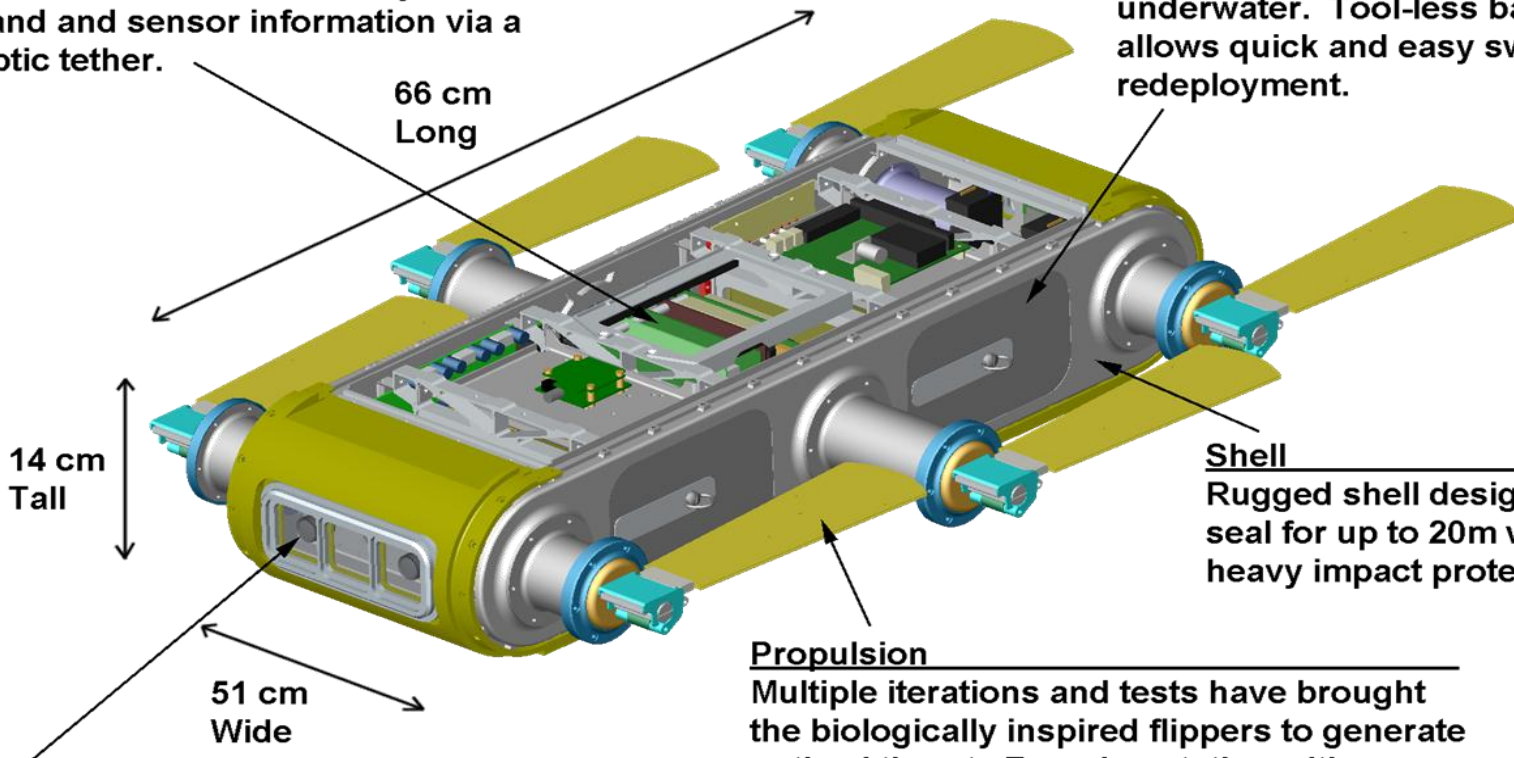


- Legged swimming vehicle
  - Hexapod with flippers, descendant of RHex
  - High mobility (can also walk, hover, etc)
- On-board cameras, IMU, computers
- Power autonomous for ~5+ hours
- Application: surveillance and monitoring of coral reefs, working in conjunction with marine biologists(s).

AQUA Components

Computation
AQUA operates with a Pentium CPU on a PC/104 stack and relays command and sensor information via a fiber optic tether.

Power
Two MIL-spec NiMH batteries allow AQUA to operate for over 5 hours underwater. Tool-less battery replacement allows quick and easy swaps for rapid redeployment.



Shell
Rugged shell design provides ample seal for up to 20m water depth and heavy impact protection.

Propulsion
Multiple iterations and tests have brought the biologically inspired flippers to generate optimal thrust. Experimentation with new swimming gaits has allowed for further improvement of AQUA's underwater performance.

Vision
2 front board cameras and 1 rear allow for remote operation of the robot. Future work will allow for visual servoing and stereoscopic 3D terrain mapping

(AQUA version 1)

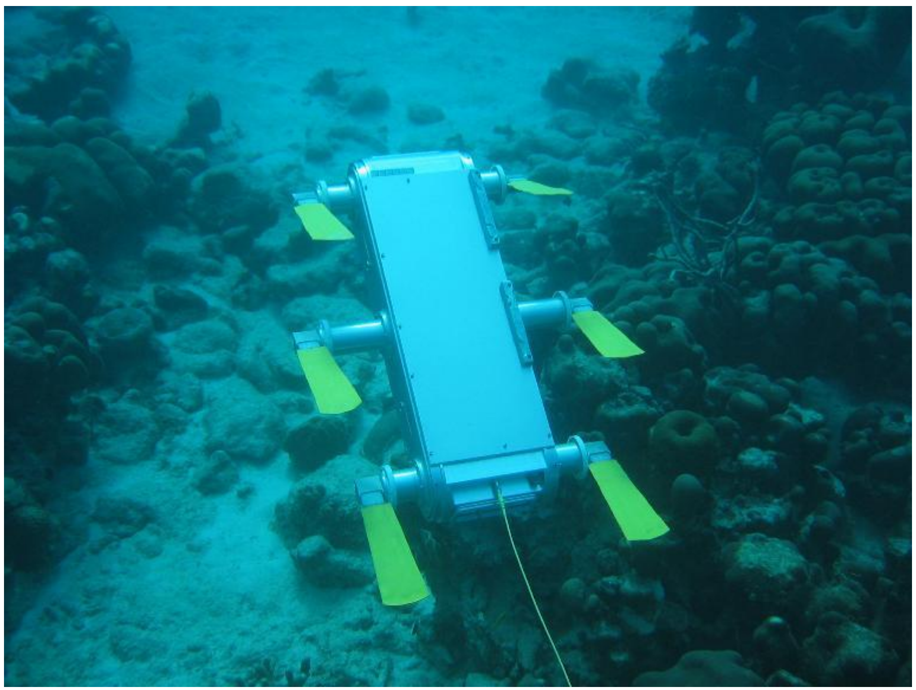
mass = 18.5kg (ballasted for salt water)

AQUA objectives

- AQUA is about developing a portable robot that can walk **and** swim, and which exhibits the ability to use vision and/or sound to know where it is and what is near it.
- The robot could be used, for example, to survey and monitor the conditions on a coral reef. By being able to land on the bottom and move around, the robot can make regular observations without disturbing the natural organisms.
- The ability to walk, swim and use vision underwater is unique to AQUA (derived from RHex [Buehler et al.])
- Allows for efficient station-keeping and surveillance.

