Requirements and Initial Testing of an Inspection Class ROV as a Benthic Habitat Inspection Tool

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The Autonomous Ocean Systems Laboratory (AOSL) at the Memorial University of Newfoundland recently acquired an inspection-class Remotely Operated Vehicle (ROV), a Saab-Seaeye Falcon ROV. The purpose of the Falcon ROV is to develop, implement and validate advanced closed-loop control and navigation algorithms to facilitate the usage of the ROV for science applications, such as marine habitat surveys. Following these developments, we are going to use the improved vehicle dynamics to artificially impose the behaviour of a different underwater vehicle onto the system. This will provide a valuable platform for autonomous underwater vehicle development.

The first stage of this development plan was the initial testing and characterization of the existing Falcon ROV, followed by a detailed list of requirements for the marine habitat surveys. In August 2010, a scientific research cruise took place in northern Labrador. The primary science sensor for benthic habitat mapping was the Falcon ROV's onboard tilt video camera. For navigation and geo-referencing of the acquired video data, an acoustic Ultra Short Baseline (USBL) positioning system was installed on board the ship "*MV What's Happening*". A multi-node network, consisting of several computers, a time-server, GPS and video-recording device was set-up to time–synchronize all scientific and engineering data.

The experiences of operating the Falcon ROV during the cruise and the resulting video data collected provided the necessary input for defining requirements for the next stage of improvements. This includes qualitative observations of pitch and roll stability, and the challenges of subsea positioning accuracy.

This presentation will discuss the advantages of using the Falcon ROV versus a drop camera for visual benthic habitat inspection, challenges and solutions for geo-referencing collected video data from the ROV, and resulting improvements desired for the dynamic performance of the vehicle. In addition, several examples of collected data will be presented.

Controlling Manipulators on Remotely Operated Vehicles

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Current submerged science endeavours such as **VENUS** [1] and **NEPTUNE** [2] off the Canadian Pacific coast are creating a surge of interest in underwater remotely operated vehicle-manipulator systems (**ROVMs**) – particularly small easily deployed variants of this class. Demonstration of ROVM capabilities in this application is also creating uptake of ROVM technology for servicing other smaller scale ocean monitoring equipment and moored aquaculture and ocean energy installed in relatively shallow waters (< 300 m). For these smaller scale applications, the need for smaller economic ROVMs is acute. Unfortunately, existing small ROV platforms lie within the inspection class and are not equipped to complete complex and interactive submerged tasks. At the UVic Subsea Robotics Lab, current research is aimed at adapting a popular small inspection class ROV, a Saab-Seaeye FALCON, into a ROVM capable of low-cost and time-efficient submerged manipulation.

The research program has three distinct phases: theoretical development of a ROVM simulation platform(s) and the synthesis of candidate control algorithms that are trialed on these simulators; development of ancillary hardware (a joystick) necessary to implement the control strategies on the FALCON platform; and, experimental trials of the outfitted FALCON in a test facility.

A distinguishing characteristic of all the control approaches studied is the reliance on a redundancy resolution (**RR**) scheme to distribute the desired end-effector motion over the ROV and manipulator in a coordinated, intelligent manner. This eliminates the standard practice of holding the ROV stationary during a task and uncovers significant potential in the small ROVM platform by transforming it into a redundant manipulator capable of the primary task plus a set of secondary objectives that improve the efficacy of the pilot interface. A large portion of the theoretical research has been experimenting, numerically, with different coordination schemes. In [3], dexterous manipulation is obtained by using the ROV degrees of freedom (DOF) to avoid singular configurations and minimize vehicle motion. A methodology that has a more complete set of objectives with a fault-tolerant property is proposed in [4]. The multiple objectives considered in [4] are: avoiding manipulator joint and velocity limits, avoiding singularity, keeping the end-effector in sight of the on-board camera, minimizing the vehicle motion; and minimizing the drag induced disturbance. The hierarchy of tasks is dynamically allocated by the Mamdani type fuzzy control. In [5], [6] and [7], a consolidated dynamic model and revised adaptive sliding mode controllers were added to the portfolio.

Execution of any of the strategies relies on an improved pilot-machine interface to gather the desired end-effector motion. A unique six-DOF joystick produced by RSI Research Ltd. has been employed, and hardware–in–the–loop simulations were performed to evaluate the performance of the proposed redundancy resolution schemes for a broad range of ROVM operation scenarios in [7] and [8]. The simulator uses an OpenGL based 3-D graphical display to emulate the visual cues provided to the pilot during actual ROVM operations. Through the simulation trials, a final control strategy employing a tri-layer structure (equivalent, adaptive and PID layers) has been chosen to work with the RR algorithm.

Now in the implementation phase, the program uses a modified Hydro-lek HLK 43000 4-DOF hydraulic manipulator designed specifically for the FALCON platform. In the first leg of the implementation, the developed controllers and visual-aided human machine interface is being implemented in collaboration with Ocean Dynamics Canada (ODC). This project also involves designing a new modular navigation skid that uses a blend of Doppler Velocity Log, compass, inertial measurements and acoustic position data to track the vehicle state at a rate commensurate with the ROVM controllers. To blend sensor data, an EKF described in [9] is used. The EKF includes a simple and direct estimation of the tether disturbance force to prevent model induced drift in instances of high tension – a development motivated by observations in [10]. Two automatic vehicle control modes, station keeping and cruise mode, are being trialed. In station keeping, an H-∞ sliding mode controller based on the work of [11] is used. In the cruise mode, the recommended tri-layer controller is used to automatically drive the ROV. For both modes, the commanded forces and moments are distributed over the on-board thrusters based on the fault tolerant, infinity-norm minimization of the thrust vector based on the work of [12].

