24/7 Multi-Robot Systems operating in real world

Stefan B. Williams

OUTLINE

- Introduction to ACFR
- Fielding Multi-Robot Systems
  - Logistics
  - Defence and Security
    - Unmanned Air Vehicles
    - Multi-vehicle Ground Vehicle Systems
  - Mining
  - Art
  - Agriculture
  - Environmental
- Conclusions
- Acknowledgements

AUSTRALIAN CENTRE FOR FIELD ROBOTICS

- An engineering research institute at the University of Sydney
- Research staff
  - 6 academics
  - 40 research fellows
  - 50 PhD students
  - 30 software, mech/aero, electrical/electronic staff
- One of the largest field robotics and intelligent systems group in the world
- Dedicated to the scientific advancement and industry uptake of autonomous robots and intelligent systems for outdoor operations


E300 Viewer
Span 4.8m
Weight 15kg
Duration 2.5Hrs

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Examples of Collaboration

Australian Government
Australian Research Council

Autonomous Systems

PATRICK

RIO TINTO

Australian Government
Department of Defence
Defence Science and Technology Organisation

MINISTRY OF DEFENCE

BAE SYSTEMS

bhpbilliton

국방과학연구소
Agency for Defense Development

TOYOTA

KOMATSU

Australian Government
Land & Water Australia

Australian Government
Department of Agriculture, Fisheries and Forestry

HAL
Horticulture Australia

mla
MEAT & LIVESTOCK AUSTRALIA

RENAULT

QANTAS
THE SPIRIT OF AUSTRALIA

IMOS
Integrated Marine Observing System

DEPARTMENT OF THE NAVY
ONR
Science & Technology

U.S. AIR FORCE

AIR FORCE RESEARCH LABORATORY

ST Aerospace

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Research and Technology Themes

Field Robotics and Complex Software Systems	• Novel Machines and Mechanisms for Air, Ground, Marine and Space • Complex Software System Development • Autonomous Information Processing
Sensors and Machine Perception	• Laser, Radar, Vision, Thermal, Hyperspectral, Inertial, GPS. • Rich Probabilistic Models and Representations • Advanced algorithms for localisation and mapping
Machine Control and Autonomous Decision Making	• Modeling complex platform motion and environment interaction • Linear and adaptive control algorithms and implementation • Probabilistic planning techniques
Learning Systems and Adaptation	• Data Mining and Classification • Machine learning for environment modelling • Reinforcement learning for control and planning
Systems of Intelligent Systems	• Multi-sensor and multi-platform data fusion and control • Large scale optimisation for operation planning • Human-machine systems and interaction

Application Areas

Field Robotics and Complex Software Systems	Human-Machine Interaction	Environmental Monitoring and Scientific Exploration	Intelligent Transport and Logistics	Agriculture and Food Production	Defence and Security	Mining and Construction
Sensors and Machine Perception						
Machine Control and Autonomous Decision Making						
Learning Systems and Adaptation						
Systems of Intelligent Systems						

Robots at Work

Enhanced Straddle Carrier

ENHANCED STRADDLE CARRIER

Durrant-Whyte, Hugh, Daniel Pagac, Ben Rogers, Michael Stevens, and Graeme Nelmes. "**Field and service applications-an autonomous straddle carrier for movement of shipping containers-from research to operational autonomous Systems**." Robotics & Automation Magazine, IEEE 14, no. 3 (2007): 14-23.

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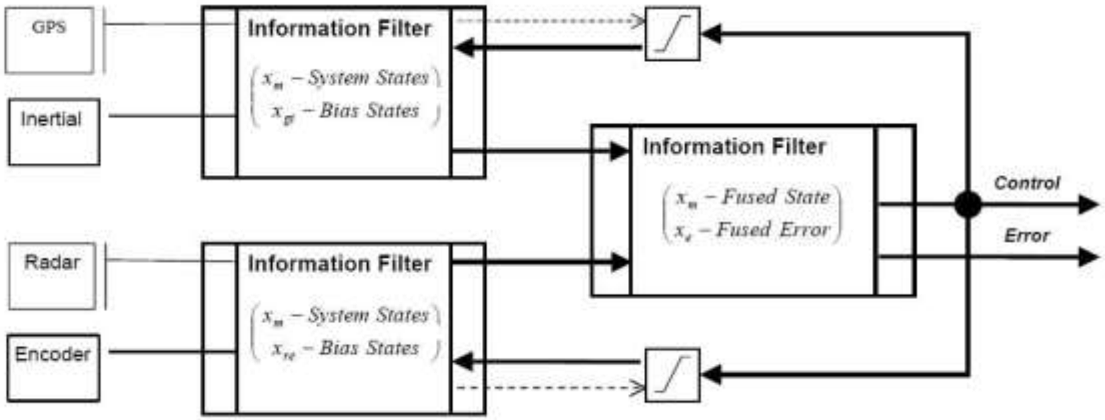
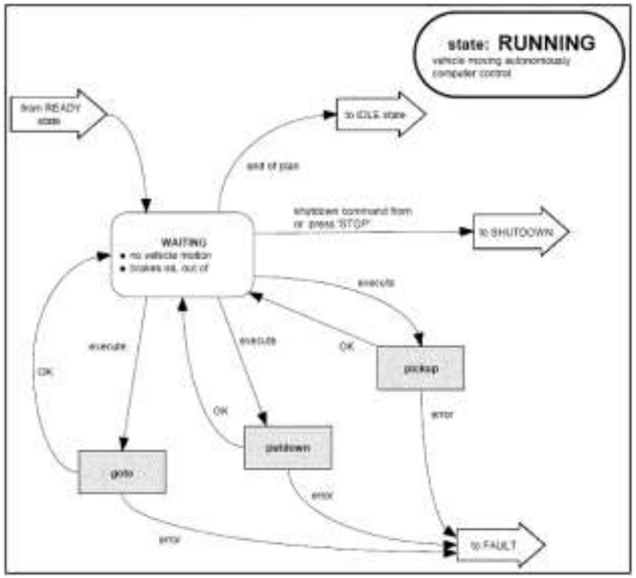
HIGH INTEGRITY NAVIGATION

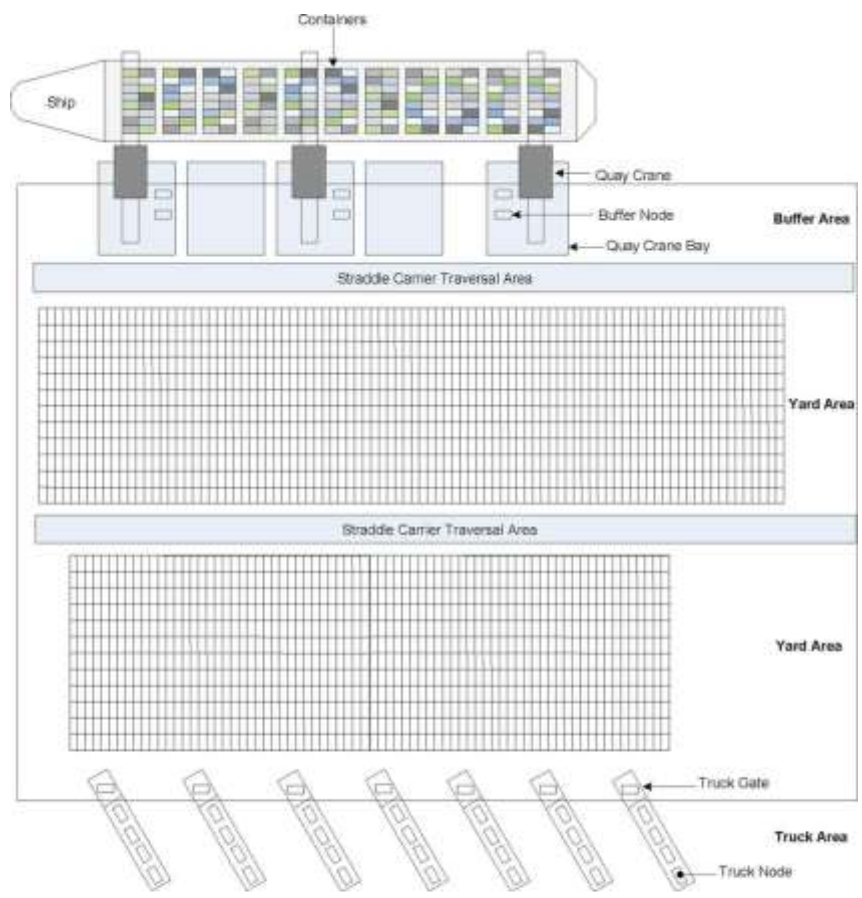




COMPLETE AUTOMATION OF A BERTH

PLANNING UNDER UNCERTAINTY

- More recent work from UTS has considered the case of planning under uncertainty
- Mutli-objective planning under uncertainty, including
  - Travelling time
  - Waiting time
  - Finishing time for high priority jobs

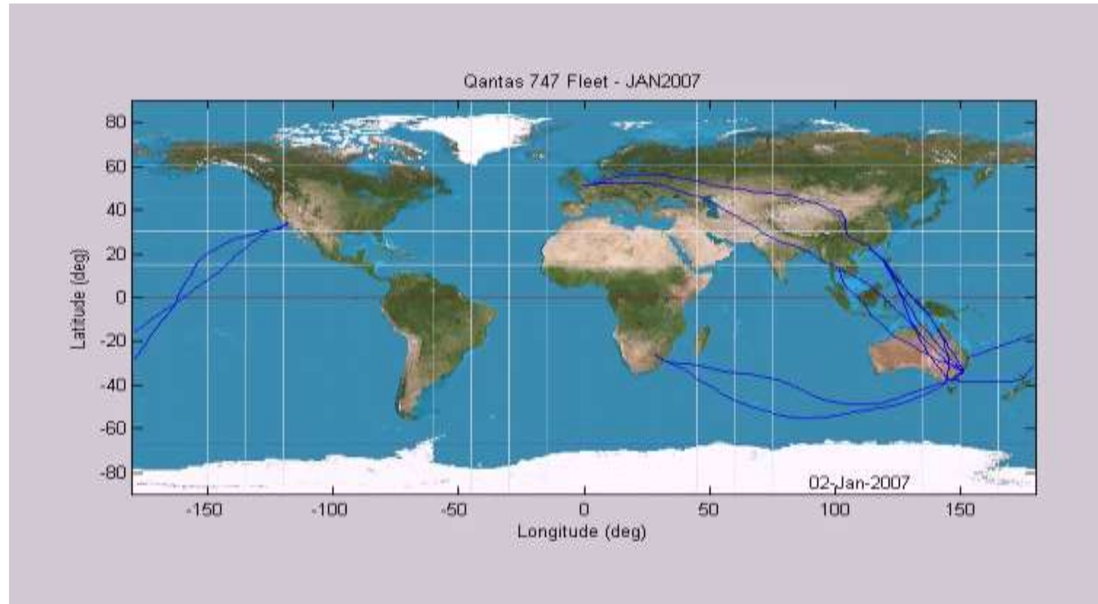


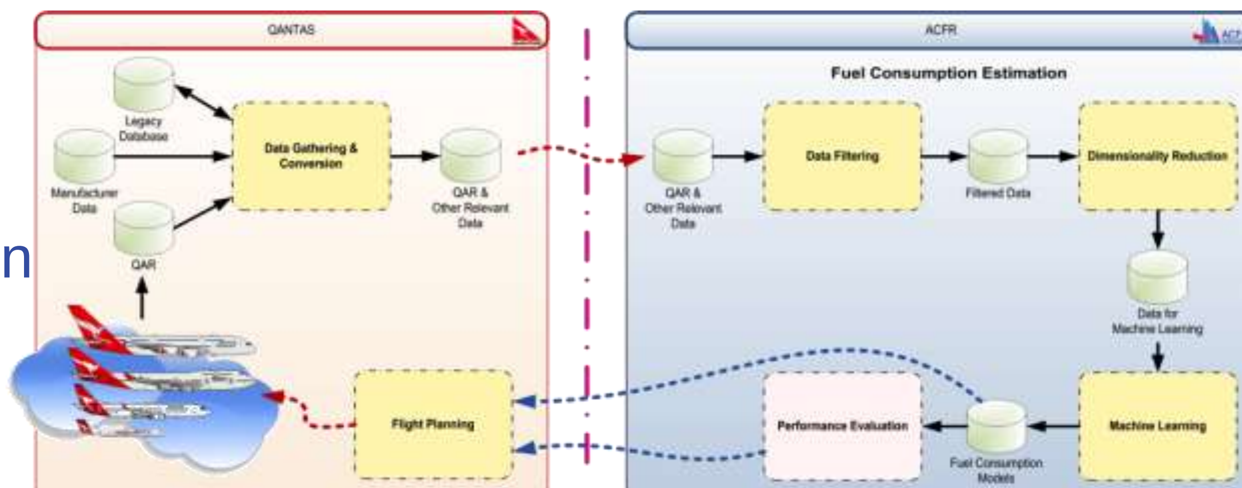
Cai, B., Huang, S., Liu, D., & Dissanayake, G. (2014). **Rescheduling policies for large-scale task allocation of autonomous straddle carriers under uncertainty at automated container terminals.** Robotics and Autonomous Systems, 62(4), 506-514.