Project objectives

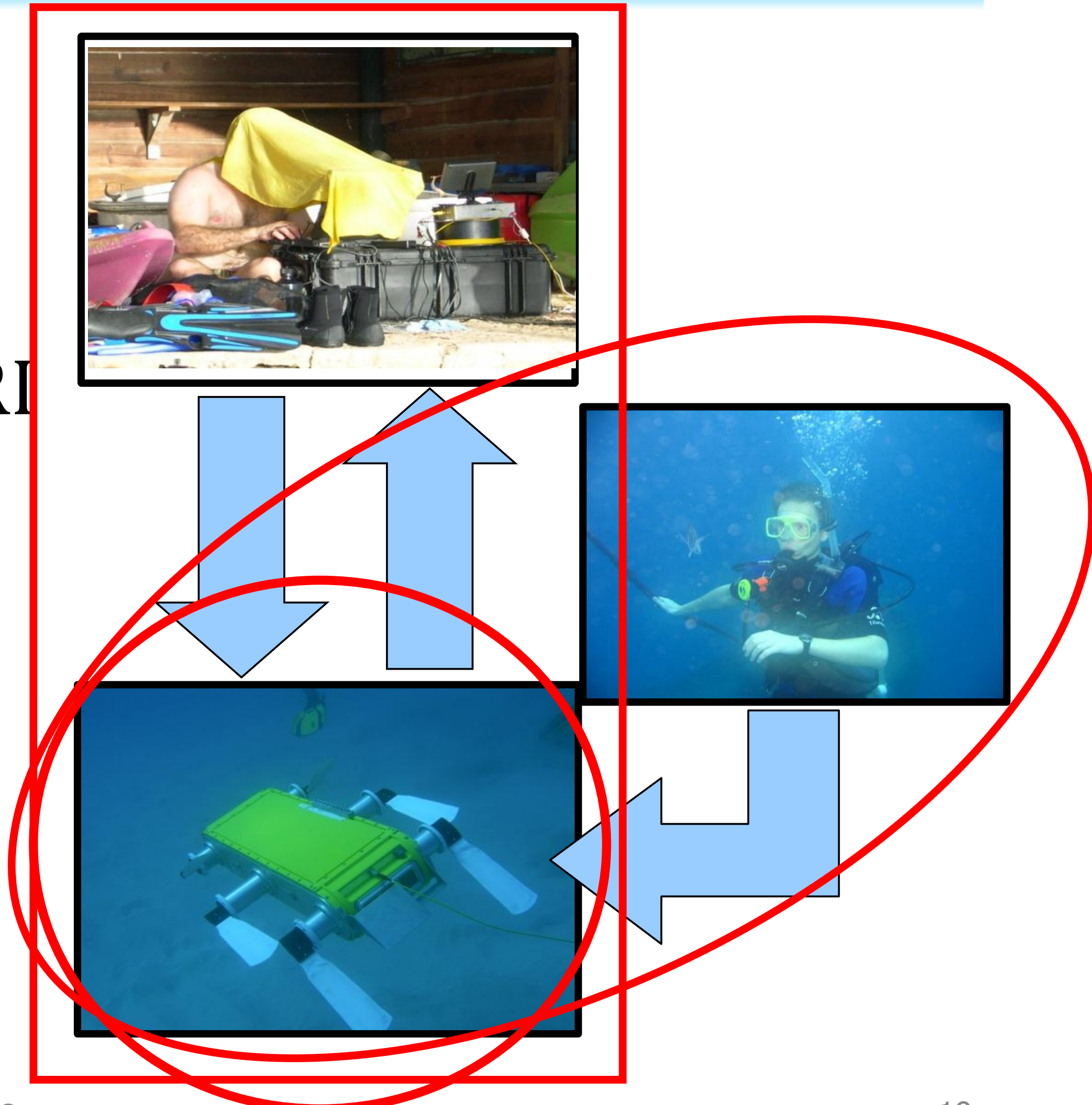
- Survey and monitor the conditions on coral reefs
- Ability to walk on land, swim, and use vision underwater
- Ability to land on the sea floor