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ROV Operations with a Sub-Bottom Profiler

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The Sub-Bottom Imager™ (SBI) is a 3D acoustic imaging tool. This tool is an evolution of the Acoustic Corer™ technology to advance conventional acoustic applications.

The SBI interfaces with an ROV and its technology is a unique fusion of beam forming, synthetic aperture sonar (SAS) processing, parametric and chirp transmission. The SBI is used for site assessment prior to pipeline laying to identify geo-hazards and debris lying in, or near, the pipeline route. It will be employed to determine the as-laid burial position of the pipeline and to conduct routine depth of burial and out-of-straightness re-surveys.

The SBI has applications for imaging buried high voltage direct current (HVDC) cables to provide cable position and depth of burial.

The SBI delivers:

- high-resolution volumetric images 5 m wide with a 5 m swath
- real-time data processing

The SBI technology:

- optimizes survey accuracy and pipeline route
- provides accurate imaging of pipe integrity and burial depth

offers accurate detection of areas requiring remedial action.

On-Board AUV Autonomy through Adaptive Control of Fins

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A knowledge-based agent was designed and validated to optimally re-distribute control authority in a torpedo-shaped autonomous underwater vehicle (AUV). The objective is greater fault tolerance in AUVs on long deployments when an AUV is unexpectedly under-actuated from a jammed control fin. The optimization is achieved through a genetic algorithm that evaluates solutions based on a full non-linear analysis of the AUV dynamics and control. The agent is implemented on-board the AUV to provide timely re-assignment of the fin control authority (gains) while underway so that the mission can continue or a potential vehicle loss can be averted. The effectiveness of the agent is assessed through a parametric analysis that compares the response of the unexpectedly under-actuated AUV with its initial gains against the optimized gains. The agent's greatest impact is in the event of a bow fin jam as the remaining functional planes maintain depth better with the agent's help. The ability to provide a timely and on-board optimal solution that adapts to a fin jam is a higher level of autonomy than has been previously reported.

Towards the Development of an Autonomous Iceberg Draft Measurement Probe (AIDMP)

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For various reasons icebergs are a major concern for off-shore operations in the Northwest Atlantic and in particular along the Labrador Coast and the Newfoundland Shelf. One of these concerns is the danger these icebergs pose to subsea installations, such as manifolds and pipelines. In this presentation we address the issue of developing a device to reliably measure the maximum draft of an iceberg in order to determine the threat this iceberg poses for subsea installations.

The goal of this project is to develop an autonomous iceberg draft measurement probe (AIDMP) which is low cost, un-tethered and safe to deploy. As an initial concept we are looking into a free- falling, rotating cylinder equipped with a depth and attitude sensor and a single-beam ice-profiling sonar. We are presenting the initial concept of operation and the custom-designed data-logging system. Furthermore we are introducing the next phase of the project in which we are conducting a series of tank tests to evaluate the hydrodynamic stability and rotational velocity of the device as a function of immersion angle, righting moment and external rotor configuration.

Collaborative AUVs for Survey and Search Missions

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Given that AUVs are being used for longer and longer survey and mapping deployments, on-board high-level decision-making and re-planning of missions (autonomy) is a necessity. This type of autonomy completely changes the way autonomous vehicles are employed. DRDC has been working to advance high level control of autonomous vehicles and in particular, Autonomous Underwater Vehicles (AUVs). This is achieved through an on-board "backseat driver" computer that oversees mission and vehicle requirements and makes decisions with a multi-agent system that accordingly tasks the AUV's vehicle control computer. DRDC's Automatic Target Recognition (ATR) tools will be integrated into the backseat driver. This results in an innovative on-board capability for an AUV as it allows in-situ and timely detection and classification of mine-like objects. This reduces the need for an operator and for multiple recoveries of the AUV. With such capabilities the AUV(s) can autonomously decide to go back and view an object from a different perspective (or task another AUV to do so) to confirm whether the object is mine-like or not. AUVs outfitted with ATR capability work collaboratively (as opposed to cooperatively) on survey missions of which mine counter-measures (MCM) is a particular example. The development of algorithms to have the AUVs work collaboratively is another objective. The work described herein advances work in AUV autonomy in general.

Design and Development of Innovative Twin-Pod Autonomous Underwater Vehicles

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As a leading provider of high-performance underwater acoustic technology, Marport Deep Sea Technologies Inc. is introducing to market next-generation sonar systems based on their advanced Software Defined Sonar (SDS) signal processing system. Seeking a demonstration platform for these new systems, Marport investigated existing Autonomous Underwater Vehicle (AUV) technology, and identified a opportunity to develop an innovative new vehicle; the SQX-500 AUV.