MULTIMODAL LOGISTICS/FREIGHT/TRANSPORT

QANTAS FLIGHT PLANNING AND FUEL OPTIMISATION

- Working closely with Qantas on the development of flight planning systems
- Small changes in weather can have a significant impact of flight times and efficiency
- Leveraging recent work in multi-objective optimisation and planning under uncertainty





Robots at Work

Defence and Security

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UNMANNED AIR VEHICLES





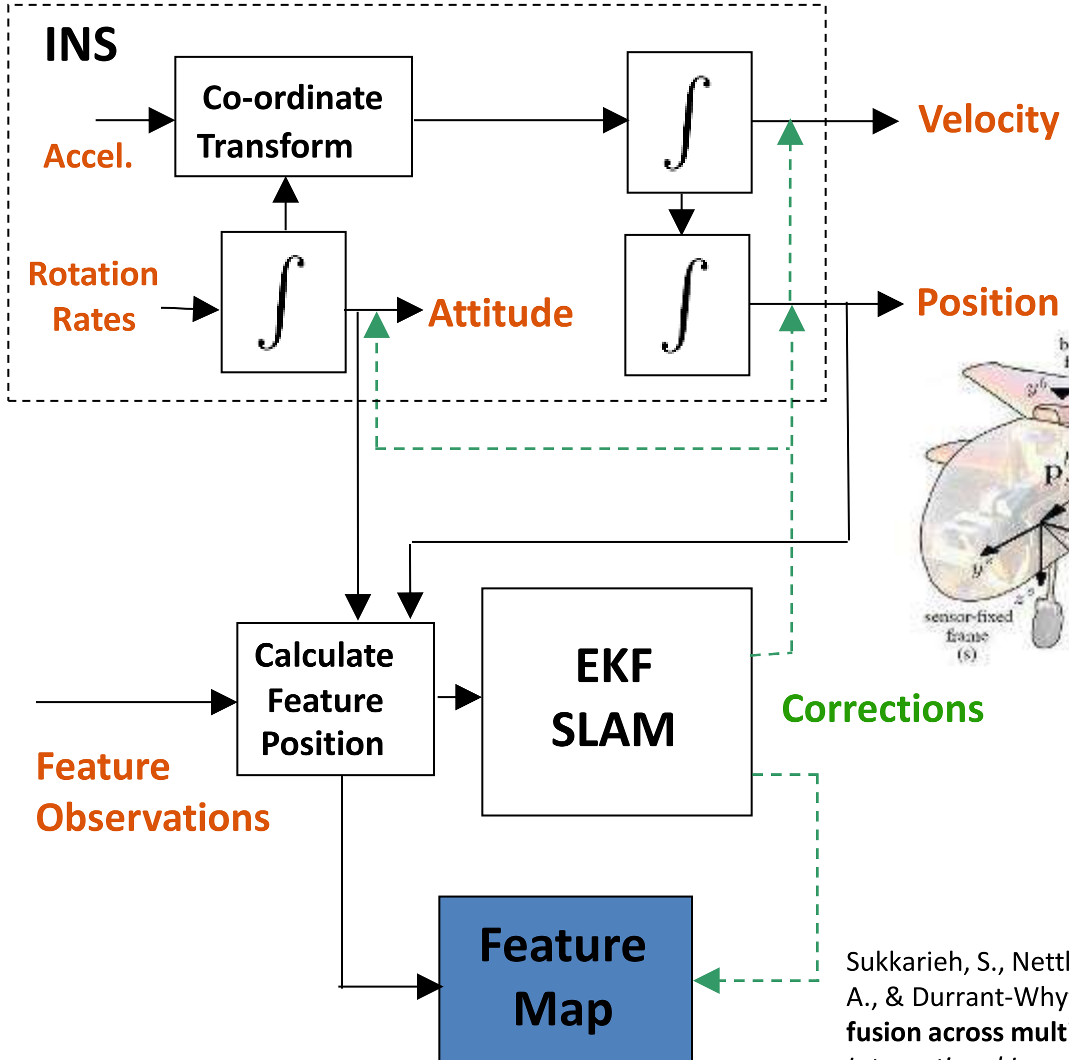



- DSTO
- BAE Systems
- ST Aerospace
- US Air Force
- Ministry of Defence UK
- US Office of Naval Research

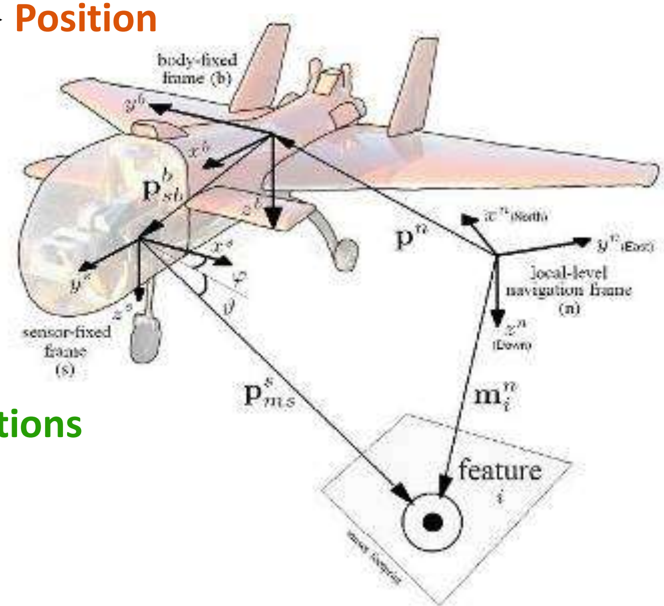
- Australian Research Council
- Department of Agriculture, Fisheries, and Forestry
- Land and Water Australia
- Australian Plague Locust Commission
- Meat and Livestock Australia

AIRBORNE INERTIAL-SLAM

IMU

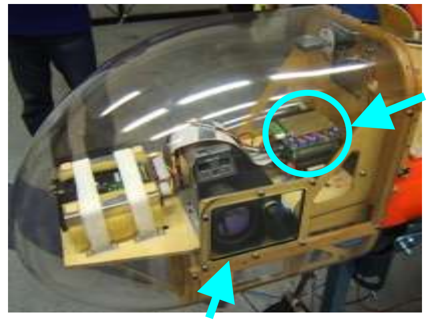


Terrain Feature Sensor



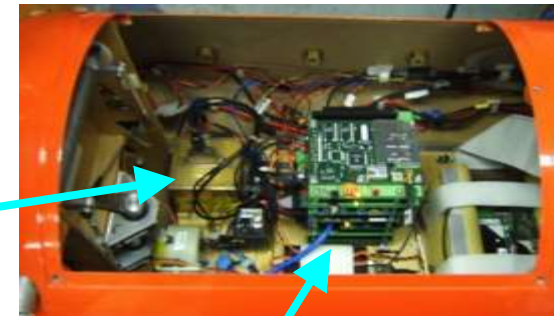
Sukkarieh, S., Nettleton, E., Kim, J. H., Ridley, M., Goktogan, A., & Durrant-Whyte, H. (2003). **The ANSER project: Data fusion across multiple uninhabited air vehicles**. *The International Journal of Robotics Research*, 22(7-8), 505-539.