Autonomy

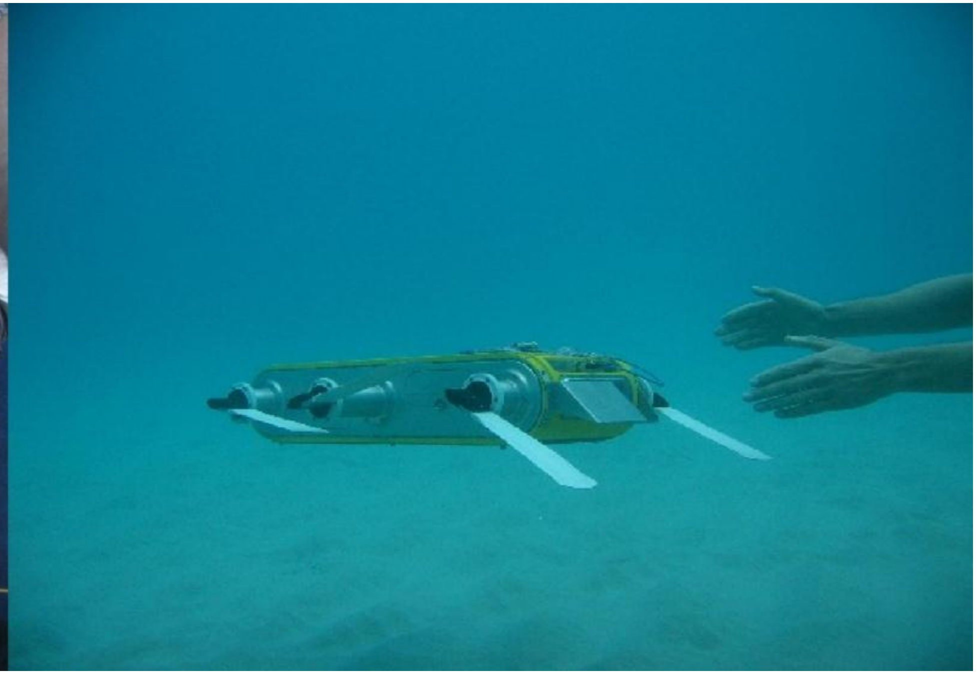
Operation Methods

- Tele-operation
- Partial Autonomy-HRI
- Full Autonomy

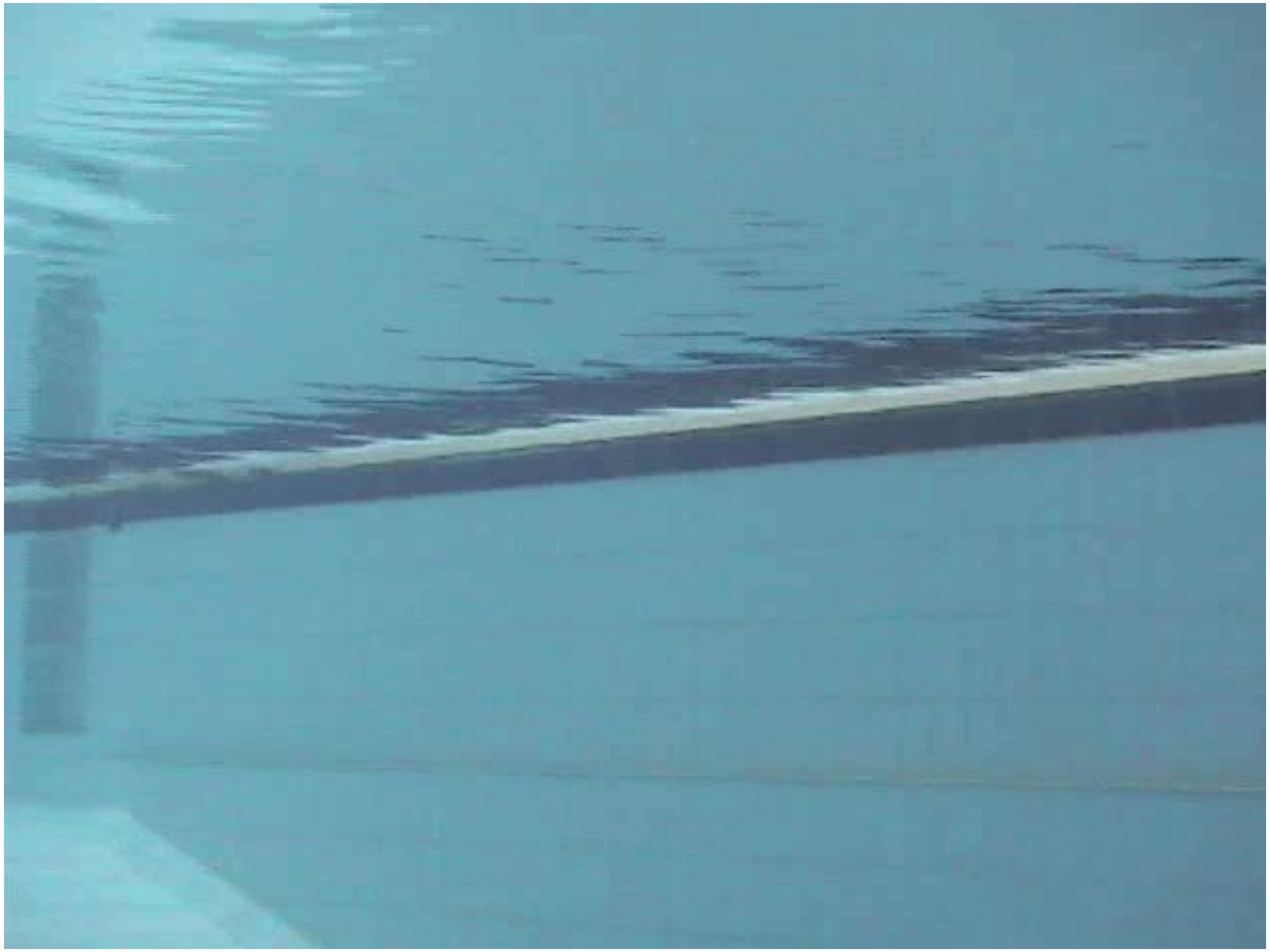


Guidance

- Small, light, moderate-cost robot
- Learn trajectories by (initially) following a diver
- Diver specifies specific actions as desired
- Diver specifies where and how data is collected

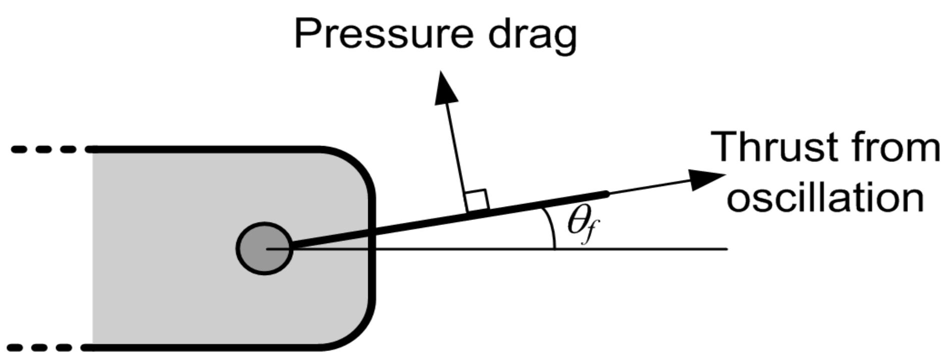


Alternative Entry Technique



Hovering illustration

- Hovering combines two distinct leg motions.
- Can also selectively tune thrust direction to minimize disturbances
- Combining hovering with motion can lead to interesting planning issues



Controllers: Objectives

- Provide trajectory tracking capabilities to the vehicle
  - Determine the required paddle force
  - Determine the appropriate paddle motion
- Stabilize the vehicle in the presence of disturbances