The SQX-500 is currently under joint development by Marport Deep Sea Technologies Inc, the Institute for Ocean Technology of the National Research Council Canada (NRC-IOT), and Memorial University of Newfoundland (MUN). The SQX-500 is a compact, lightweight AUV designed for search and survey applications in coastal waters up to 500 metres in depth. Employing a unique propulsion and control concept based on thrust vectoring, the SQX-500 is passively stable in pitch and roll, and features high manoeuvrability with capabilities such as hovering, and a zero-turning radius.

With a twin-hull design, and a novel propulsion and control system, the SQX-500 provided several unique challenges during the design and development process. Through this joint development, these challenges have been met with a variety of tests and experiments, and the benefit of cumulative design experience from a wide variety of backgrounds. This presentation will discuss the design and development process of the SQX-500, highlighting some of the key learning experiences, and continue with plans for future vehicles, future payloads and deeper depths.

A Hydrodynamics Simulator Developed for a Twin-Pod AUV

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A novel autonomous underwater vehicle (AUV) is presently under joint development by Marport Canada Inc, the Institute for Ocean Technology of the National Research Council Canada, and, Memorial University of Newfoundland. The concept for this twin-pod AUV is derived from the "SeaBED" vehicle at the Woods Hole Oceanographic Institution (WHOI). However the Marport SQX-500 AUV includes a novel propulsion and control system which uses individually-controlled vertical and horizontal control surfaces and propulsors. A patent application has been filed for this 3D thrust-vectoring system. Benefits of this system include the ability to hover, turn in place, and, translate in both the vertical and lateral directions, in adverse ocean currents.

In order to support the design of the vehicle, a software simulator has been developed for fast prediction of the hydrodynamic performance of the vehicle. The simulator is developed and implemented in MATLAB™ and solves the six-degree-of-freedom (DOF) equations of motion under different operational conditions.

The hydrodynamic modeling for the twin-pod vehicle is greatly simplified by applying the approach of the component-build-up method, which was originally developed for aerodynamic predictions. This method assumes that the hydrodynamic loads exerted on the vehicle can be expressed as the sum of the loads on the different components that form the vehicle, and, that these components can be analyzed separately. The estimates for the different components are made using several different approaches: (i) results from model-scale towing tank experiments, (ii) data from publications, and, (iii) some empirical methods. In addition to the description of the software development, the presentation will demonstrate results from case studies of the vehicle manoeuvrings, such as turning circles, zig-zags, spirals and a helical dive.

Marion Hyper-Sub Provides Daily Subsea Access Through An Improved Economy Model

Reynolds Marion
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The goal of Marion Hyper-Sub is that of making manned subsea access a common and easy everyday occurrence, across many different market sectors, through a universal platform that has been designed around a concept of improved “deployment economics” which effectively eliminates the prohibitive expense, safety concerns and deployment logistics that has always restricted the world's ease of manned access to the subsea environment.

Though (in its production form) the Hyper-Sub will be a 1,200 foot depth capable machine (using its optional steel pressure hull), it is also a true surface vessel that takes advantage of the same **low cost economy** and other proven benefits (range, payload flexibility and freedom) that all other surface vessels possess. Yet, it is still a submarine and therefore by default surpasses the mission flexibility of traditional surface craft.

Key in its design, to insure that such surface craft benefits would be practical and useful in both its surface and subsurface state, a system called hyper-ballasting (a large, two-axis, 30,000 lbs compartmentalized variable buoyancy envelope) was incorporated. Once blended with the final addition of known (certified) pressure hull designs and life support systems, a complimentary affect between the two was realized, yielding not only a high tolerance for variable payload configurations but also yielding vastly improved passive safety characteristics as well, far beyond those found in historical designs.

The end result is a platform that is not only readily deployable and incredibly safe but also one that operates at massively lower costs creating demand for its use in coastal and port security, oil and gas activities, tourism, underwater archaeology and research. But, as with the helicopter, practical access also makes the deployment of existing technologies more feasible while aiding in the rapid testing and development of other promising ideas as well.

After 21 successful dives our concept vessel is bringing the world much closer to realizing that a new era in easy and economical subsea access is now at hand and that such access (and the benefits that can be gained) could be unlimited.

Integration of a 400 kHz Acoustic Doppler Current Profiler (ADCP) into a Webb Slocum Ocean Glider

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In this presentation we report on results from the integration of a 400 kHz 3-beam Nortek Acoustic Doppler Current Profiler (ADCP) into a Webb Slocum ocean glider. Our goal is to obtain profiles of absolute current velocity, not just shear velocities, over the full profile range of the Slocum glider, roughly 200 m, by using a bootstrapping sampling method. We will address the hardware and software integration of the sensor and will discuss the tradeoffs of the choice of power, volume, range and resolution associated with frequency. Field deployments have revealed several system integration challenges that must be addressed. We will present sample data collected during tests conducted in coastal, inshore waters with the glider floating at the surface. A 300 kHz broadband Workhorse RDI ADCP was deployed in an upward looking moored mode to provide calibration data to determine range and data quality of the data from the glider-based ADCP.

Progress and Future Directions with a Hybrid Glider

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The hybrid glider is a standard 200 m Slocum electric glider augmented by a low-power propeller-driven propulsion system. This propulsion system is integrated into the glider at the rear of the vehicle, replacing the 500 gram emergency drop weight. The introduction of the propulsion force at the rear of the vehicle has the potential to create instabilities in pitch and therefore has the potential to have a detrimental effect on the ability of the hybrid glider to hold a constant depth while maintaining forward speed.