SLAM IN ACTION – SINGLE VEHICLE



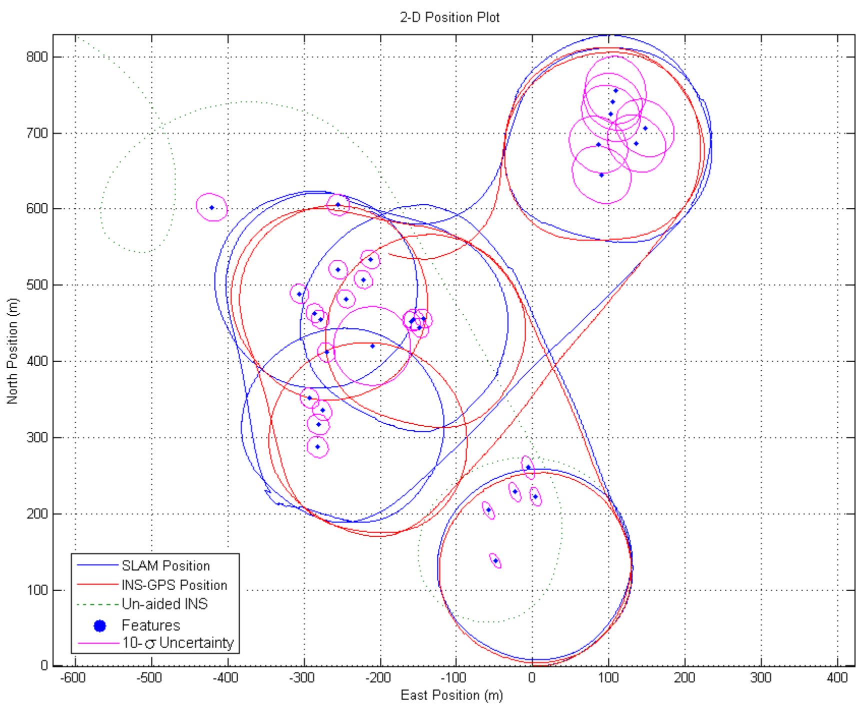
Vision CPU

IMU



Colour Camera

Flight Control Computer

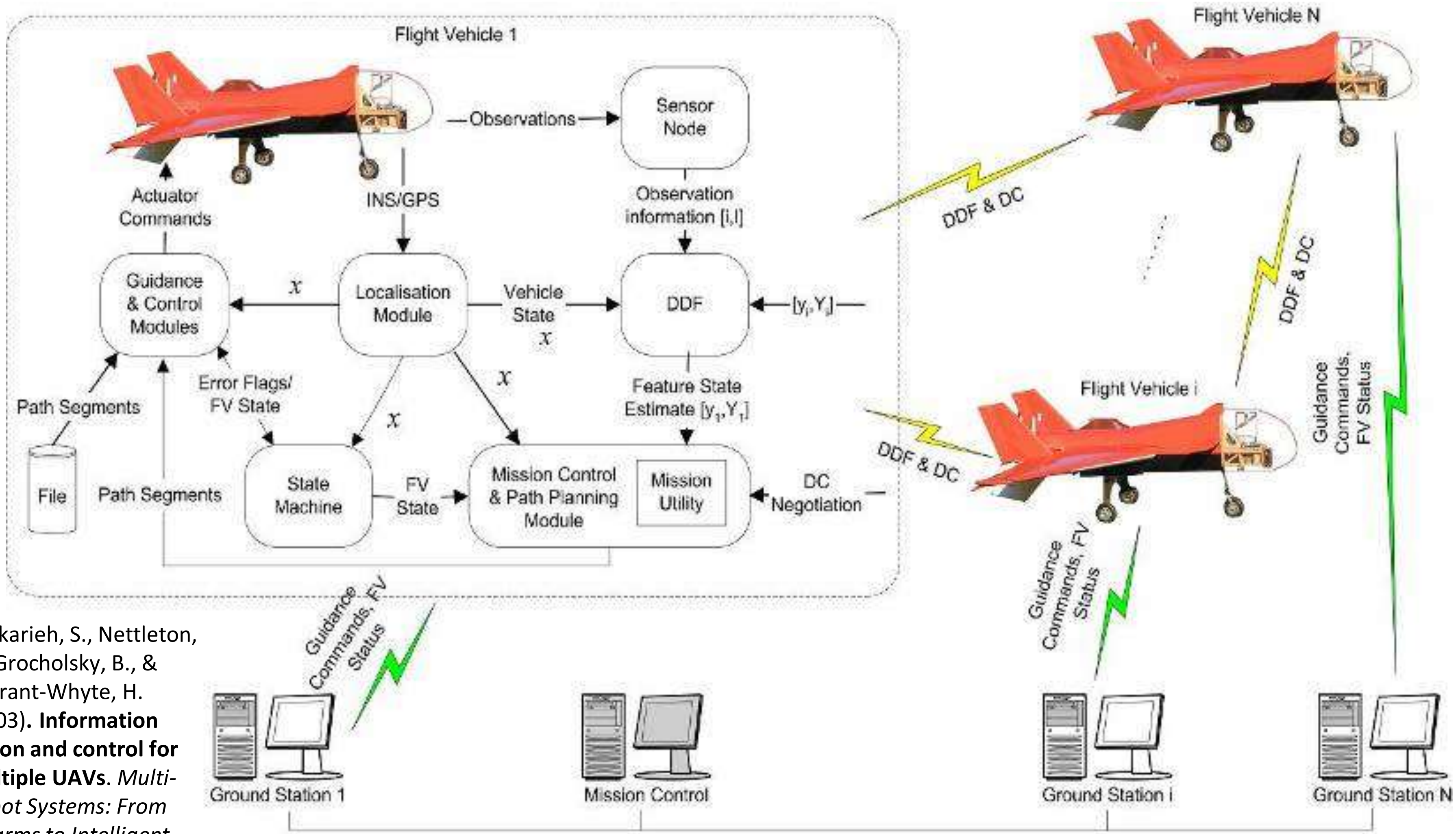


2000-2004
ANSER 1 – Demonstration of a Decentralised Air Surveillance System

2005-2006

ANSER 2 – Demonstration of a Decentralised Air/Ground Surveillance System

SYSTEM ARCHITECTURE

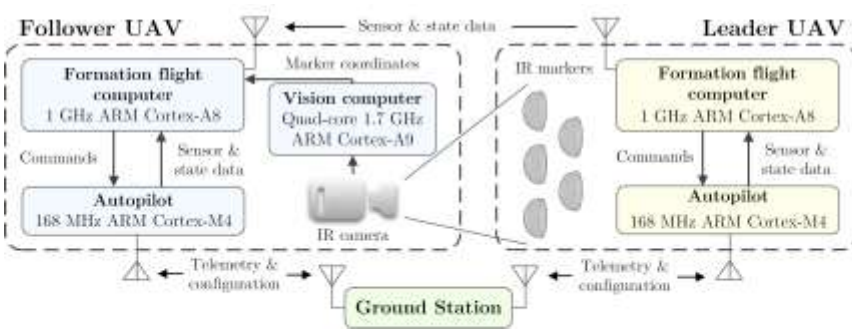


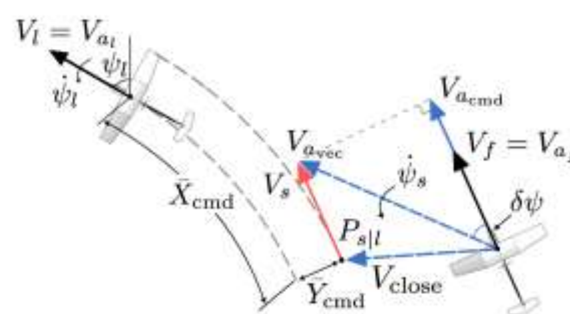
Sukkarieh, S., Nettleton, E., Grocholsky, B., & Durrant-Whyte, H. (2003). **Information fusion and control for multiple UAVs**. *Multi-Robot Systems: From Swarms to Intelligent Automata*, 2, 123-134.

Autonomous UAV Docking for Aerial Refueling

Daniel B. Wilson

Dr Ali Haydar Göktoğan

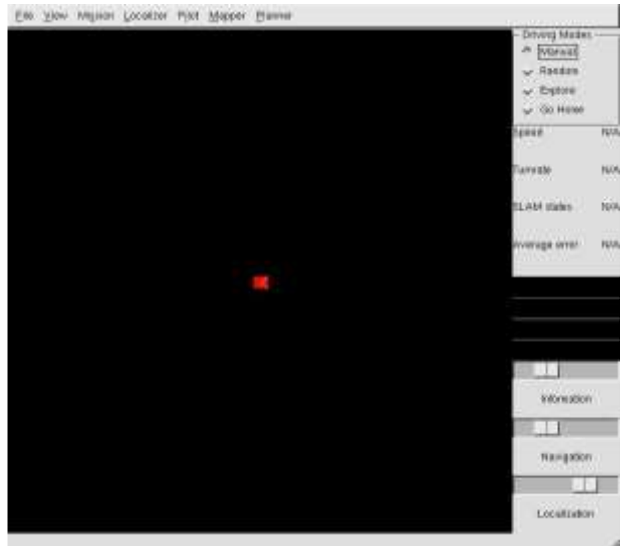




Wilson, D. B., Göktogan, A. H., & Sukkarieh, S. "**Guidance and Navigation for UAV Airborne Docking"**., Robotics: Science and Systems, 2015 (winner Best Paper)

SPECIAL FORCES TRAINING

- Work on indoor SLAM and exploration
- Received a request from Australian Special Forces training facility for assistance with the development of a flexible, robotic system
- An internally funded project had spent 12 years developing a prototype



SPECIAL FORCES TRAINING

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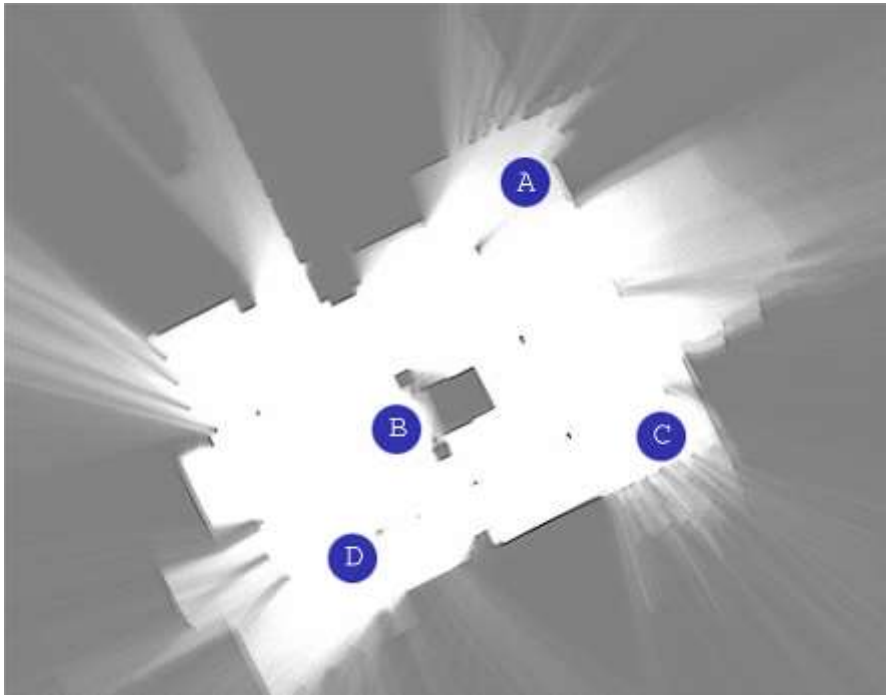
SPECIAL FORCES TRAINING

LOCALIZATION

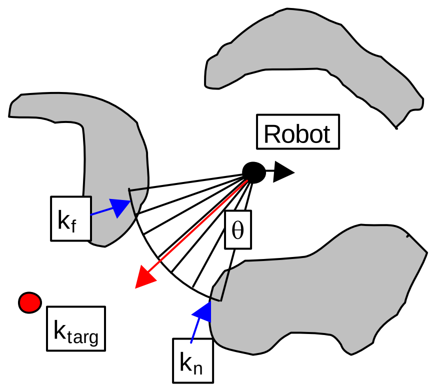
- Odometry
  - Wheel encoders to estimate forward speed and turn rate
- Laser features
  - Surveyed into the range
  - Easily identifiable targets
- Data Fusion
  - Fusing encoder data with the laser observations yields best estimate of vehicle pose
  - Initialisation from unknown location depends on recognizing feature arrangements
- Alternative methods
  - GPS – suitable for outdoor environments
  - Wi-Fi Strength

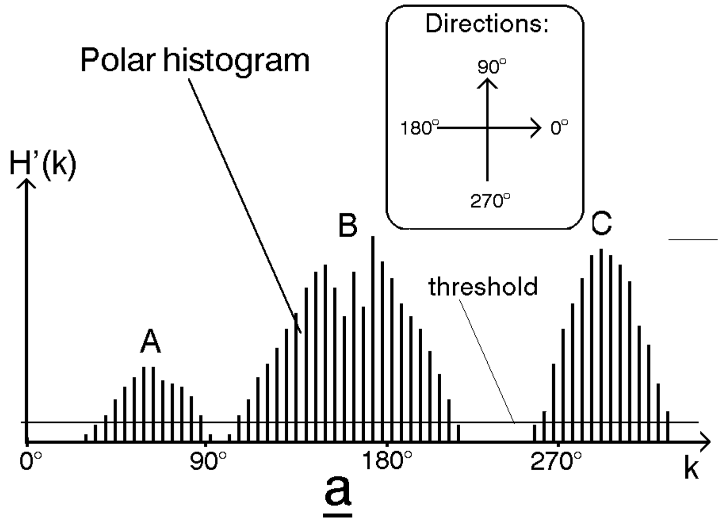
MAPPING

- Feature based localization and AMCL require map of environment
- Deployed Simultaneous Localisation and Mapping
- Occupancy Grid Mapping algorithms
- Autonomous Mapping to create maps using the vehicle sensing capabilities



OBSTACLE AVOIDANCE





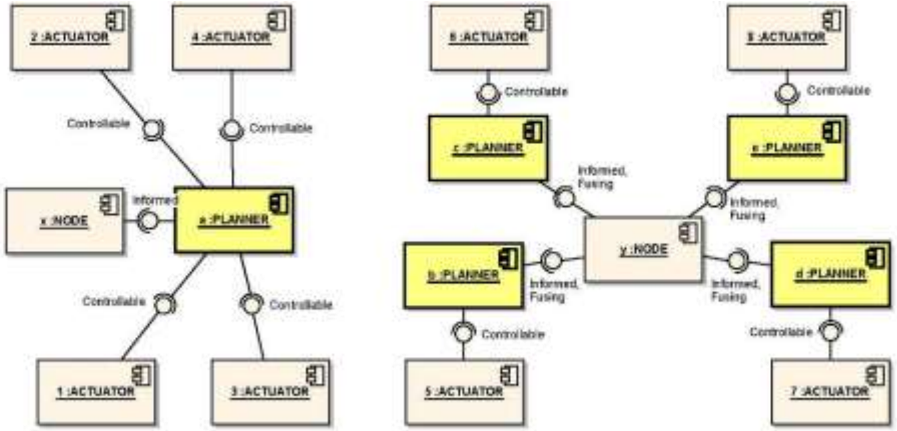
- Laser used for obstacle avoidance
  - Allows local decisions about best path to next waypoint
  - Presents flexibility in plan execution
  - Continuation of game post shot
- Vector Field Histogram
  - Fast obstacle avoidance technique
  - Discretization of area around vehicle
  - Choice of direction towards goal which minimizes chance of collision
- Significant tuning required to operate with multiple platforms in confined spaces

PLANNING AND CONTROL

- Scenario planning to be overseen by an operator
- A simple waypoint based interface used to designate timed waypoints for each platform
- No explicit coordination of platforms
- Local control of each platform facilitates waypoint following and dynamic obstacle avoidance

COMMUNICATIONS

- Development of ORCA interprocess communication framework
- Based on an existing open source project (OROCOS)
- Pre-ROS



Makarenko, A., Brooks, A., & Kaupp, T. (2006, October). **Orca: Components for robotics. In International** Conference on Intelligent Robots and Systems (IROS) (pp. 163-168).