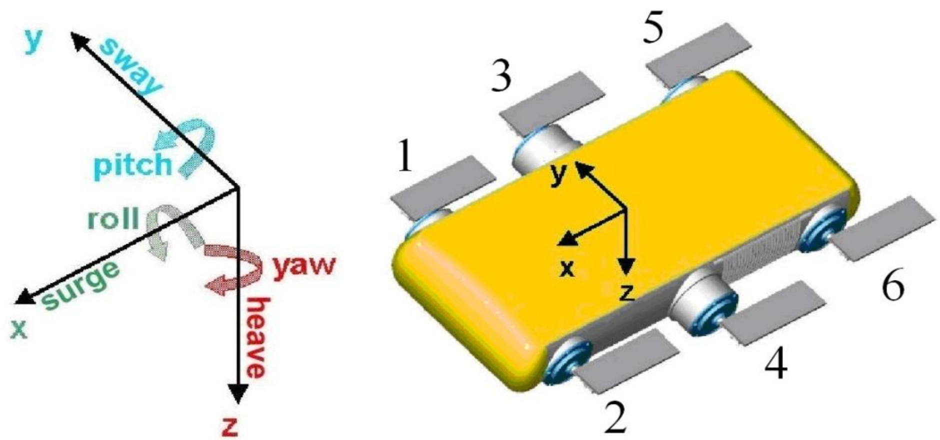
Linear Model

- Nonlinear model is linearized to allow use of linear systems theory

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \boldsymbol{\tau})$$

$$\downarrow$$

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\boldsymbol{\tau}$$



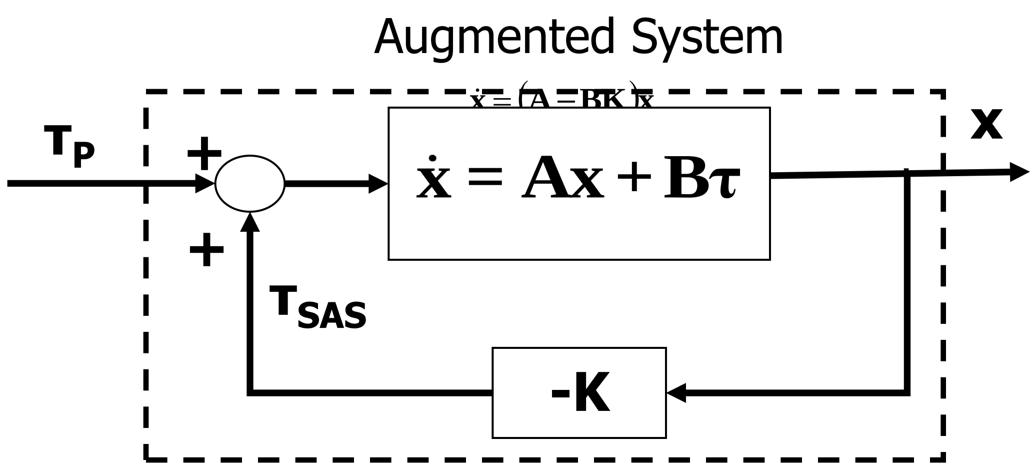
- State vector $\mathbf{x} = [u \quad v \quad w \quad p \quad q \quad r \quad x \quad y \quad z \quad \varphi \quad \theta \quad \psi]^T$
- Force vector $\boldsymbol{\tau} = [f_{x1} \quad \cdots \quad f_{x6} \quad f_{z1} \quad \cdots \quad f_{z6}]^T$

Model Based Control

- PID controllers used
- Both Linear and Non-Linear models used to augment the PID controller

Stability Augmentation System

- Linear system is weakly unstable in yaw
- SAS aims to return state perturbations to zero



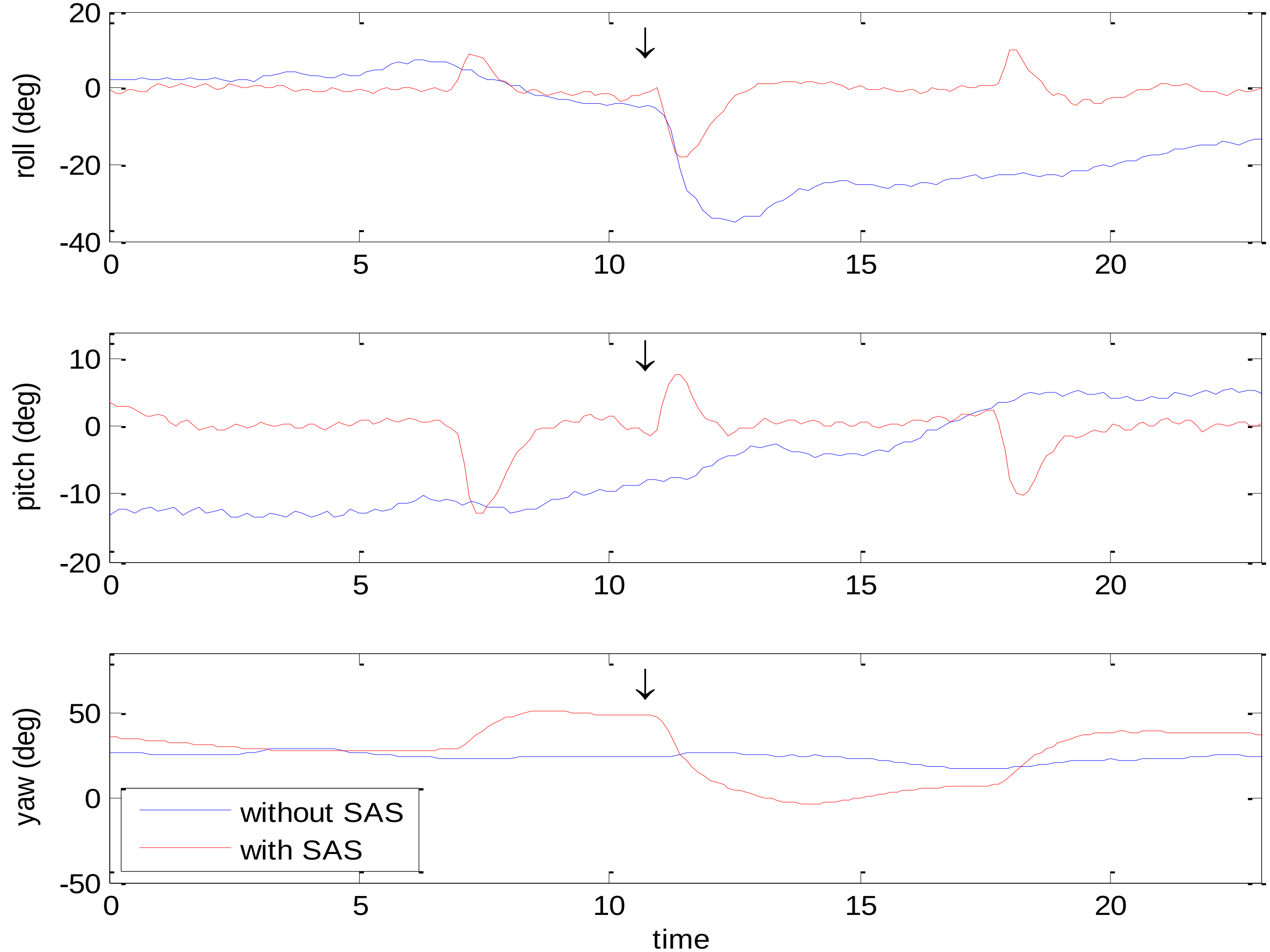
Experimental Validation

- Forward velocity of approximately 0.5m/s
- Roll and pitch impulse disturbances introduced by a swimmer
- Inertial Measurement Unit (IMU) data logged