Tests have been performed to evaluate the stability of the vehicle during horizontal flight in the NRC-IOT Ocean Engineering Basin. The results of these tests show that for the lower forward speeds, i.e. 0.2 m/s to 0.4 m/s**,** the vehicle is capable of controlling its pitch and depth over the test distance. For the higher speeds the distance of 30 m is not sufficient to draw such a conclusion, however, the data shows no extreme instabilities being present. To expand on these tank tests, field trials are being conducted in the ocean off the coast of Newfoundland where the glider is driven at a predetermined depth over larger distances. In parallel to these experimental tests we are developing an analytical model to look at the stability of the hybrid glider. The results from the analytical model will be compared with the experimental outcome of the longer-range open-water flight tests.

Future work with the hybrid glider will involve working with the manufacturer to integrate the system into their product line. This work will require the adaptation of several of the controllers to meet the stability requirements, hardening of the design and development of sample missions for ease of use by others. Our research program and the development of the hybrid glider continue to be motivated by the desire to use underwater vehicles year-round in the potentially ice-infested waters off the coasts of Newfoundland and Labrador. To this end energy-optimal navigation solutions with limited to no surface access are currently under investigation.

A Study on Drag Estimation for an Underwater Glider using CFD

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Underwater gliders have been developed mainly to carry out long-duration oceanographic surveys while operating autonomously. Part of the reason that these gliders have been so successful is due to their energy-efficient "buoyancy engine" which is used to change the net weight of the glider in water. When heavier than water, the glider descends; when lighter than water, the glider ascends.

The resistive force which the water exerts on the glider must be minimized in order to achieve long-duration missions. When a new sensor is installed on the hull, or, when a modification to the shape of the glider is needed to meet the requirements of a new mission, the changes in the hydrodynamics loads which act on the glider must be studied in detail in order to optimize the operational performance of the glider.

In this study, CFD (Computational Fluid Dynamics) techniques are applied to predict the hydrodynamic loads which act on the underwater glider. Our focus is on the resistive force because the required capacity of the buoyancy engine depends strongly on the overall vehicle drag. Part of flow over the glider will be laminar and part of the flow will be turbulent, thus these effects must be modelled appropriately.

In the case of an ocean glider, considering the range of Reynolds Numbers experienced during gliding, the concept of the use of a transition model is quite suitable in comparison with the use of a fully-turbulent model; the latter might be required for bodies which experience higher Reynolds Numbers. Among the available turbulence models, the four-equation SST (shear-stress transport) laminar-to-turbulent transition model was selected; for comparative purposes the SST k-omega model was selected.

Since our research focuses on the performance of the Slocum electric glider, this hull form was used for the CFD predictions. These predictions were then compared with our experimental results, which are from our voyages with the full-scale glider in Conception Bay.

Acoustic Technology for Glider Long-Range Navigation and Communications

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Gliders and long range AUVs could provide persistent, high-resolution, basin-wide sampling in ice-covered regions. However, navigation and telemetry for these platforms relies on satellite positioning (GPS) and communications (Iridium, ARGOS) that are poorly suited for areas, where partial or complete ice cover restricts access to the sea surface. Although the data rate of long-range acoustic communications is much less than satellite communications, and, the precision of acoustical navigation is not comparable with GPS, the underwater acoustical systems are the only way to provide basin-wide geo-location and telemetry in ice-covered regions and to allow the research community to employ AUV and gliders to address wide range of actual problems in Arctic research.

The modern acoustical technology for basin-scale, and region-scale tomography communications and navigation is considered. The existing underwater navigation systems are based on the traditional 260 Hz or 780 Hz RAFOS narrow band organ-pipe sound sources with temperature compensated quartz clocks. Such systems appear very unreliable as reported at the Workshop on Acoustic Navigation and Communications for High-latitude Ocean Research (ANCHOR) 2006, UW, Seattle, Washington; WHOI ACOBAR workshop 2006. Teledyne suggests a powerful, broadband 100 Hz swept frequency sound sources with high precision atomic clock, which can essentially increase precision and range for underwater navigation. Such sound sources are currently used in Philippine Sea ocean acoustic tomography and in the Fram Strait ACOBAR system for tomography and glider navigation. A possibility to build an affordable very low-frequency sound source with frequency range below 100 Hz for basin scale underwater navigation and long-range communications is considered.

AUVs can't survive in a long-term mission without duplex underwater communications and reliable long-range navigation. Although early investigations show that for long-range Arctic propagation the signal frequency must be below 50 Hz, many Arctic researchers have observed a good signal for a carrier of 780 Hz at a distance of more than 100 miles. The Arctic environment is changing; ice-thickness decreases, the expanding fresh water layer from melting ice is shielding the underwater ice roughness and making reflection from ice more stable. The assumptions about propagation conditions in the Arctic should be revised. The long-range underwater communications with a glider needs a small, light and highly-efficient low-frequency sound source. Such a sound source was designed and built on the base of a composite carbon-fiber free-flooded tube and tested during the September 2010 voyage of the ice-breaker *Svalbard*. The source has 694 Hz resonance frequency with approximately 20 Hz bandwidth and weight about 6.75 kg in water. Carbon-fiber tubing dimensions: diameter 20.4 cm, length 47 cm pipe, wall thickness 4 mm. Source radiation parameters are: SPL 186 dB re 1 microPascal at 1 m, efficiency > 50% with the directivity gain 3 dB. Although the sound source was transmitting from a depth of only 100 metres we see an intensity signal from one hydrophone at a distance of 100 km in an area completely covered by ice. Such promising results will allow us to design an efficient long-range system for under-ice glider control and navigation. Duplex under-ice communications will allow combining a group of gliders into an underwater network and increasing the operational area. Such systems will support long-term missions in the Arctic and even will make possible glider missions to the North Pole.