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OUT OF THE LAB

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ON SITE DEMONSTRATION

MULTI-ROBOT SYSTEM

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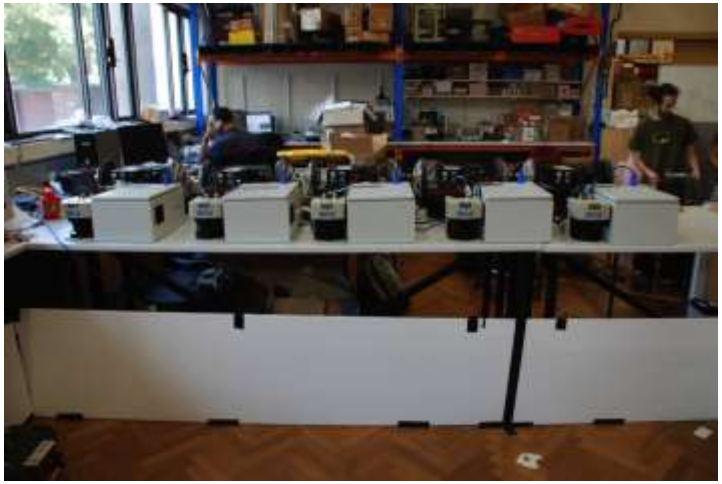
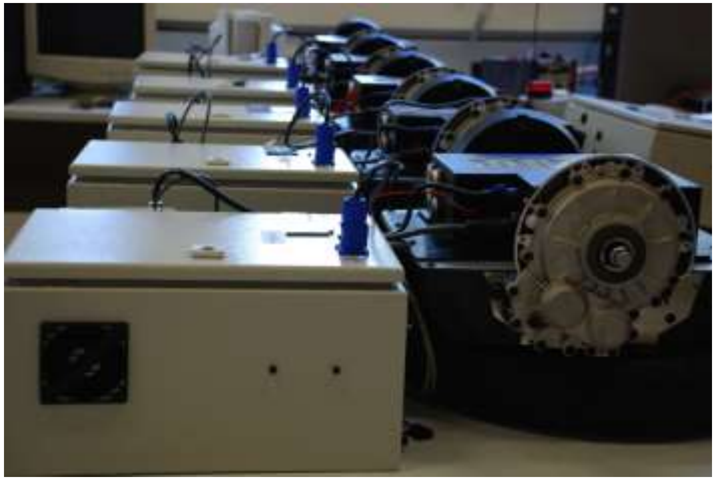
MULTI-ROBOT SYSTEM





SPECIAL FORCES TRAINING

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MARATHON TARGETS

- Marathon Targets established to exploit the technology
- Supplying flexible robotic training systems to special forces around the world
- Requirement for a multi-robot system with a SLAM based mapping system that can be run by non-specialist operators
- Significant engineering investment in reliability and robustness
- Entire system essentially redesigned from the ground up

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SEMI-URBAN OPERATIONS

SEMI-URBAN OPERATIONS

Robots at Work

Autonomous Mining

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Mining

- The Rio Tinto Centre for Mine Automation represents one of the world's largest commercial automation projects
- Established in 2007 to exploit developments in autonomous systems for mining applications
- Automated drill rigs originally developed at the ACFR are now in continuous 24/7 operation and can be controlled from a Remote Operations Centre in Perth
- Work continues to increase safety and efficiency through the use of:
  - Novel sensing techniques
  - Machine learning
  - Data fusion
  - Systems engineering

Mining

- Complex system of systems
  - Centralised, hierarchical control
  - ‘Chain of command’
  - Bounds on responsibility
- Trusted systems
  - Different OEM implementations
  - Commanding / interfaces
  - Monitoring / safety
- Humans & autonomous systems at different levels
  - Levels of autonomy
  - Manned → Autonomous
    - Machine operators
    - Supervisors of autonomy
    - Planning (level of detail)





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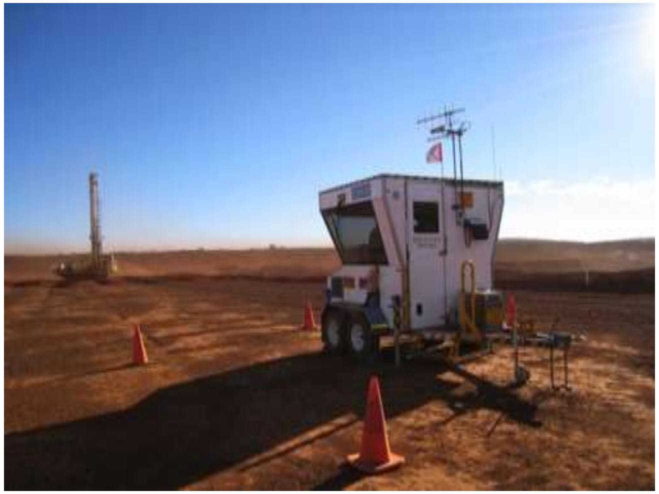
AUTONOMOUS DRILLING

RIO TINTO



Robots at Work

Art

ROBOTIC ART

- Requires
  - Consideration of aesthetics
  - Focus on form rather than technology
  - Human robot interaction

Robots at Work

Agriculture

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AGRICULTURE (GROUND)

- Long-term perception problems
- New sensor modalities
  - Hyper-spectral
  - Gamma log
- Mutli-robot survey
  - Air/ground collaborative mapping
  - Harvest yield estimation
- New robots
  - Ladybird
- Manipulation of the environment




Robots at Work

Environment (marine)

FRONTIERS IN MARINE ROBOTICS

- Long history of successful adoption of robotic systems in marine sciences (oceanography, biology, geoscience, archaeology, etc.) and industrial applications (exploration, oil and gas, minerals, etc.)
- Strong 'pull' from end users – requirement for remote and robotic systems
- Support from governments around the globe



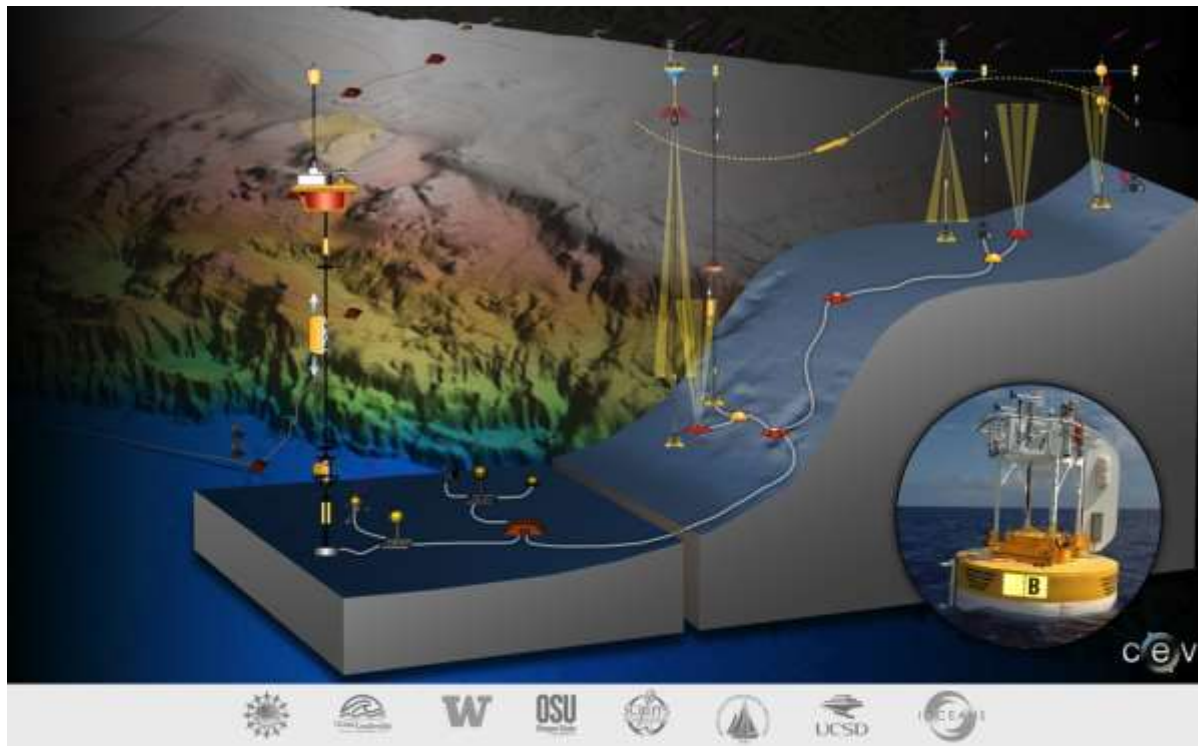




Images courtesy of WHOI, FAU, URI, iRobot, MBARI, Reuters

FRONTIERS IN MARINE ROBOTICS

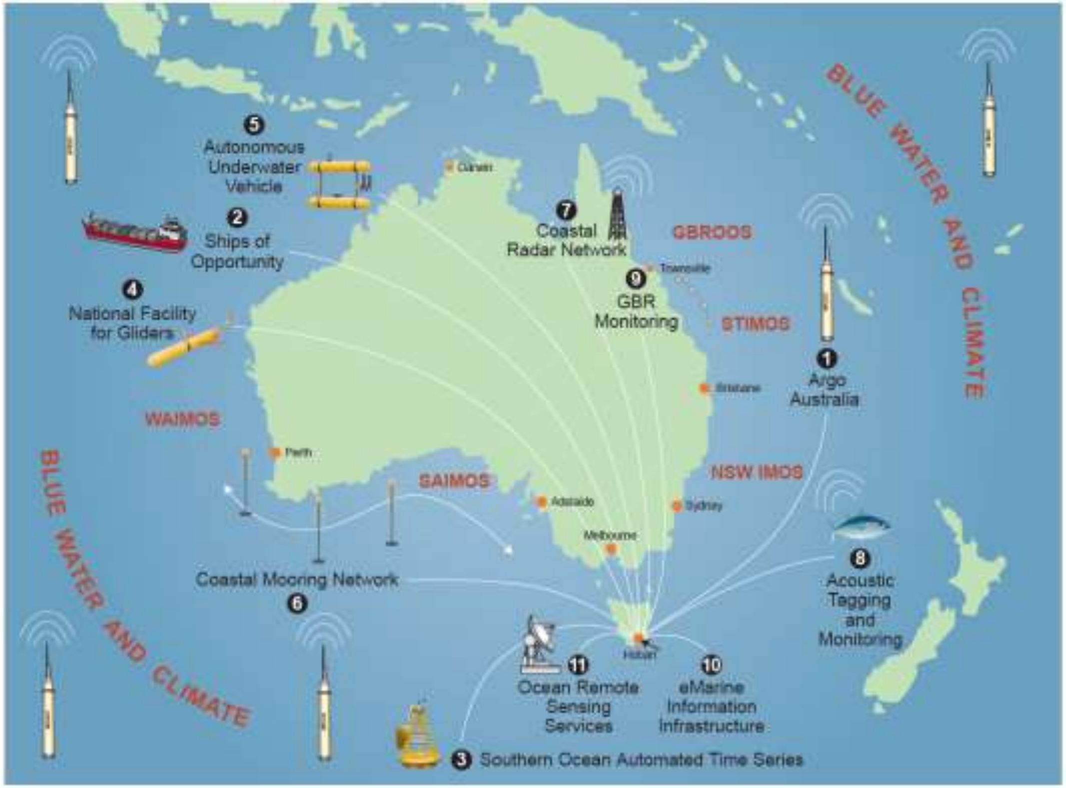
- Initiatives in Ocean Observation designed to understand ocean dynamics
- Integration of modeling with observations provided by satellite and in-situ systems including ship-borne sensors, moorings, gliders and AUVs
- Challenges in navigation, communication, data assimilation, coordination, planning in dynamic fields and long term deployments



