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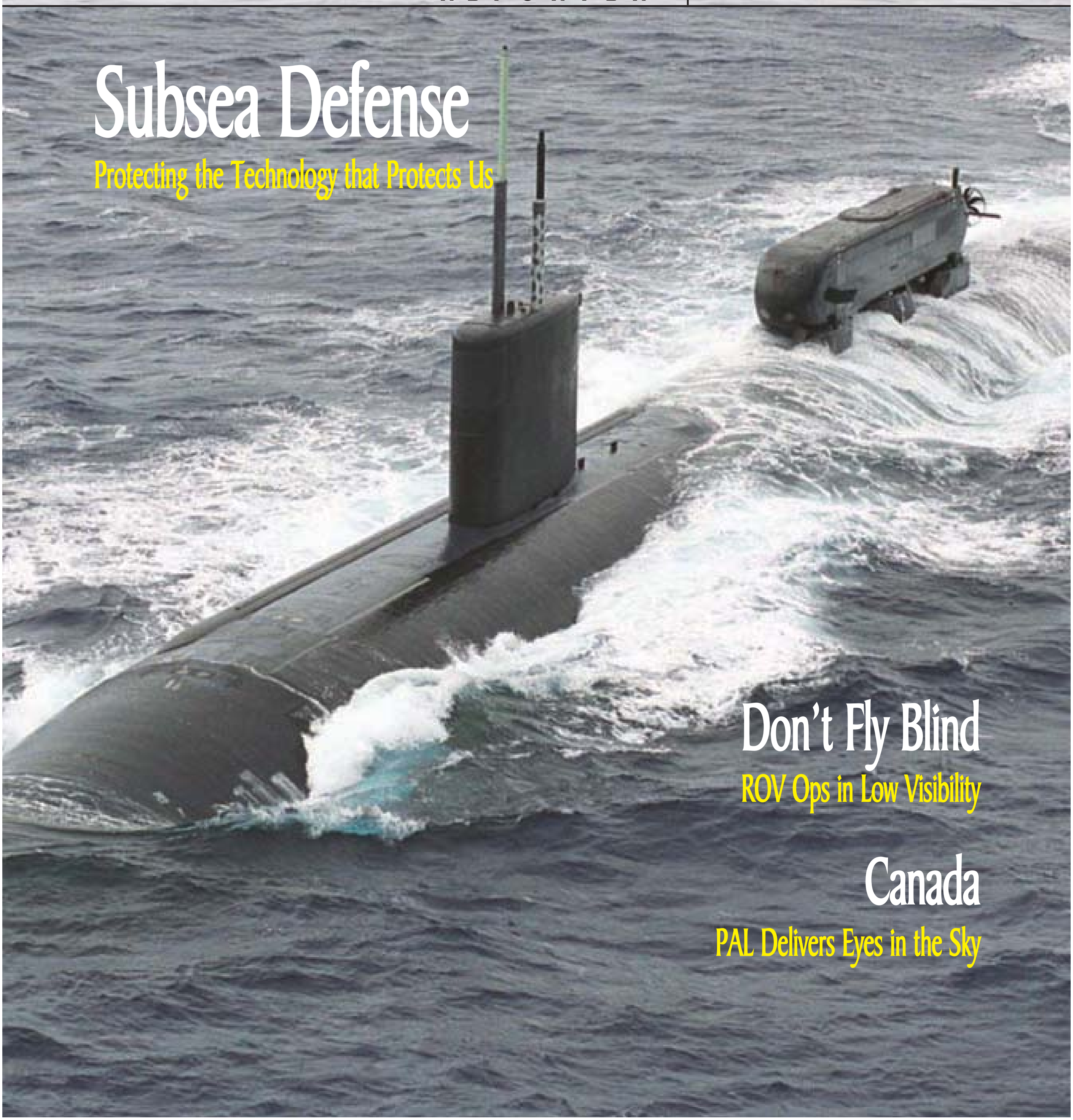