Hydrothermal Vent and Oil Spill Tracking with an AUV

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This presentation outlines the role which AUVs play in the tracking of plumes from hydrothermal vents and the recent Deepwater Horizon oil spill in the Gulf of Mexico. This presentation focuses on the technologies which were developed for searching for and locating plumes from hydrothermal vents using the ABE AUV, and, how that experience prepared the team for searching for, locating, making chemical measurements, visualizing the measurements in real-time and the dynamic re-tasking an AUV during a pre-defined mission [1].

This presentation addresses the complexity of oil spills and the typical fates of spilled oil products, including the action of microbial degradation. Also outlined are the challenges which such scientific investigations face in the public eye, and, the role of peer review and the media.

First measurements were made along an encircling circular path with a towed body which was outfitted with the new TETHYS mass spectrometer which was programmed to detect the presence of methane. The results of the tow-yo measurements indicated that the oil-spill plume was located at a height of about 100 m above the seabed and was about 200 m thick and was travelling westward from the well.

Another set of measurements made with a Didson sonar and a DVL were used to estimate the mass flow rate in the plume, while performing chemical samples with traditional CTD rosette. Samples were gathered with a new gas-tight isobaric fluid sampler. Finally the "Sentry" AUV, which was equipped with the TETHYS mass spectrometer, was used to track the westward drift of the plume to a distance of 35 km from the well. Real-time feedback from "Sentry" via an acoustic modem link was used to guide water sampling with CTD casts.

The results show that various research groups use different techniques and sensors to make measurements that produce differing conclusions since each group made their measurements in different locations, and, at differing times. The result was that the media portrayed the findings as contradictory and often inconclusive which made it difficult for the general public to conclude what was really happening.

The results of WHOI oil-spill plume investigation were reported in [2] on 19 August 2010.

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Recent Field Operations with the Sentry and Nereus Vehicles

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This presentation reports recent operations with the *Sentry* AUV and the *Nereus* HROV and some of the navigation and telemetery technologies used on these expeditions. In collaboration with researchers at Johns Hopkins University and the Australian Centre for Field Robotics, Woods Hole researchers have used these vehicles for water column surveys at altitudes exceeding 500 m. The absence of bottom-lock Doppler velocities at these altitudes required us to use a dead-reckoning navigation solution that exploited vehicle velocity estimates from a dynamic model of the forces acting on the vehicle. This technique is sensitive to drift and we provided position corrections from the support vessel using an acoustic modem. This approach, while simplistic, enabled us to undertake water column surveys during two recent expeditions. The first expedition used the *Nereus* HROV in AUV mode to help discover hydrothermal vents at the Mid-Cayman Rise. The second expedition, a rapid response cruise to the April 2010 Deepwater Horizon oil spill, used the *Sentry* AUV and a mass spectrometer to localize and map an underwater plume of hydrocarbons. During these dives, we dynamically re-tasked *Sentry* using the acoustic link to improve our estimates of the vertical and horizontal extent of this plume.

3D Path Planning of a Communication and Navigation Aid Vehicle for Multiple AUV Operations

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Autonomous underwater vehicles (AUVs) are used for underwater surveys, pollution monitoring, and hunting for mines and IEDs (Improvised Explosive Devices). The use of multiple AUVs is constrained by the inherently low underwater communication bandwidth and the lack of references (such as GPS) for accurate navigation. This presentation describes a solution that addresses these challenges through the use of a single AUV or unmanned surface vessel (USV) as a Communication and Navigation Aid (CNA) to multiple deeply submerged AUVs. The CNA aids communication by acting as a mobile gateway buoy to the submerged survey AUVs and to the surface mission control station. The CNA uses an acoustic modem to exchange information with the survey AUVs and maintains radio and/or satellite communication with surface stations. A CNA aids navigation by providing its global position (through GPS) as a reference to the survey AUVs. The survey AUVs can use this along with their position relative to it, to derive a good estimate of their own global positions. This localization method is potentially more efficient than current localization methods which either require the survey AUVs to periodically surface to obtain their own GPS positions or to employ a field of submerged communication and navigation buoys.

This presentation explores whether a USV or an AUV should be used for the CNA, the CNA's path-planning requirements in order to optimize communications to the survey AUVs, and finally to what extent the CNA improves the effectiveness of multi-AUV operations. Previous work largely ignored optimizing the CNA path, using a pre-determined path and also does not consider the relative depth between the CNA and the survey AUVs. Comparisons between the effectiveness of USV and AUV CNAs have not been reported. In addition, few survey AUV patterns have been tested against the previously devised CNA path planning algorithms. The author has developed an algorithm to account for survey AUV depth in CNA path planning. Simulations of the path planning algorithm will be followed by detailed simulations of a group of heterogeneous AUVs surveying with the aid of a CNA and with in-water trials involving two or more AUVs.