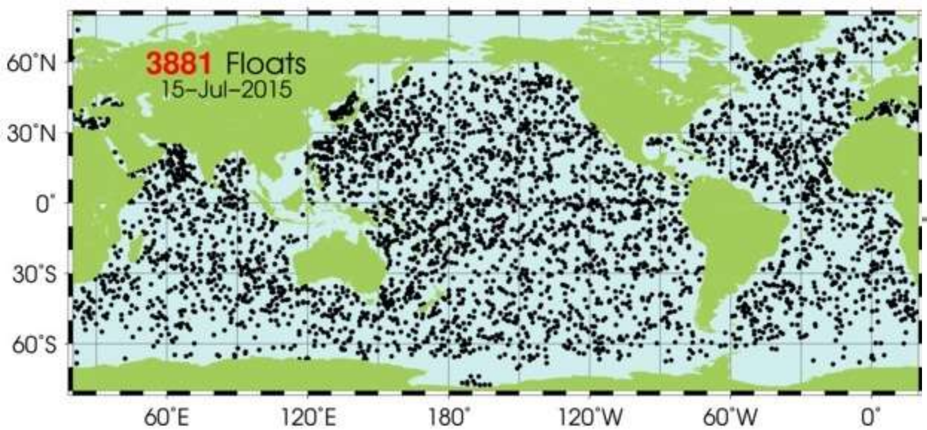
Images courtesy of Ocean Observatories Initiative (http://www.oceanobservatories.org/)

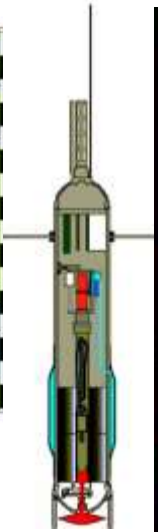
INTEGRATED MARINE OBSERVING SYSTEM

- NCRIS is a program designed to provide infrastructure to support national research priorities
- Marine Science designated as one of 8 priority programs
- A $150M program to provide infrastructure to support the marine sciences in Australia (2007-2016)

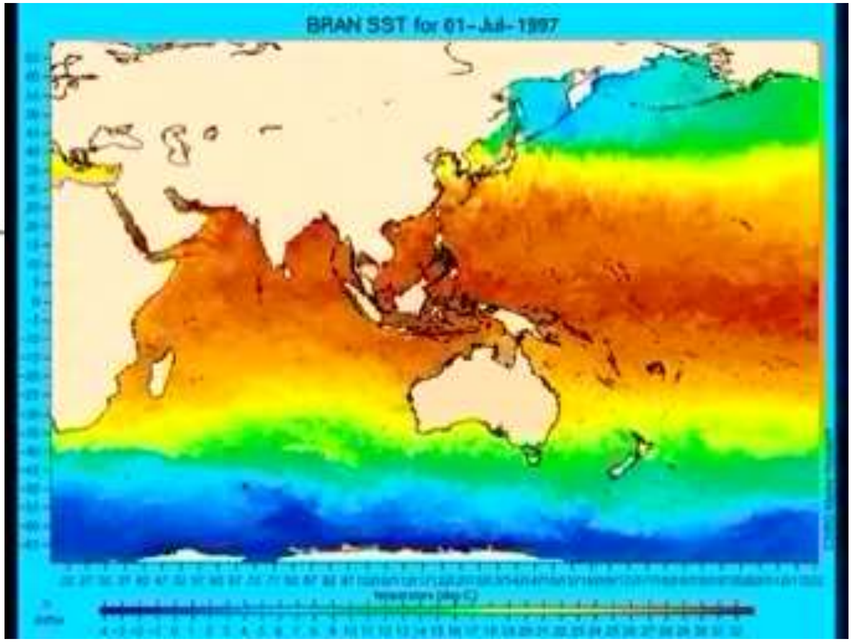


ARGO FLOATS





Floats

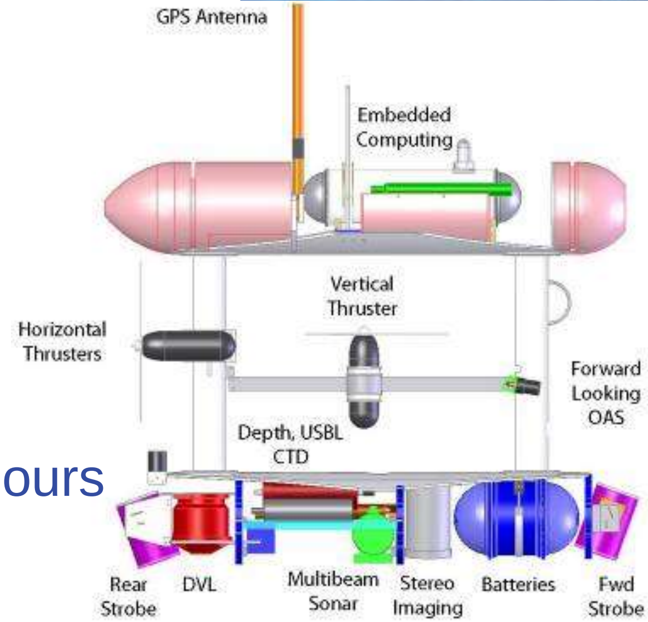


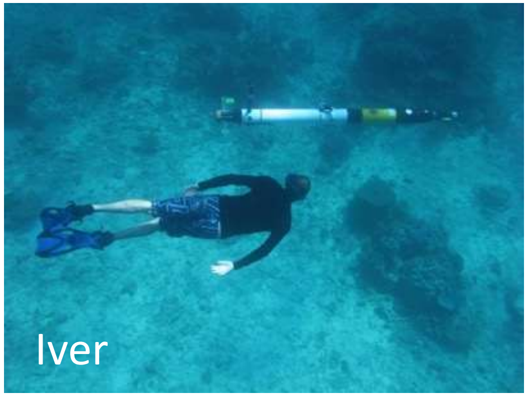
Gliders

Animal tagging and telemetry

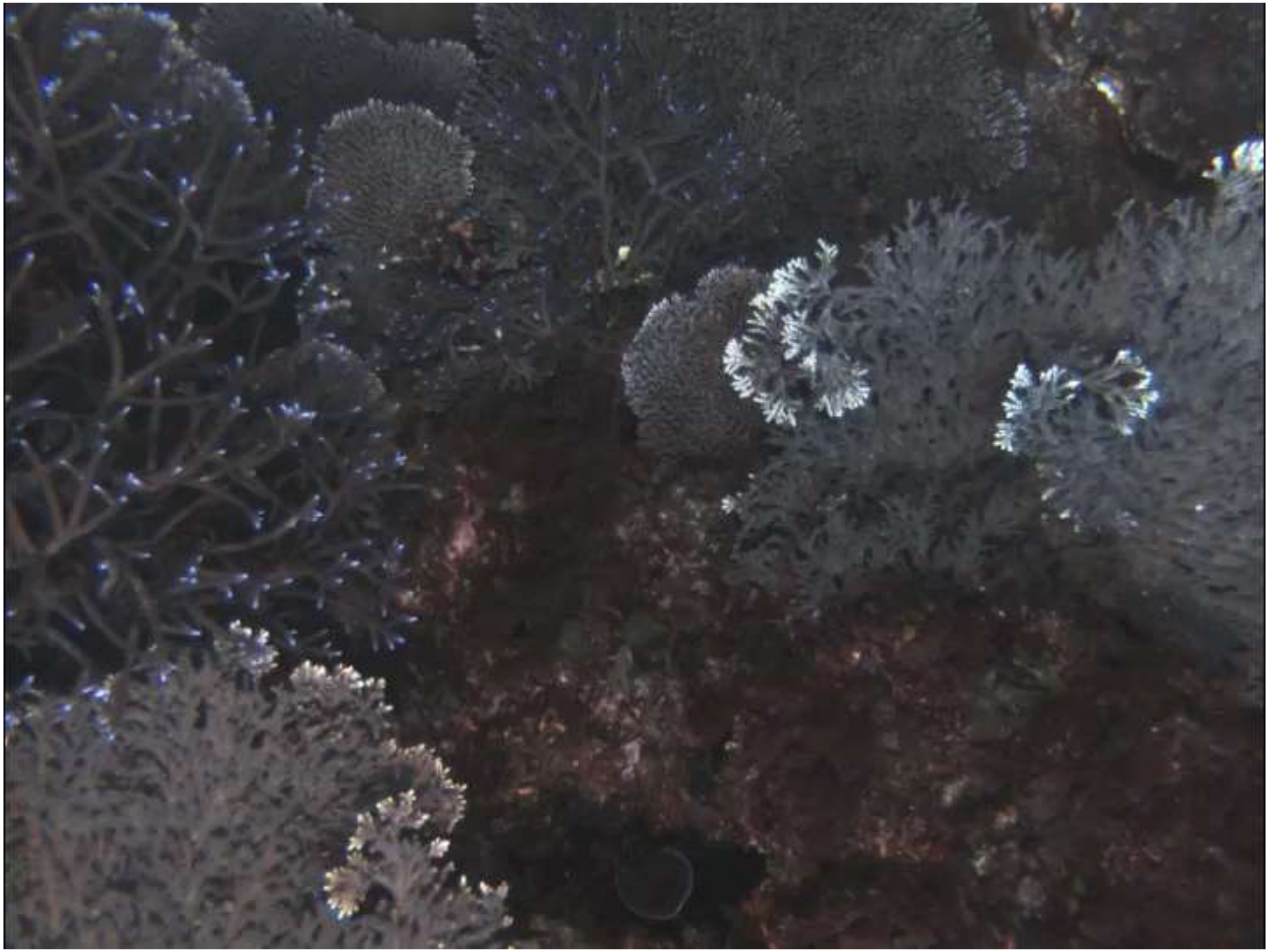
IMOS AUV FACILITY

- Flexible, mobile, high resolution data collection device
- Objective to monitor benthic processes and relate changes to oceanographic processes
- Sensors include
  - Vision (stereo)
  - Sonar (multibeam, imaging and fwd obstacle avoidance)
  - DVL
  - Compass
  - Pressure
  - Water Chemistry
  - Up/down looking hyperspectral
- Depth to 800m
- Mission Time up to 12 hours