Stability Augmentation and Model Based Control improved performance

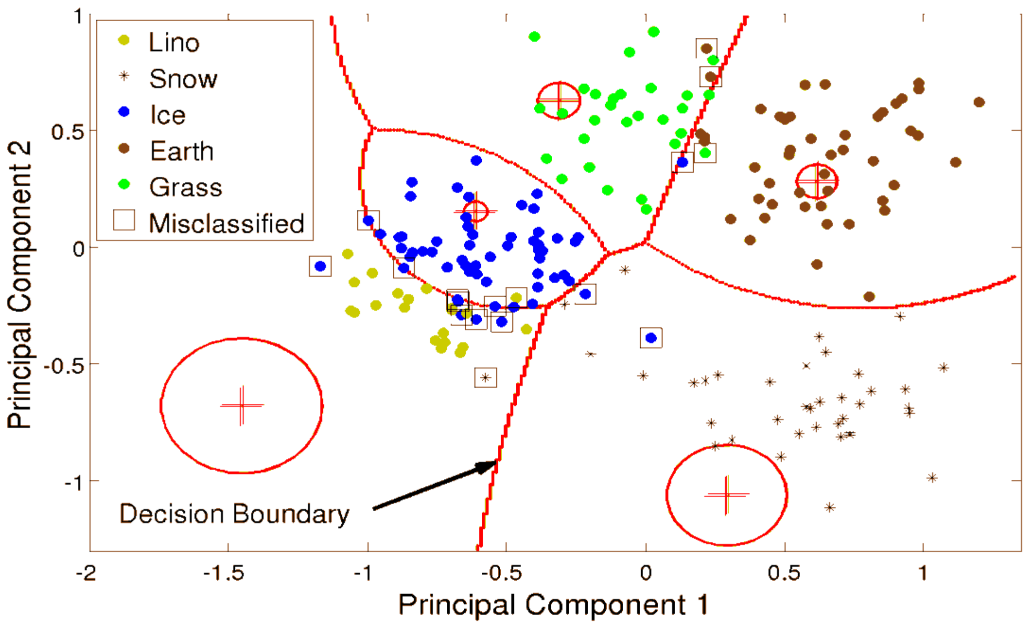
Results – Roll and Pitch Disturbance

$K_p = 0$, $K_\varphi = 4$,
$K_q = 1$, $K_\theta = 8$,
$K_r = 0$, $K_\psi = 0$



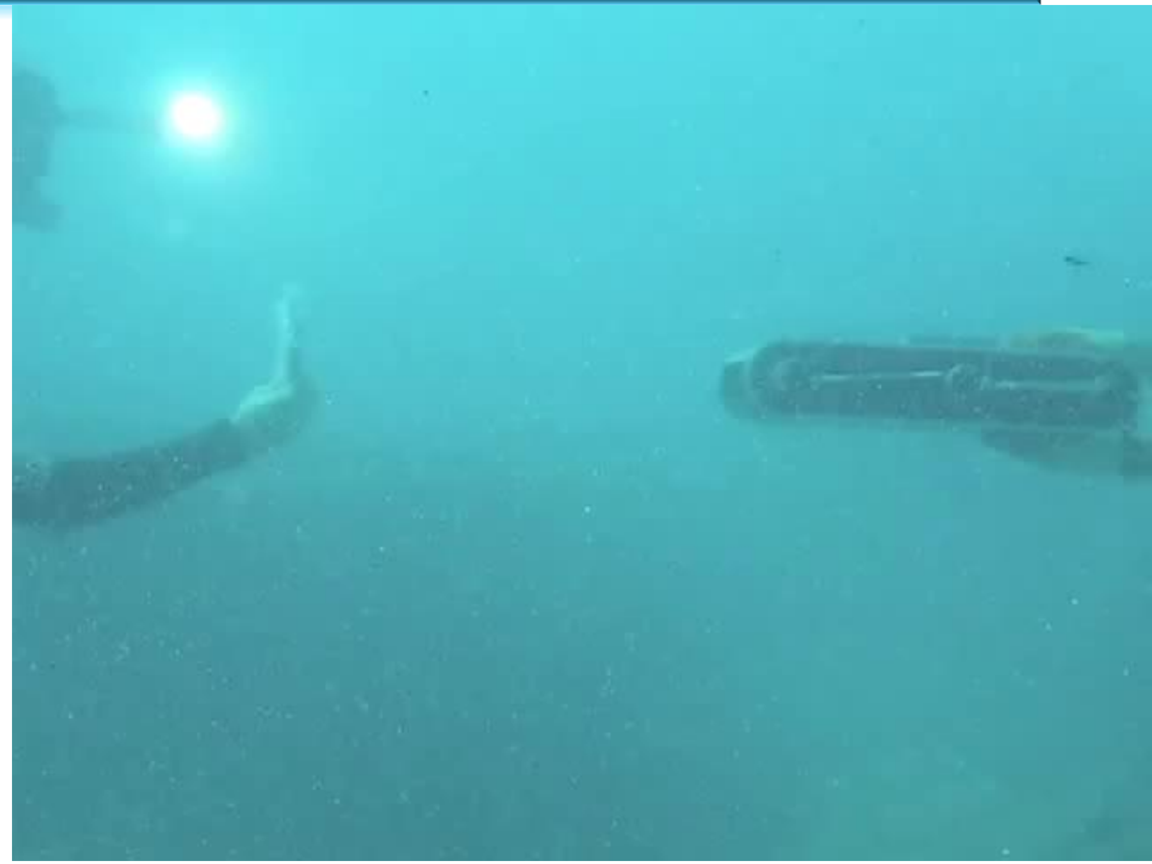
Terrain identification

- Vehicle is capable of using contact forces to identify terrains
- This allows gaits to be selected or adapted as a function of terrain type



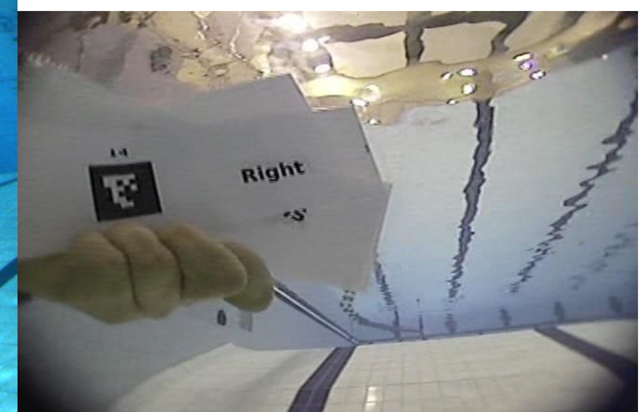
Vision-Based HRI

- Easier than conventional methods (e.g. type, touch screens)
- Requires no extra input mechanisms or sensors other than a camera
- Advantages of machine vision
  - Problems lie in interpreting 'gestures'
  - Fiducials as tokens



Visual Language

- Gestural robot programming language
- Real-time interpreter
- Low-level constructs: robot action commands (e.g. MOVE_FORWARD)
- High-level constructs: loops, iterators, functions
- Commands coded in scripting language (Lua)



Features

```
for (i = 0; i < 4; i++) {
    angle = 90;
    duration = 2;
    Turn_Left(angle, duration);
    Move_Forward(duration);
}
```

C-like Pseudocode
(38 input tokens)

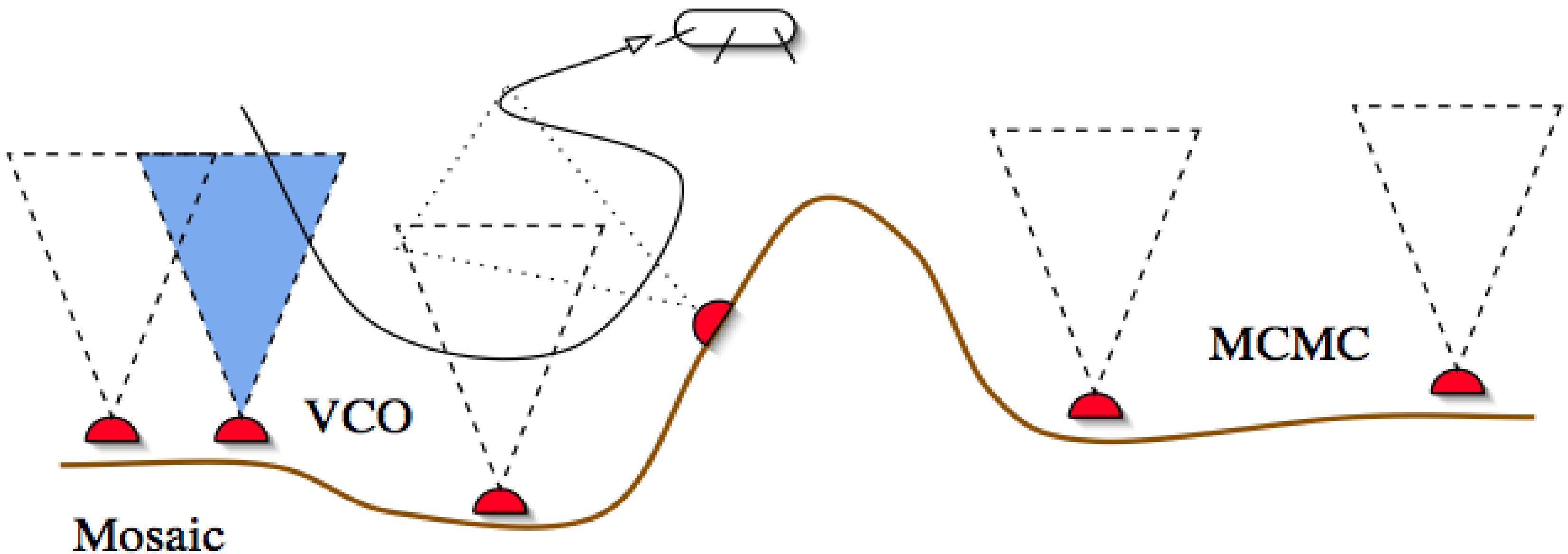
```
4 REPEAT
    9 0 ANGLE
    2 DURATION
    TURN_LEFT
    MOVE_FORWARD
END

EXECUTE
```