PINZON: A Path Planner for Underwater Gliders

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In this presentation we will introduce Pinzon, a path planner for glider piloting, and its associated path planning algorithms.

We will present algorithms that have evolved from the basic A* algorithm, but have been modified and adapted to the specifics of the problem. Recall that standard A* algorithm discretizes the search space with a uniform grid, so the possible bearings are discretized too. Some other authors have applied variants of this AI path planning method for gliders moving through a uniform grid of ocean currents. These approaches result in non-constant time intervals between consecutive surfacings.

Instead of finding the path over a uniform grid, that would produce unrealistic non-constant-time surfacings, we have engineered the path planner to obtain constant-time surfacings. We allow any bearing angle and integrate the actual glider trajectory.
Our approach manages continuous space and time domains, which is reflected in the integration of the glider trajectory and may be strongly conditioned by the ocean currents. Since the glider is no longer forced to reach a node of a grid, any bearing is allowed. This, along with the incorporation of drift produced by ocean currents, provides us with better estimations of real trajectories, and the bearings obtained are more realistic and well-informed.

We will also discuss both a probabilistic version of the path planning algorithm, that incorporates an Adaptive Bearing Sampling (ABS) procedure which reduces the computational cost of the search with low impact on the results, and present results achieved with a new approach based on iterative non-linear optimization.

Automated Ballast Control System for an Autonomous Underwater Vehicle

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Underwater vehicles are frequently used for various deep-water ocean applications such as surveying and cable-laying, where accurate control of depth and trim is needed. The use of manually-set ballast tanks on-board an underwater vehicle is commonly used in conjunction with control surfaces to adjust the vehicle's depth and trim. To increase the autonomous capabilities of underwater vehicles while underway, it is desired to develop an automated ballast control system that runs in parallel with existing control systems used to adjust the control surfaces on the vehicle. The challenges with controlling the depth and trim of an underwater vehicle include nonlinear hydrodynamic forces as well as inherent time delays and relatively slow response times associated with water tank level changes and valve adjustments.

To meet these challenges, this paper proposes a unique ballast-tank control approach that may be suitable for large autonomous underwater vehicles. The chosen ballast tank control system was designed to help control vehicle parameters such as center of mass, center of buoyancy, position, and velocity. The ballasting system consists of two water tanks positioned aft and forward of amidships. The ballast tanks are then automatically filled or emptied of ocean water as desired. Depth-control numerical simulations have been carried out on a two-dimensional vehicle simulator developed using MATLAB™ and Simulink™ to test the performance of the proposed ballast control system. The simulation results show that, for the assumptions and conditions tested, the proposed controller is versatile and capable of achieving a set-point depth with minimal error by effectively utilizing the ocean water in combination with an internal air compressor and water pump.

Unmanned Underwater Vehicle Docking with Submarines

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Unmanned underwater vehicles (UUVs) are effective autonomous intelligent (AI) systems which provide covert intelligence, surveillance, reconnaissance, minehunting, mapping, communication, and payload delivery capabilities. Integrating UUVs with ships and submarines amplifies the capabilities of each; however, no satisfactory method exists for recovering UUVs after their missions, especially for submarines. This project proposes a novel automated docking approach to address this roadblock.

Most UUV docking strategies use a passive dock displaying an acoustic transponder toward which the UUV steers. Docking is unreliable because of position sensing error, environmental disturbances, and the inability of the UUV to make rapid lateral position corrections. Our new approach relieves the UUV of all but longitudinal control during final docking. It proposes a new active dock with independent optical tracking and exceptional lateral manoeuvrability to keep the dock accurately aligned with the oncoming UUV until precise contact is made.

Feasibility of deploying Hydrocarbon Sniffers on AUVs and ROVs for Subsea Pipeline Monitoring

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Exploration and production activities for oil and gas are steadily increasing in subsea areas. Various methods exist to detect and localize subsea oil and gas emissions (DNV Report, 2009) but the 2010 oil and gas spill in the Gulf of Mexico has demonstrated that there is still a lack of understanding of the processes of subsea leakages, and technologies to detect and localize emissions from subsea installations at an early stage have to be improved.

Detecting and localizing subsea oil and gas emissions means dealing with warm multiphase outflow consisting of an oil phase, gas bubbles and dissolved gas (mainly CH4), formation water, mixing with cold seawater, and sometimes even the formation of additional solid gas hydrate phases (Zeng et al., 2002). Recent field observations and hydrodynamic models of CH4-rich fluid transport at natural seeping sites (e.g. Schneider von Deimling et al., 2007; McGinnis et al., 2006 and 2010) indicate the distinct behavior of CH4-dominated fluids in seawater. A successful leak detection strategy must focus on the different physicochemical fluid characteristics of CH4 as a tracer for subsea oil and gas emissions in general. The feasibility of Hydrocarbon Sniffers for detection, localization and subsequent validation of subsea oil and gas emissions has been proven in several scientific and commercial projects.