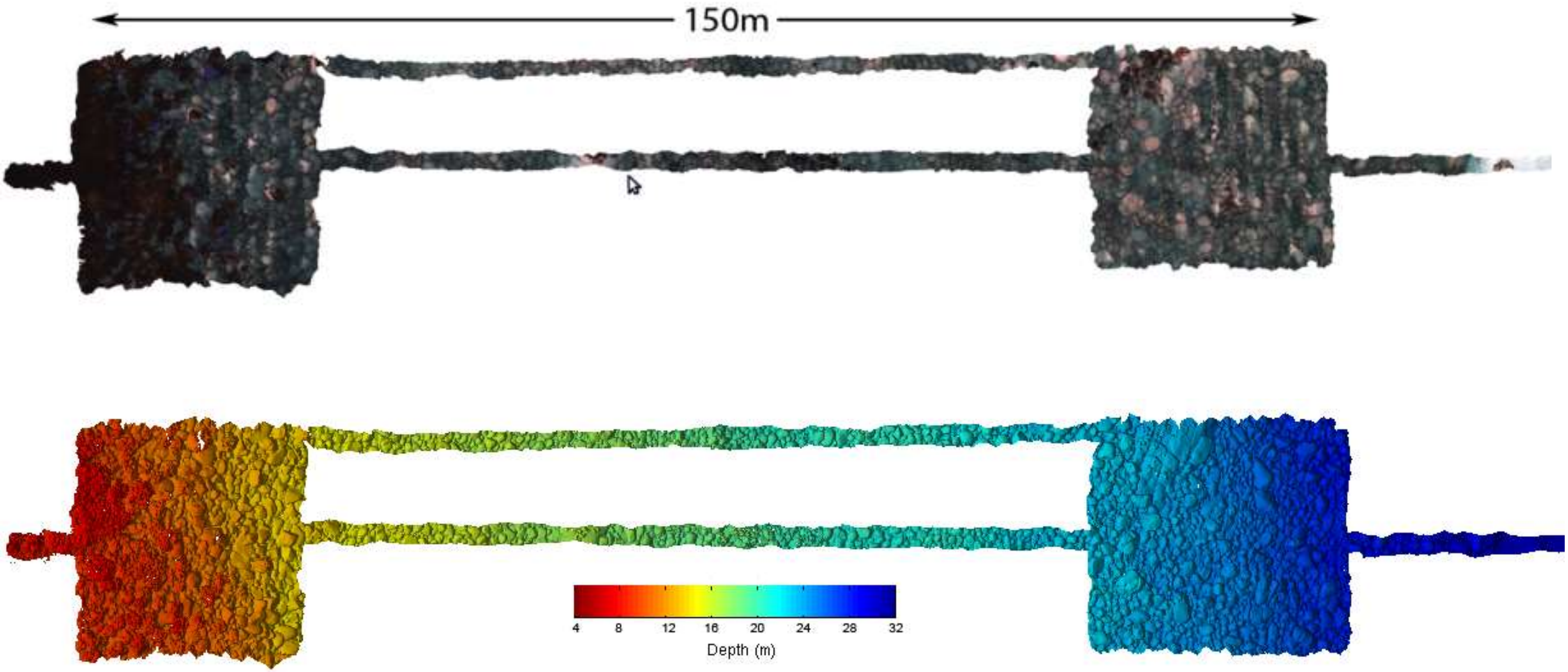




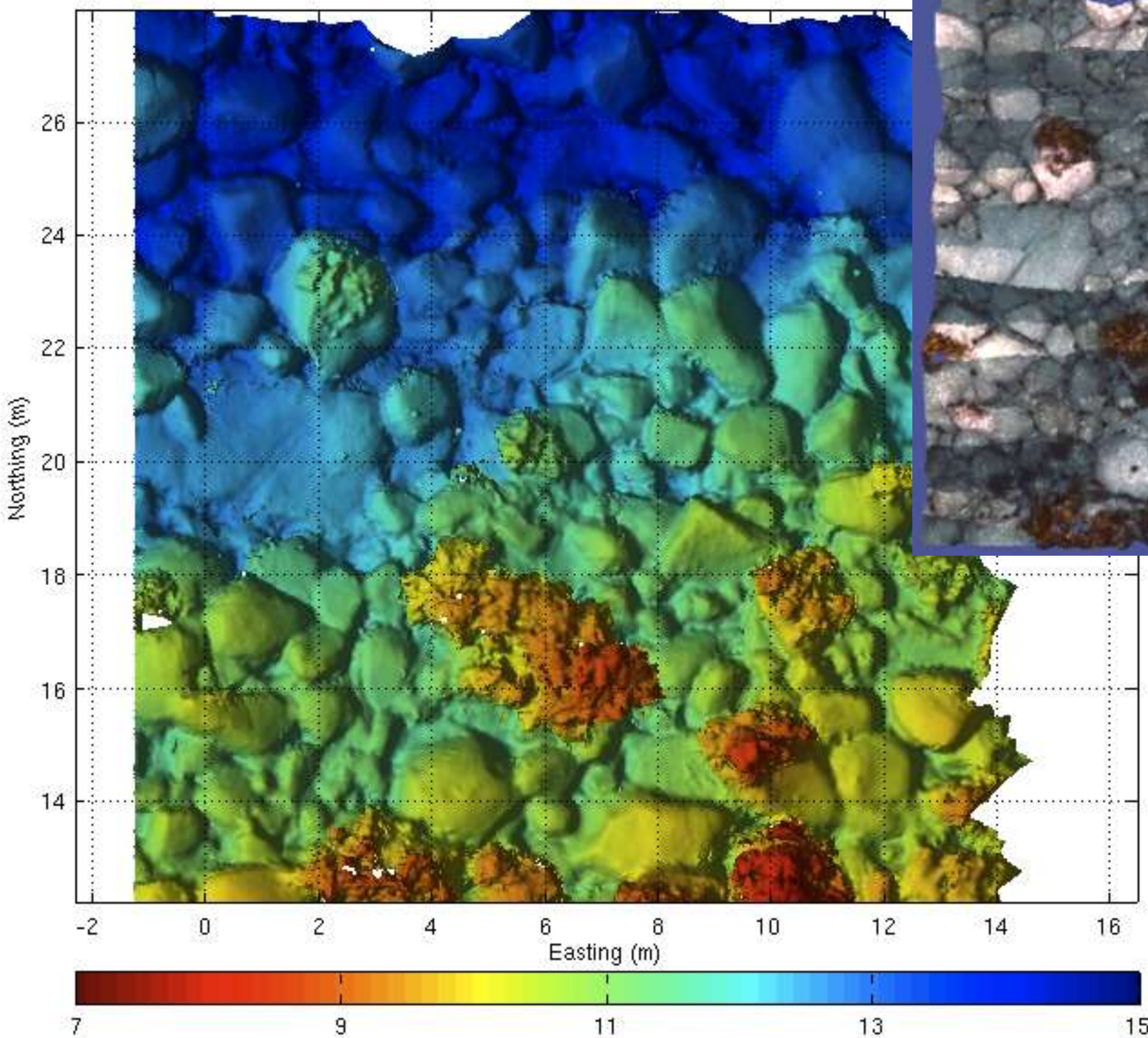
AUV PLATFORM - IMAGING

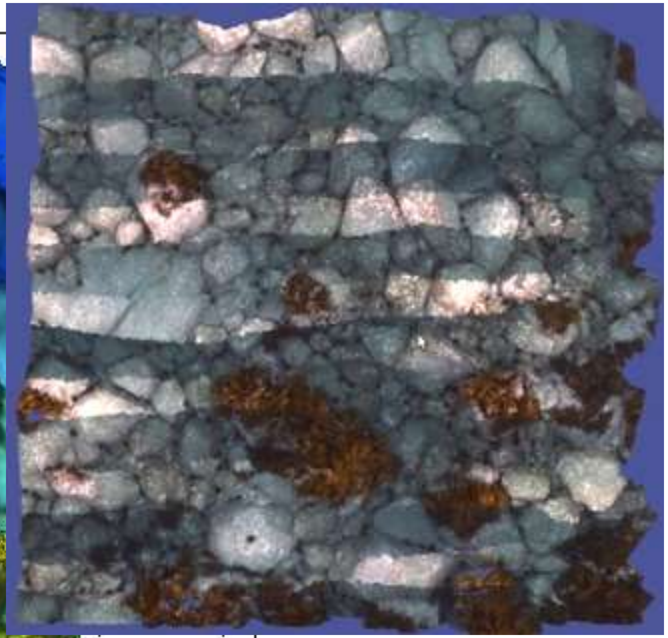


BATHYMETRY FROM STEREO

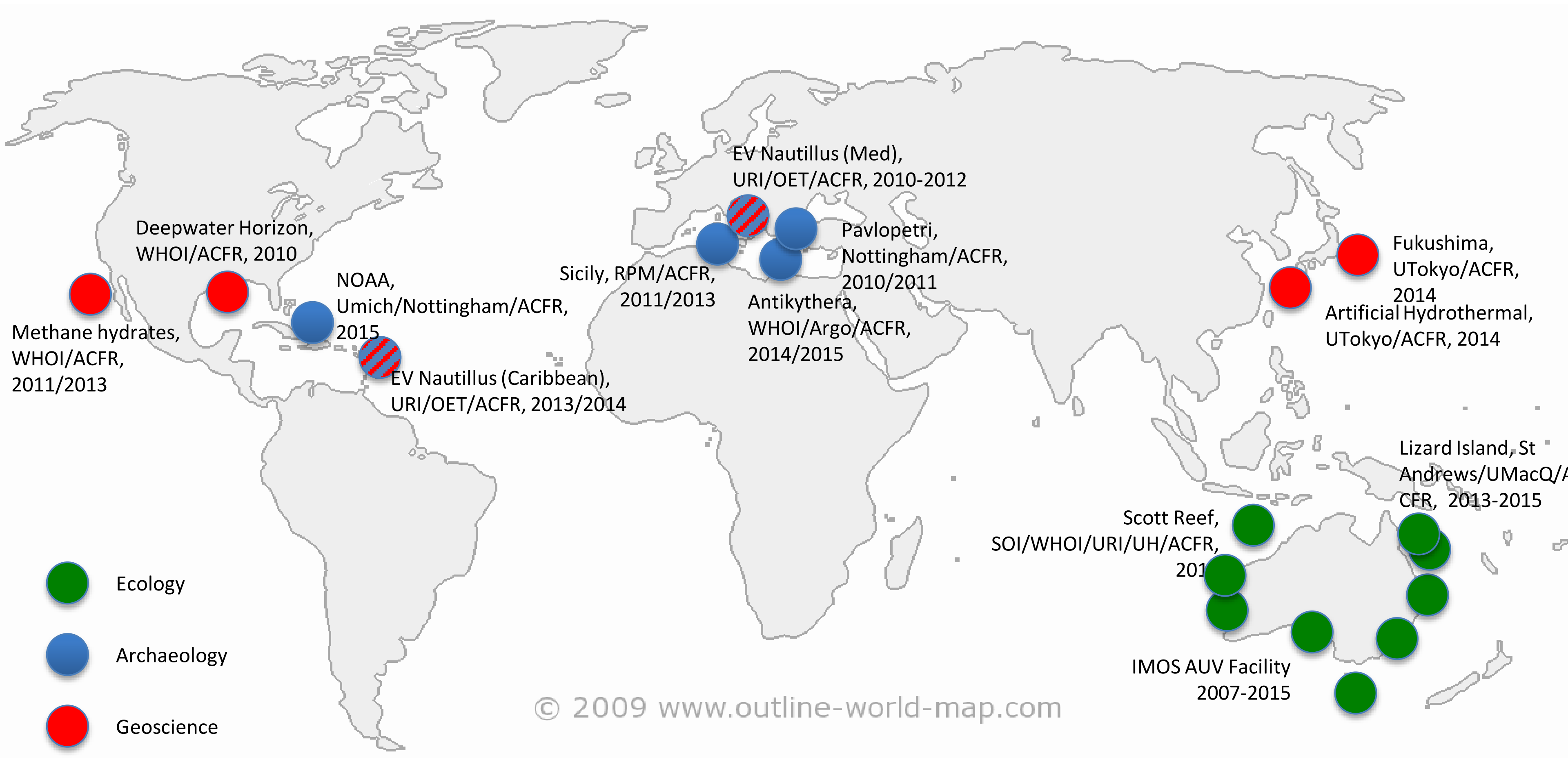


BATHYMETRY FROM STEREO

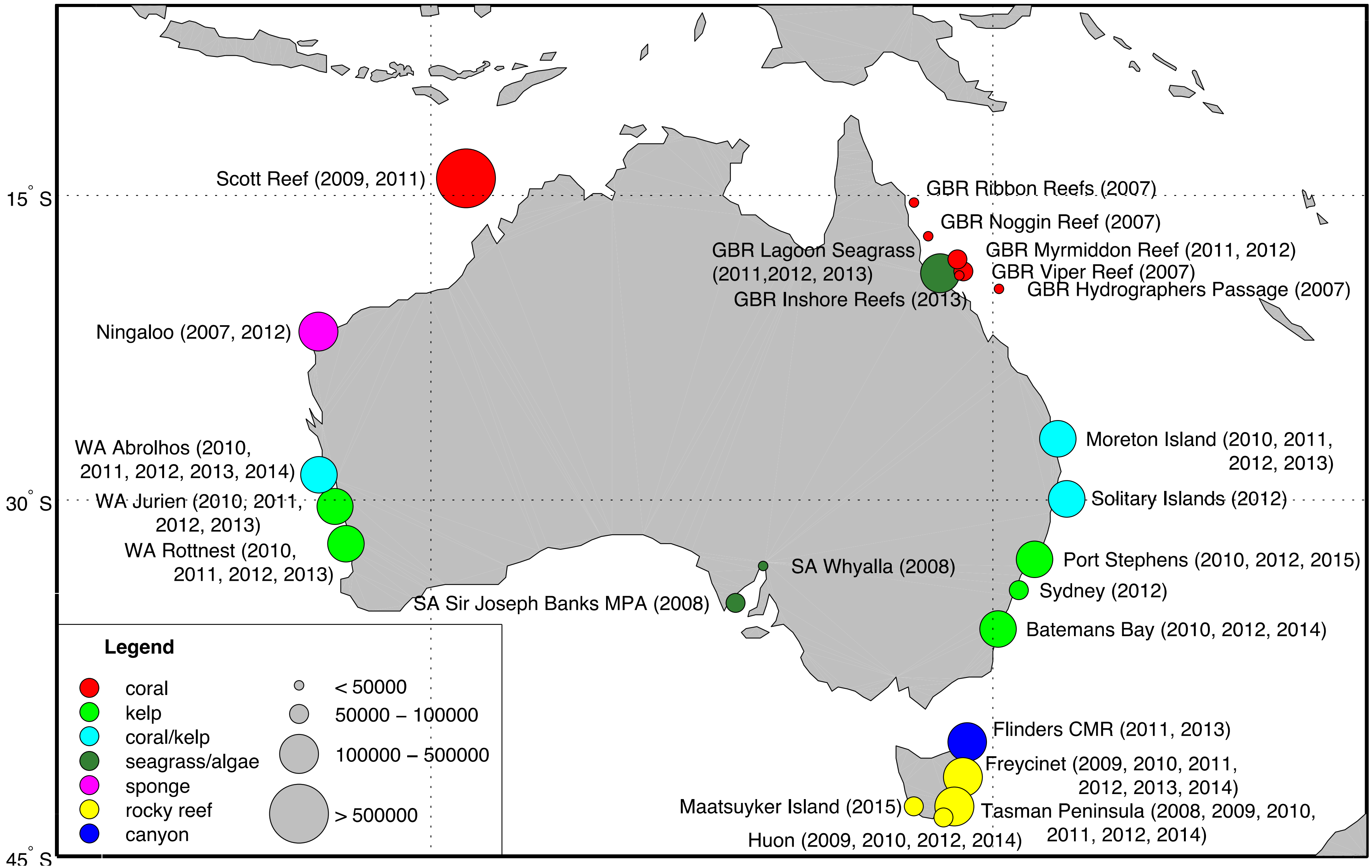




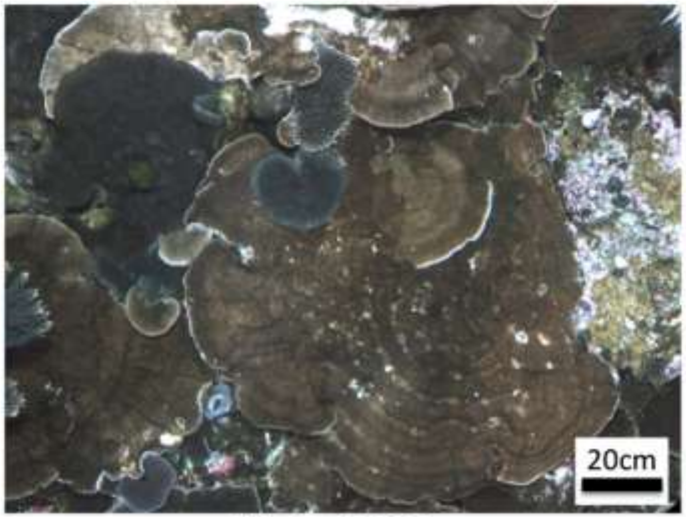
AUV AND ROV SEAFLOOR SURVEYS



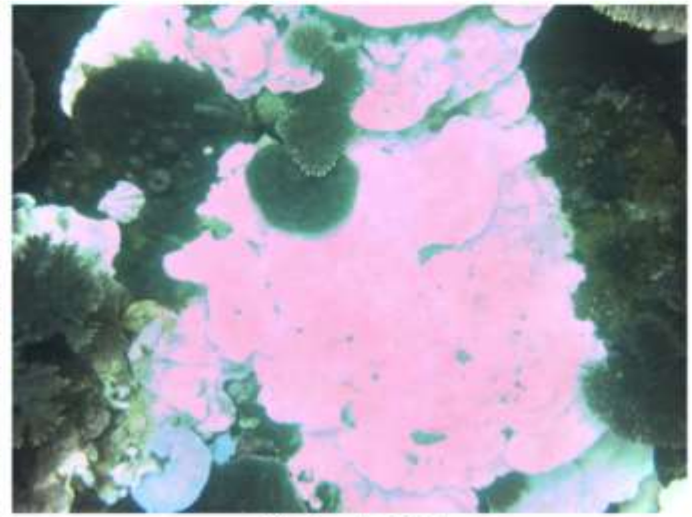
IMOS AUV DATA ARCHIVE



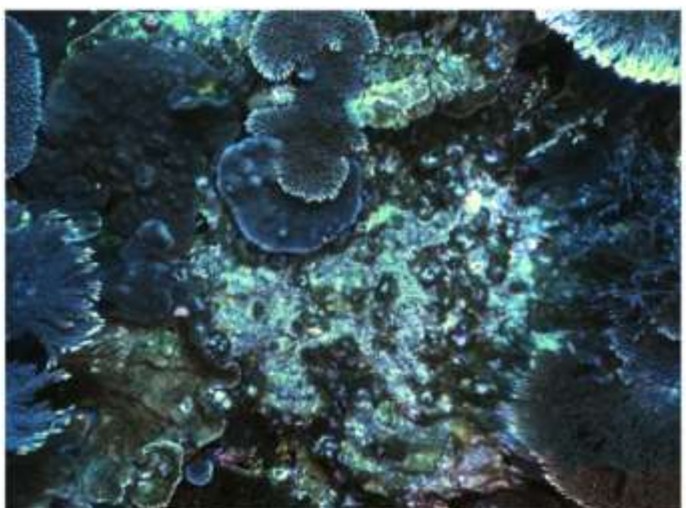
REGISTERING MULTI-YEAR DATASETS



(a) April 2010



(b) April 2011

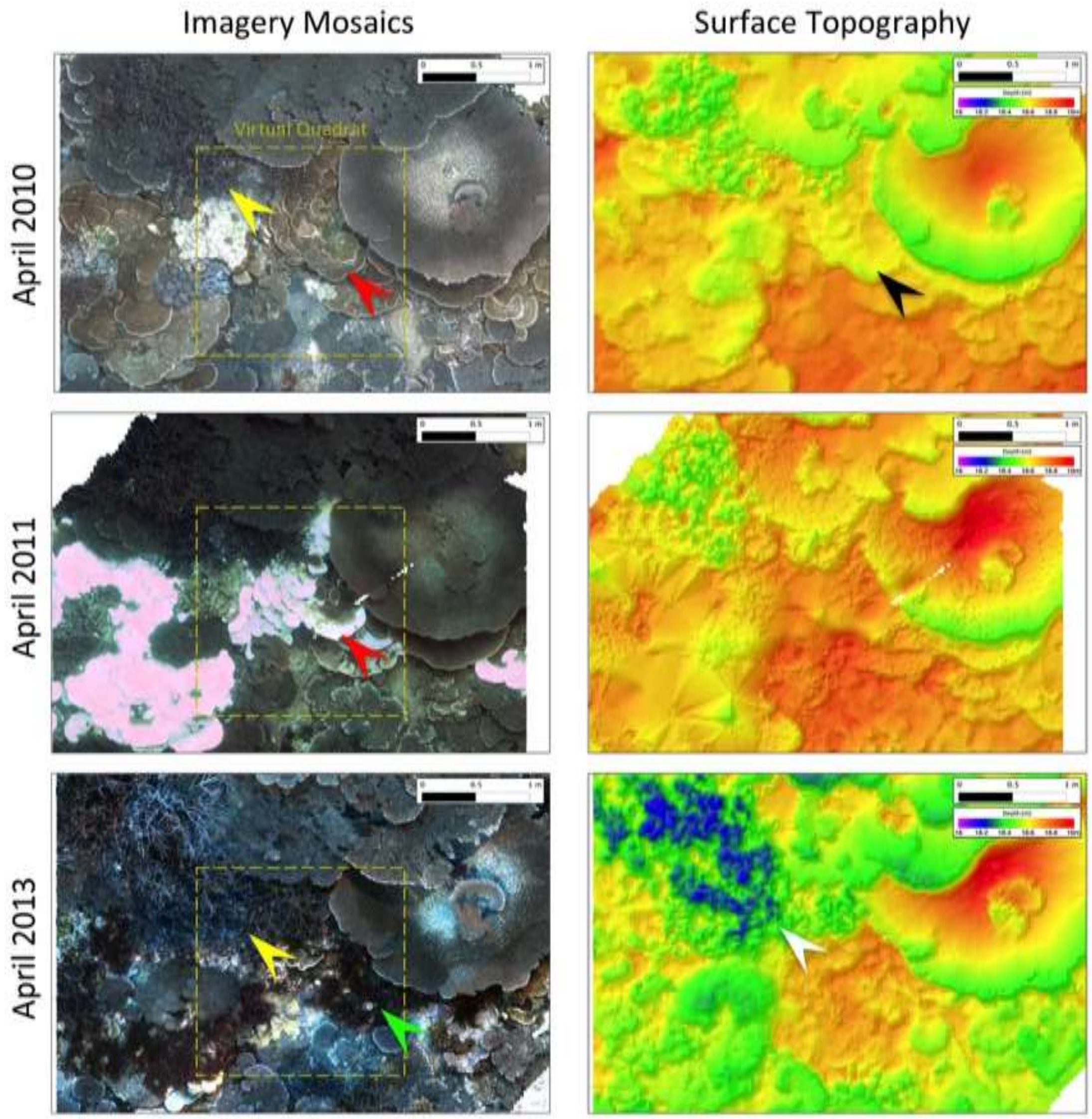


(c) April 2012

(d) April 2013

REGISTERING MULTI-YEAR DATASETS

- Now examining detailed changes in structural complexity across plots
- Some areas show decreases in complexity due to mortality
- Others are increasing in complexity as branching corals begin to grow



MULTIPLE VEHICLE DEPLOYMENTS