RoboChat snippet
(11 input tokens)

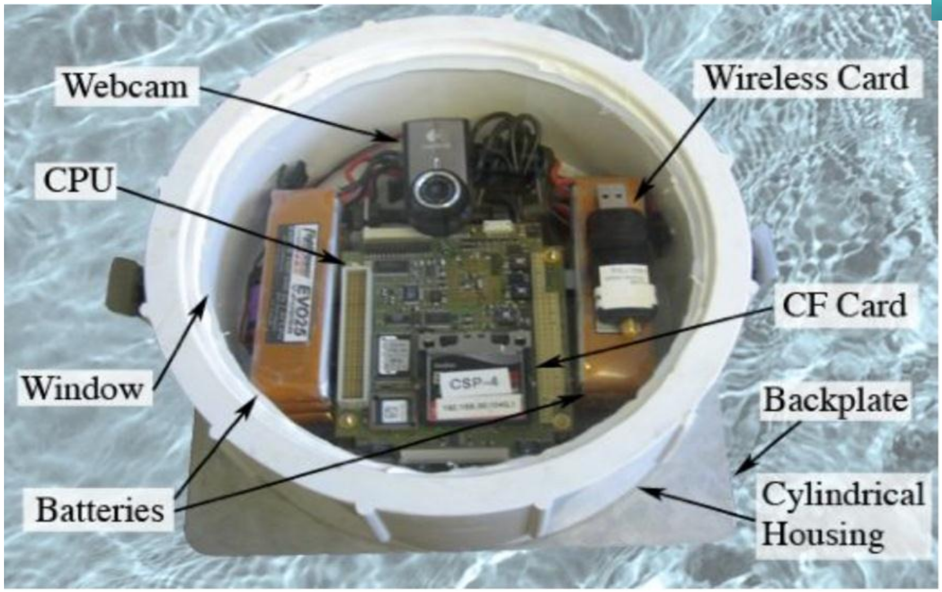
- Use of Reverse Polish notation to minimize unnecessary syntax artefacts (e.g. then, {...} *etc*)

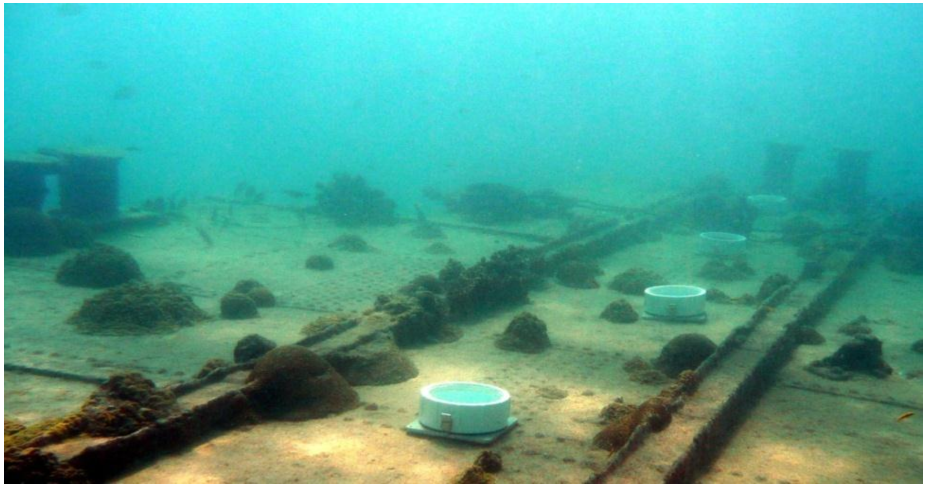
Vehicle/Sessile Multirobot network

- Sessile sensor nodes
  - Some close to one another (metric relations)
  - Some well separated (metric or topological relations)
- Moving vehicle(s)
  - Vehicle-carried odometry (VCO: topological -> metric)



Sensor nodes





Corrected Image Content

Noisy data collected from an underwater node

Conclusions

- Autonomy in underwater scenarios is challenging
- Model based control increases the operational capabilities of our vehicle
- AQUA-Diver communication increased the autonomy capabilities of the vehicle

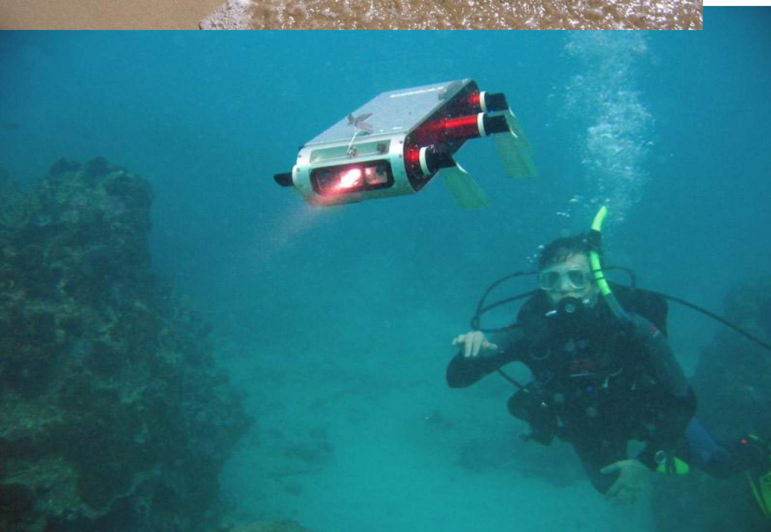
Future Work

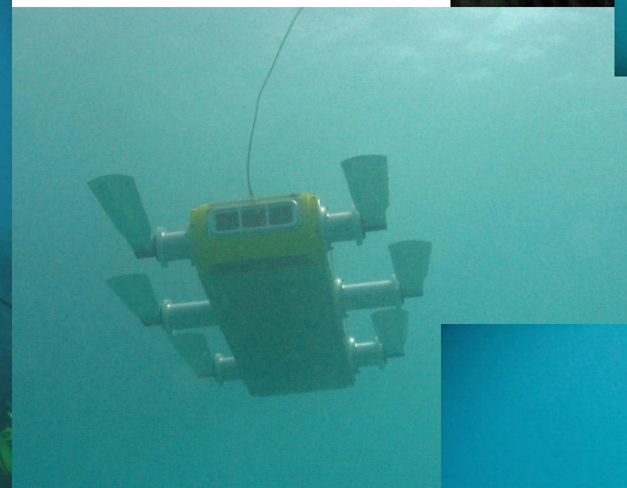
- Cooperation between AQUA and the Sensor Nodes
- Develop Image based Localization
- HRI employing the Microsoft Robotics Studio