In the past three months the Contros CH4 and PAH sensors have been deployed on AUV and ROV systems operated by the University of Mississippi, the University of Southern Mississippi, NRCan, MBARI and the University of Quebec.

The MUN Explorer AUV: Current developments for under-ice research

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Autonomous Underwater Vehicles (AUV)s are a leading technology for operations under the ice. The capability for an unmanned and un-tethered vehicle to collect data from beneath the ice is invaluable for the understanding of polar regions and the ocean as a whole.

Memorial University of Newfoundland's Marine Environmental Laboratory for Intelligent Vehicles (MERLIN) operates a 3000 m depth rated Explorer class AUV, manufactured by International Submarine Engineering, Port Coquitlam, BC. This 4.5m vehicle has a large payload capacity, long endurance and is a highly stable platform suitable for under-ice surveys. The current focus of MERLIN is to develop the Explorer as the ideal vehicle platform for under-ice missions.

Recent developments at the MERLIN lab have included an under-ice docking system that has been tested in the Canadian High Arctic and is currently employed as part of Canada’s ongoing work to bolster its claim under the UNCLOS Article 76.The CATCHY system is a simple and robust solution for prolonged AUV missions under the ice. The key elements of CATCHY are a small footprint and the ability to operate in highly remote regions.

Current ongoing work is focused on new developments in the areas of target recognition, navigation and new survey capabilities as part of a multi-year AIF funded project called Responsive AUV Localization and Mapping (ReALM). As well, partnerships with the University of Tasmania and the Australian Antarctic Division will see developments in risk mitigation, robust localization and under-ice profiling in support of an upcoming mission to perform under-ice data collection in the southern ocean ecosystem.

The UNCLOS Project - How AUVs are assisting Canada via Project Cornerstone

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When Canada ratified the United Nations Convention on the Law of the Sea (UNCLOS) in 2003, it embarked upon a 10 year program to collect the necessary scientific information to substantiate its submission to the Commission on the Limits of the Continental Shelf (CLCS) in order to establish definitively the outer limits of the continental shelf. It was understood that acquiring the necessary data in the arctic was going to be challenging, and a comprehensive program to collect bathymetry and seismic information was started. By 2008, it was clear that techniques other than spot soundings through the ice might be needed in order to acquire all of the desired bathymetry data by the 2013 deadline. After consultations with Defence Research & Development Canada (DRDC), a proposal was submitted to the Canadian UNCLOS Program Steering Committee to use autonomous underwater vehicles (AUVs) to collect bathymetry data in the arctic ice covered waters. In June 2008, this proposal was approved, and Project Cornerstone began.

Cornerstone is an interdepartmental project between DRDC, Natural Resources Canada, and Fisheries and Oceans, to purchase two commercial AUVs, modify them for the very challenging arctic missions, and operate the vehicles in the arctic to collect bathymetry data during the 2010 and 2011 spring arctic operations.

In order to meet the very challenging time constraints associated with the first arctic field operation in March 2010, it was necessary to refine our concept of operation, prepare specialized logistics for deploying the AUVs in the arctic, and develop novel subsystems for the AUVs themselves in order that they could complete the desired missions. The overall concept of operation for the 2010 operation was to employ two ice camps. The main ice camp was located on shore fast, multiyear ice just south of Borden Island. The ice here was between 2 and 3 metres thick. At this camp, in addition to the many accommodation and support tents, there were two large AUV tents that were erected over an immense ice hole that was 2m x 3m x 7m. Creating this hole required the removal of almost 30,000 kg of ice! The AUVs were flown out to the main camp in 6 sections and assembled using a rail system mounted on the floor of the tents. Once assembled, a gantry system was used to lower the vehicles into the water. The second ice camp was located about 300 km north-north-west of the main camp, in the more dynamic ice pack of the Arctic Basin. The infrastructure for the operation of the AUVs was much smaller at this camp, with only a single, relatively small tent covering a 0.75m x 1.2m ice hole. This smaller hole was used for recharging the AUV batteries, downloading the data, and programming a new mission into the vehicle.

This concept of operation required very unique capabilities to be developed for the AUVs. First, in order to enable the AUV complete these long missions, each AUV has 48.5 kWh of lithium-ion batteries. This large number of batteries is one of the key drivers of the somewhat long, 7 m length. The AUVs use a Knudson single beam echo-sounder and a Kongsberg EM2000 multi-beam bathymetric sonar to collect the bathymetric data. Having two sensors provides redundancy, as well as the ability to vary the overall power consumption by using either one or both of the sensors. An accurate inertial navigation system (INS) provides accurate positioning of the bathymetry. In order for the AUV to reliably return to the drifting remote ice camp, each vehicle employs a novel homing system. A 7 element hydrophone array is located in the nose of each vehicle. Using a custom built, high acoustic power, underwater source deployed at the remote camp, the vehicle processes the signals from the array and can determine the appropriate bearing angle to the ice hole. This allows the AUV to directly home to the moving ice camp from as far away as 50 km. The vehicle uses a variable ballast system to park under the ice – both at the remote camp and the main camp. This system, which can operate at depths of 3500 m, can be used to park the AUV on the sea bottom during certain failsafe conditions. Finally, the vehicles have been designed to allow recharging of their batteries while remaining in the water. An special apparatus holds the vehicle in place while the somewhat large charging connector and cable is attached to the AUV. The apparatus also allows the AUV INS to be aligned, if needed.