- Latest expedition to Scott Reef in WA, supported by Schmidt Ocean Institute, aimed to demonstrate multi-vehicle, coordinated operations
  - ACFR: AUV Sirius, 2x Iver AUVs
  - URI: Imaging float
  - WHOI: Slocum glider
  - UH: Wave glider
  - EvoLogics: USBL Communications and tracking
- Surveying a 300 km^2 coral lagoon
- Live tracking of vehicles broadcast online
- Upload of images for online annotation and remote visit of ship to support outreach

MULTIPLE VEHICLE DEPLOYMENTS

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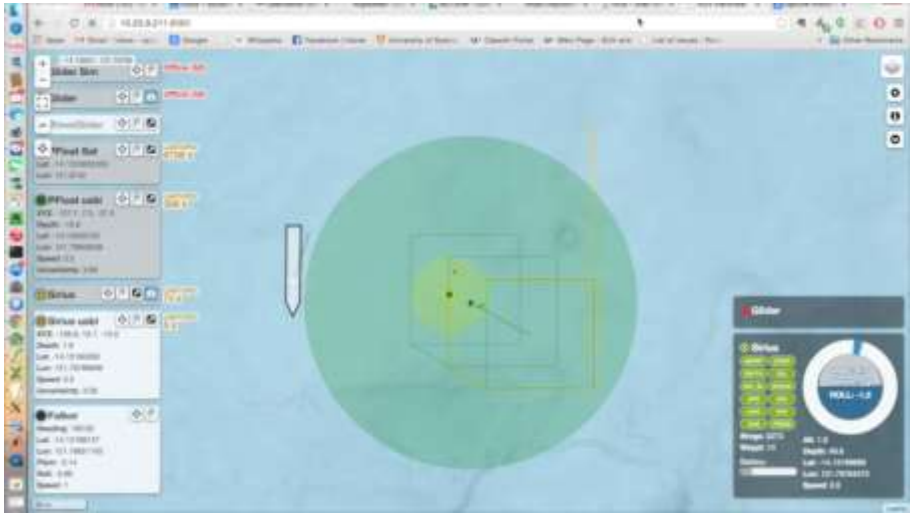
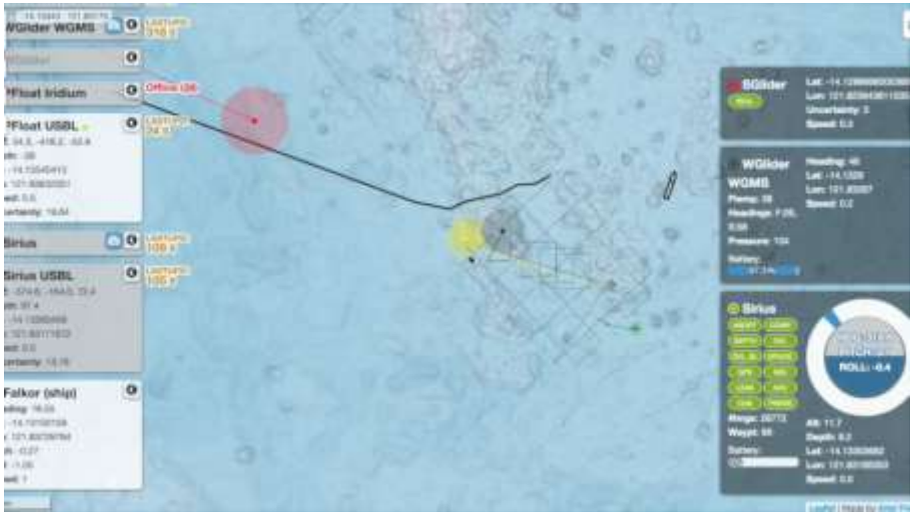
- One of the key building blocks for these multi-robot systems is the communications and visualisation infrastructure required to track multiple platforms
- Coordinated deployments of up to 4 platforms operating around ship
- Initial experiments conducted in online replanning and collaborative survey