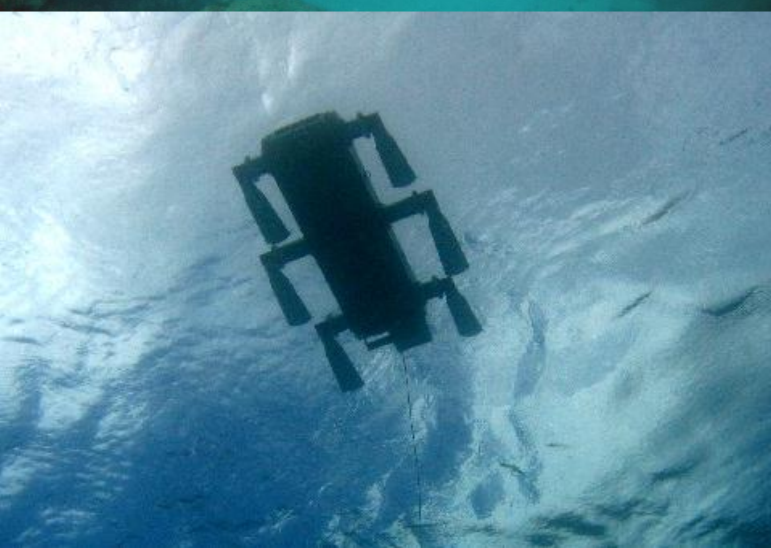
AQUA ROBOT is available to other labs

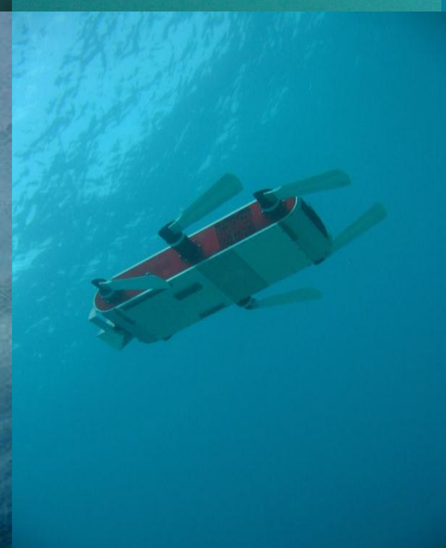
http://www.aquarobot.net

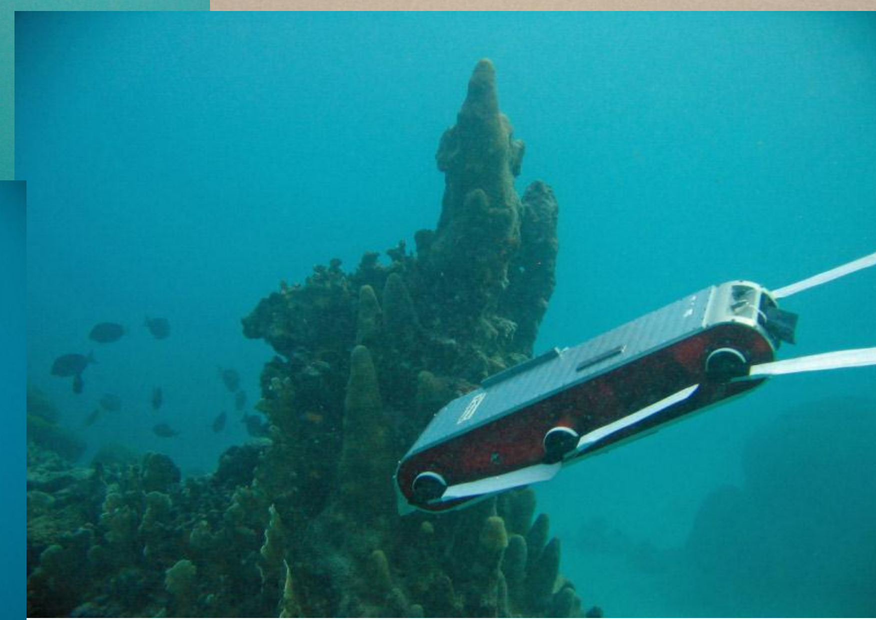
Questions











Controllers: Inputs

- The inputs to the controller are actual and desired trajectory:

Desired velocity: $\mathbf{v_d} = [u_d \quad v_d \quad w_d \quad p_d \quad q_d \quad r_d]^T$

Desired position: $\mathbf{s_d} = [x_d \quad y_d \quad z_d \quad \phi_d \quad \theta_d \quad \psi_d]^T$

Actual velocity: $\mathbf{v} = [u \quad v \quad w \quad p \quad q \quad r]^T$

Actual position: $\mathbf{s} = [x \quad y \quad z \quad \phi \quad \theta \quad \psi]^T$

Velocity error: $\mathbf{e_v} = \mathbf{v_d} - \mathbf{v}$

Position error: $\mathbf{e_s} = \mathbf{s_d} - \mathbf{s}$

Controllers: PID

Controller form: $$\mathbf{f} = \mathbf{K_d}\mathbf{e_v} + \mathbf{K_p}\mathbf{e_s} + \mathbf{K_I}\int \mathbf{e_s}\,dt$$

K_d, K_p and K_I are diagonal matrices with positives entries

Equation of motion: $$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(n_2) + \mathbf{b}(n_2) - \mathbf{K_d}\mathbf{e_v} - \mathbf{K_p}\mathbf{e_s} - \mathbf{K_I}\int \mathbf{e_s}\,dt = 0$$

Controllers: Model-based Linearizing

- The objective of this controller is to remove every nonlinear term in the equation of motion of the robot
- This gives a linear system with decoupled degrees of freedom

Controller form:

$$\mathbf{f} = \mathbf{M}\dot{\mathbf{v}}_{\mathbf{d}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(n_2) + \mathbf{b}(n_2) + \mathbf{K}_{\mathbf{d}}\mathbf{e}_{\mathbf{v}} + \mathbf{K}_{\mathbf{p}}\mathbf{e}_{\mathbf{s}} + \mathbf{K}_{\mathbf{I}}\int \mathbf{e}_{\mathbf{s}}\,dt$$

Equation of motion:

$$\mathbf{M}\mathbf{e}_{\mathbf{a}} + \mathbf{K}_{\mathbf{d}}\mathbf{e}_{\mathbf{v}} + \mathbf{K}_{\mathbf{p}}\mathbf{e}_{\mathbf{s}} + \mathbf{K}_{\mathbf{I}}\int \mathbf{e}_{\mathbf{s}}\,dt = 0$$