This presentation describes in further detail the arctic logistics and AUV developments that were part of Project Cornerstone. It also presents a discussion on the arctic field operation undertaken from March 1 to May 1, 2010, with a quick look at some of the initial results and lessons learned.

Manoeuvring Experiments Using the *MUN Explorer* AUV: An Overview of the Vehicle's Response during Sea Trials

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Autonomous Underwater Vehicles (AUVs) are rapidly emerging as an important tool in ocean exploration. The potential of AUV technology in undersea surveys and the significant improvement in the quality of data acquired using these platforms, is gradually replacing the conventional ship-borne methods. The advantage of using an AUV as opposed to other platforms is its versatility to deploy a wide range of sensor payloads and the ability to send the vehicle to remote locations where standard oceanographic methods of sampling, mapping etc., are not feasible. In hostile weather conditions where surface operations are unsafe, in regions covered by ice where deployment of manned submersibles are risky and tethered vehicles are of limited use, AUVs hold the best promise for freely working on the seafloor.

The underwater vehicles research group at Memorial University of Newfoundland, in pursuit of advancing marine research in the areas of ocean environmental monitoring, seabed mapping, water column sampling, extending to the ambitious plans of exploring the under ice regions of Canadian Arctic, acquired an ISE Explorer-class AUV (*MUN Explorer*) in the year 2006. The *MUN Explorer*, a survey-class AUV of length 4.5 m and a maximum diameter of 69 cm, was built by International Submarine Engineering Ltd., in Port Coquitlam, British Columbia, Canada.

The availability of the *MUN Explorer* AUV at Memorial University facilitated the performing of a series of manoeuvring trials at sea. The trials included straight-line tests, turning circles, zigzags in horizontal and vertical planes and a descending-ascending helix. These trials were planned and executed with the idea of collecting experimental data to validate a hydrodynamic model developed based on the *component build-up* method for streamlined axisymmetric underwater vehicles. Apart from providing data for the validation of this model, these manoeuvring trials also formed a means to evaluate the performance of the vehicle during different manoeuvres or operational scenarios. This presentation will provide a summary or overview of the observations and general responsive behaviour of the vehicle during different manoeuvres.

High Resolution Seabed Sub-Bottom Profiler for an AUV

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Memorial University of Newfoundland (MUN) has recently begun working in an exciting area of research and development related to its large, flight class autonomous underwater vehicles (AUVs). Design work for a new project involving Memorial's *AUV Explorer* AUV commenced in spring 2010 to enable this AUV to complete ocean sub-bottom survey research in remote locations that are not normally accessible to other vehicles restrained by a tether or surface link.

The aim of this project is to provide a means to conduct high-resolution sub-bottom seabed surveys in water depths up to 1000 metres using a new imaging sub-bottom profiler. The Sub-bottom Imager has 10 cm spatial resolution, and has never before been used on an AUV. This new sonar technology, developed by PanGeo Subsea Inc. of Canada, comprises a multi-element hydrophone array and employs conventional beam forming and Synthetic Aperture Sonar (SAS), stabilized by the vehicle's Inertial Navigation System (INS), to directly image buried geological structures and man-made objects, such as pipelines and cables.

Design work for this project involves integrating this long-array sub-bottom image device into the AUV *Explorer*. This will be accomplished by building a new vehicle wing section with a span of 3.5m to house the hydrophone array. The intent is to take advantage of the vehicles modular design to make the new equipment easily adaptable and removable from the *Explorer* AUV with minimal interruption to operations.

The preliminary design of the new wing and its integration into the existing AUV began over the summer of 2010. A design was generated using three dimensional computer aided design software and is in the computer modelling/approval phase before construction of a physical model begins. The initial quasi-static lift and drag characteristics of all the proposed lifting surfaces have also been calculated.

Before the construction of a physical model of the new wing, the vehicle's capability to meet the profile design specifications must be validated. The sub-bottom imager manufacturer specifies an operation speed less than 1.0 m/s at a preferred altitude of 3.5 m above the ocean floor. It is currently unknown exactly how the reduced velocity will impact vehicle stability and control. Slow speed, shallow water testing will examine control surface manipulation, proximity to desired mission completion, and ability to respond to environmental stimuli at this condition before the addition of the new wing section

Upon successful completion of slow speed validation, a foam replica of the proposed wing is to be mounted on the existing AUV to conduct tank tests of the complete configuration. This will allow for the study of the interaction between the new wing and the existing control surfaces including how these interactions affect the vehicle's flight characteristics. Furthermore, shallow water tests are anticipated after validation of the vehicle hydrodynamic properties in a controlled environment in order to determine the open water operability of the system. The final phase of the design is the construction of a new section capable of carrying the sub-bottom profiler to depths of up to 1000 m.

The *AUV Memorial Explorer* equipped with this new sub-bottom profiler capability is slated for tested during 2011 and operation in 2012. This presentation discusses the underlying design criteria and challenges of integrating this specific sub-bottom imaging technology into a flight class AUV. In the presentation a preliminary concept design is described and coarsely evaluated for technical feasibility. Additionally, a tentative time line is given for future project milestones.