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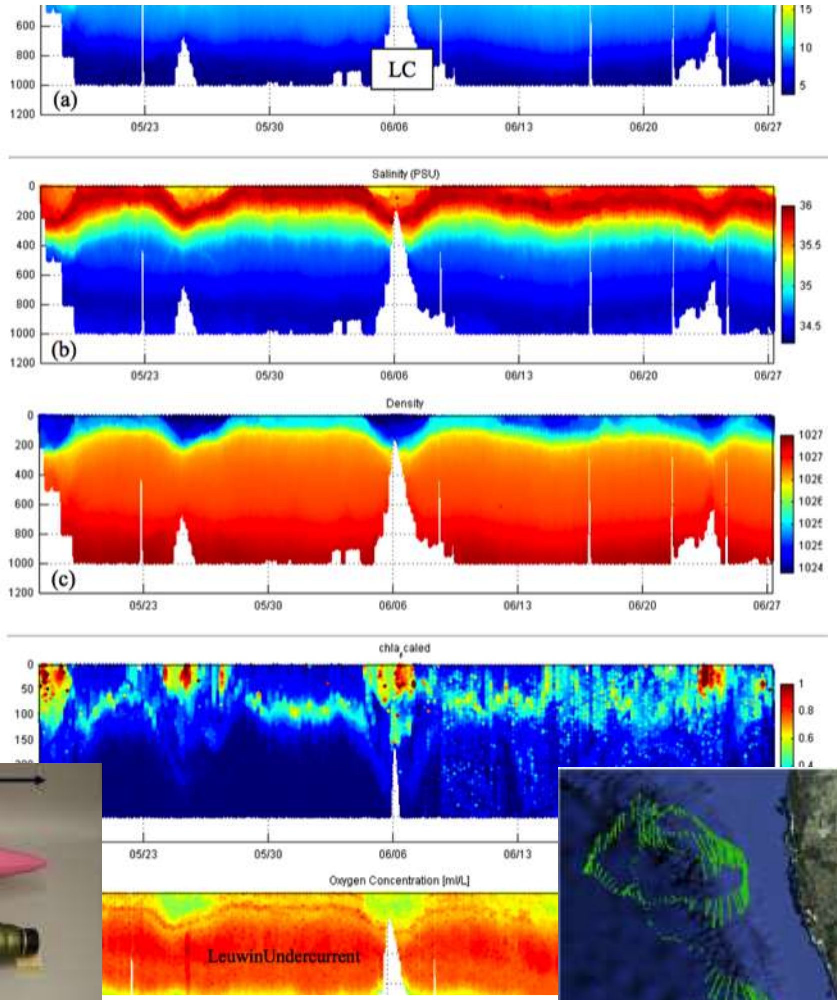
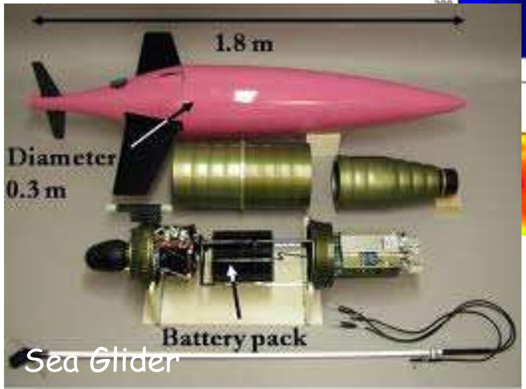
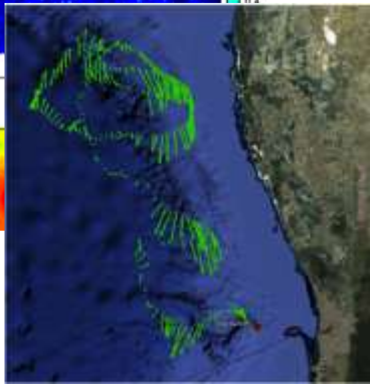
LONG RANGE GLIDERS

- Oceanic gliders currently have endurances of several months using buoyancy engines
- New thermal propulsion mechanisms promise to extend these endurances to multi-year deployments



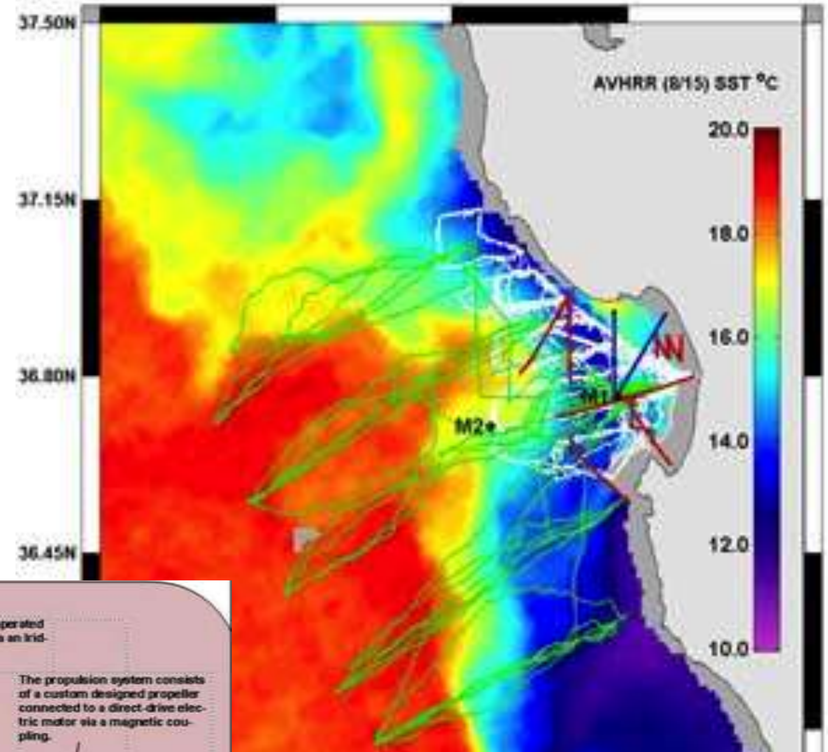


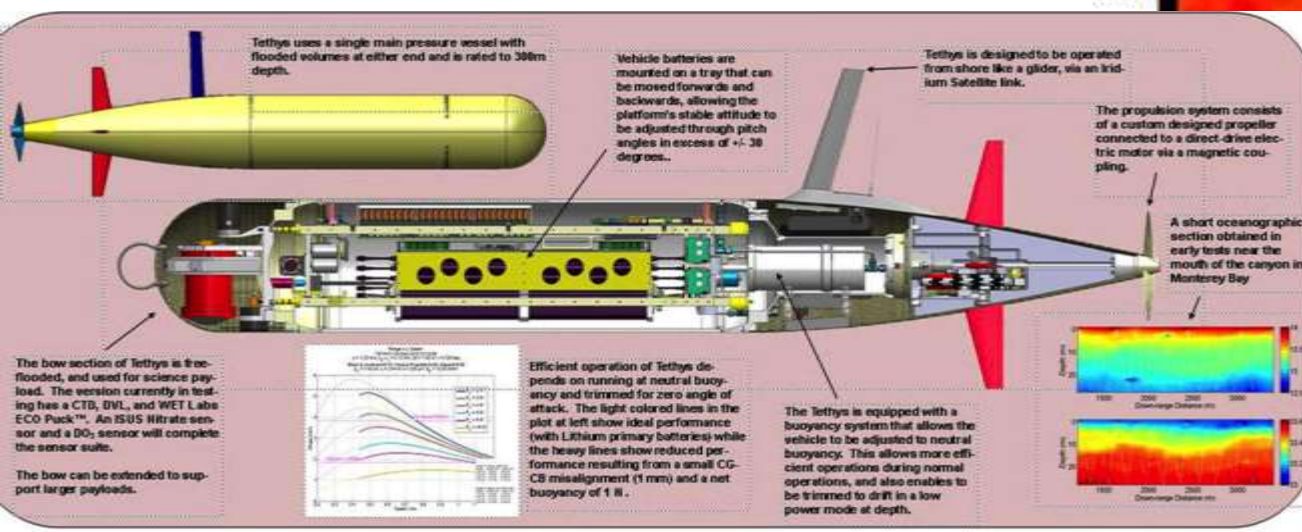
Images courtesy of Webb, U Washington and UWA



LONG RANGE AUVS

- A number of organisations are now developing long range AUVs
  - MBARI: Tethys vehicle (range: 1000km)
  - Southampton: Autosub long range (range: 6000km)





Images courtesy of MBARI and NOC

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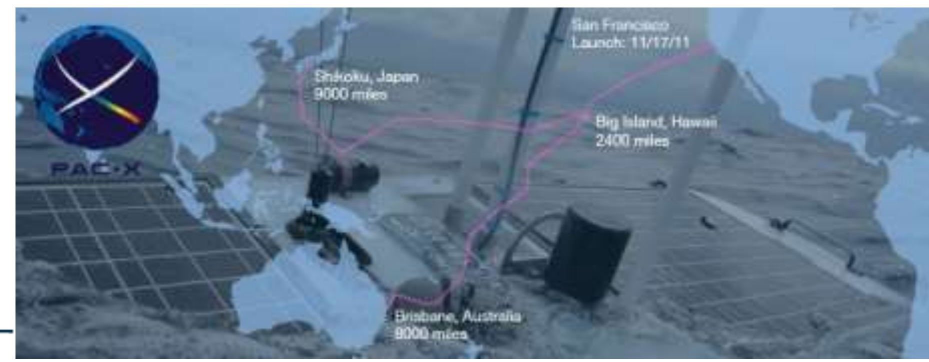
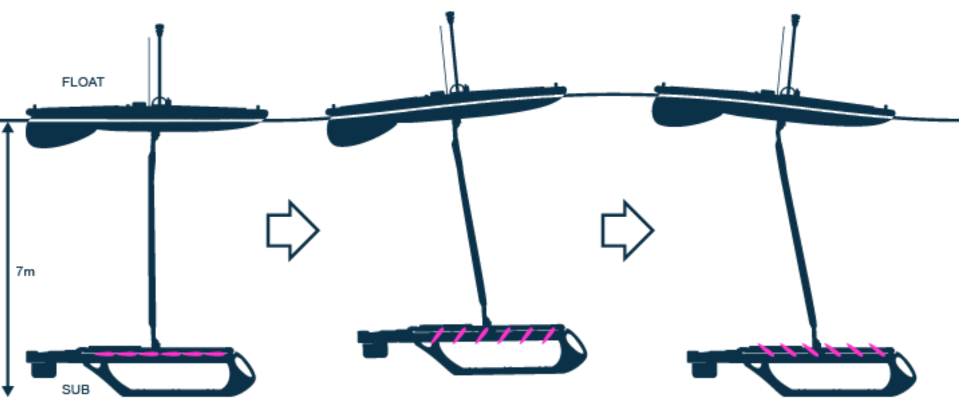
LONG RANGE USVS

- Wave glider uses wave energy for propulsion
- Long range/duration capability (recently completed ~17000 km crossing of Pacific)





Images courtesy of Liquid Robotics

FUTURE DIRECTIONS

- Novel sensing payloads and vehicle systems
- Further improvements in navigation and planning
- Supervised autonomy under communication constraints
- Multi-vehicle, heterogeneous operations
- Adaptive mission planning
- Long term deployments
- Intervention (grasping and manipulation)

CONCLUSIONS AND FUTURE WORK

- Fielding multi-robot systems requires considerable engineering work in addition to algorithmic development to build reliable systems
- Engaging with end user communities in exploring the application of these technologies to a variety of application domains
- Exciting challenges and novel applications likely to drive developments in these areas

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HAL
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IMOS
Integrated Marine Observing System

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Agency for Defense Development

TOYOTA

KOMATSU

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