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$$+\mathbf{K}_{\mathbf{d}}\mathbf{e}_{\mathbf{v}} + \mathbf{K}_{\mathbf{p}}\mathbf{e}_{\mathbf{s}} + \mathbf{K}_{\mathbf{I}}\int \mathbf{e}_{\mathbf{s}}\,dt$$

Equation of motion:

$$\mathbf{M}\mathbf{e}_{\mathbf{a}} + \mathbf{K}_{\mathbf{d}}\mathbf{e}_{\mathbf{v}} + \mathbf{K}_{\mathbf{p}}\mathbf{e}_{\mathbf{s}} + \mathbf{K}_{\mathbf{I}}\int \mathbf{e}_{\mathbf{s}}\,dt = 0$$

Also a more complex Non-Linear controller is used

Controllers: Model-based Nonlinear

- The objective of this controller is to input the ideal force that would be required to achieve trajectory tracking
- The proportional, integral and derivative gains were added to account for uncertainties in the model

Controller form:

$$\mathbf{f} = \mathbf{M}\dot{\mathbf{v}}_\mathbf{d} + \mathbf{C}(\mathbf{v}_\mathbf{d})\mathbf{v}_\mathbf{d} + \mathbf{D}(\mathbf{v}_\mathbf{d})\mathbf{v}_\mathbf{d} + \mathbf{g}(n_2) + \mathbf{b}(n_2) + \mathbf{K}_\mathbf{d}\mathbf{e}_\mathbf{v} + \mathbf{K}_\mathbf{p}\mathbf{e}_\mathbf{s} + \mathbf{K}_\mathbf{I}\int \mathbf{e}_\mathbf{s}\,dt$$

Equation of motion:

$$\mathbf{M}\mathbf{e}_\mathbf{a} + (\mathbf{C}(\mathbf{v}_\mathbf{d})\mathbf{v}_\mathbf{d} - \mathbf{C}(\mathbf{v})\mathbf{v}) + (\mathbf{D}(\mathbf{v}_\mathbf{d})\mathbf{v}_\mathbf{d} - \mathbf{D}(\mathbf{v})\mathbf{v}) + \mathbf{K}_\mathbf{d}\mathbf{e}_\mathbf{v} + \mathbf{K}_\mathbf{p}\mathbf{e}_\mathbf{s} + \mathbf{K}_\mathbf{I}\int \mathbf{e}_\mathbf{s}\,dt = 0$$

Simulation results: Maneuvers

Surge maneuver:

$$x_d = \frac{200}{3}\left(\frac{t}{100}\right)^{1.5} + \frac{1}{2}\left(1 - \cos\frac{t}{3}\right)$$

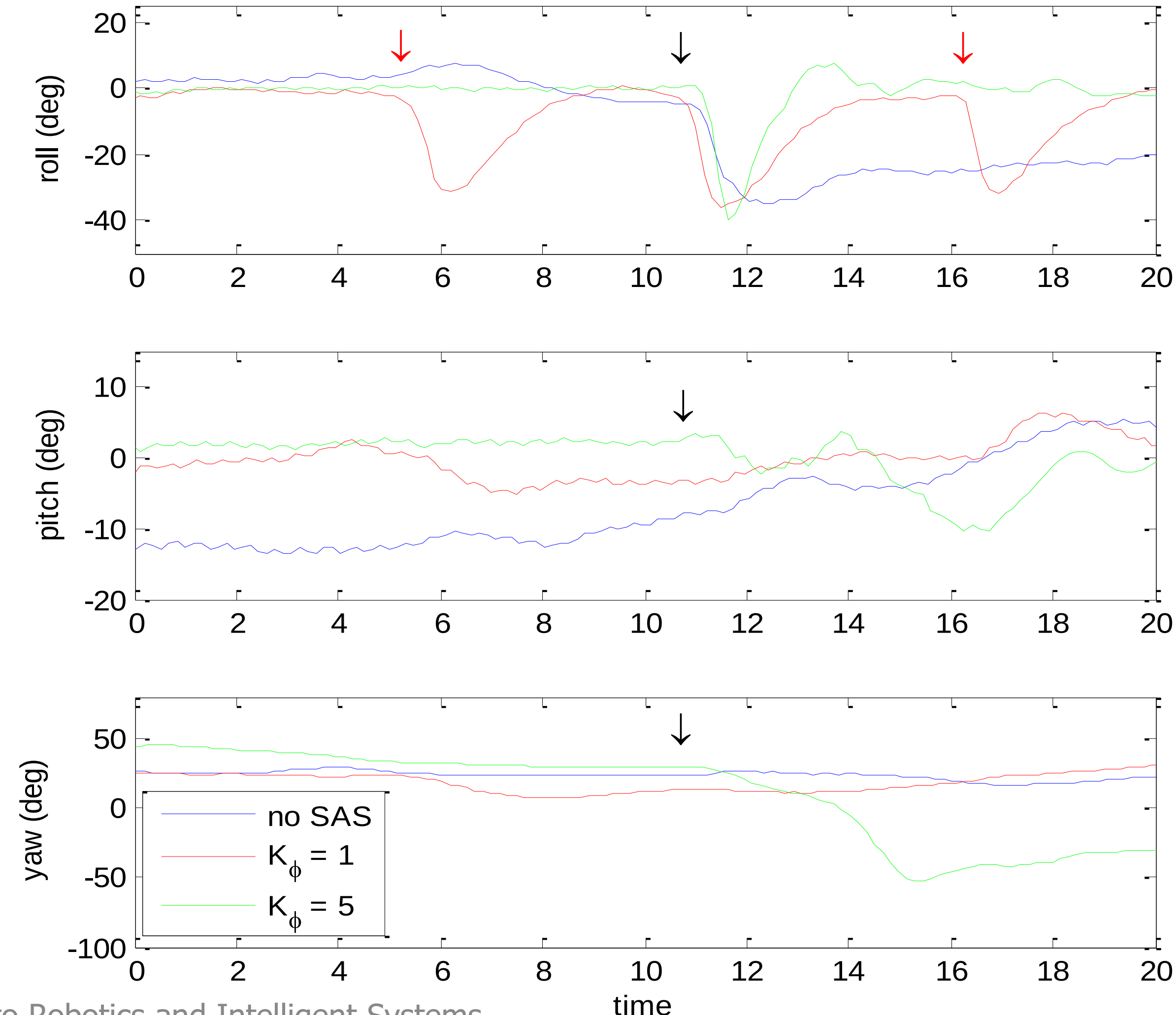
$$u_d = \sqrt{\frac{t}{120}} + \frac{1}{6}\sin\frac{t}{3}\,\frac{\mathrm{m}}{\mathrm{s}}$$

Roll maneuver:

$$\phi_d = \frac{1}{2}\left(1 - \cos\frac{t}{4}\right) rad$$

$$p_d = \frac{1}{8}\sin\frac{t}{4}\,\frac{rad}{s}$$

SAS Results – Roll Only Disturbance



SAS Results – Pitch Only Disturbance