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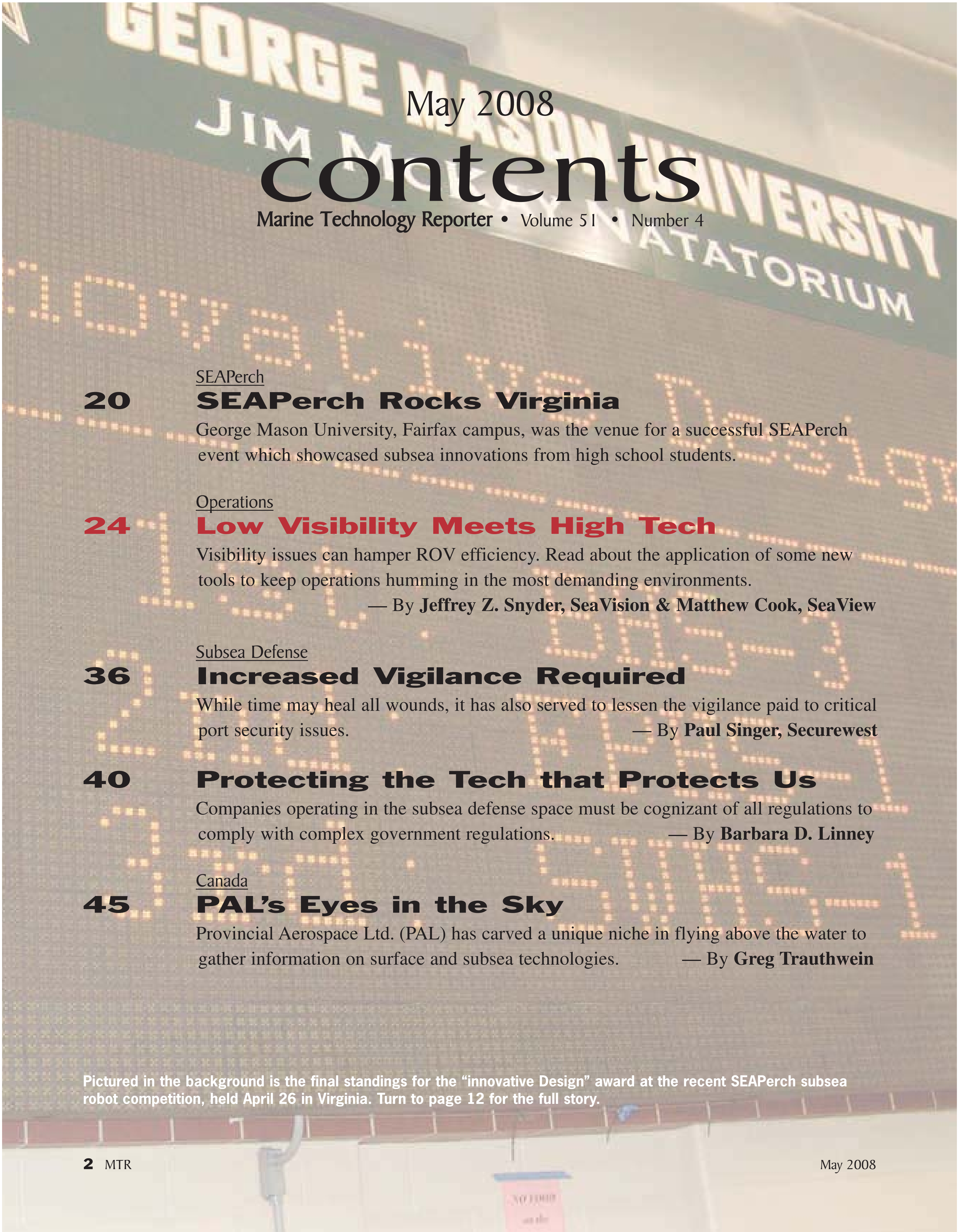

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Pictured in the background is the final standings for the "innovative Design" award at the recent SEAPerch subsea robot competition, held April 26 in Virginia. **Turn to page 12 for the full story.**

ROV Ops in Low Visibility *3-D Models and Inertial Navigation*

By Jeffrey Z. Snyder, SeaVision Marine Services LLC & Matthew Cook, SeaView Systems Inc.

Inspection-class ROVs provide an excellent option for confined access underwater investigation, particularly when the project locations, operational depths, and access conditions preclude investigation or intervention by divers. Such situations are frequently encountered in flooded tunnels and pipelines.

When operational conditions such as poor visibility, and complicated structural layouts with expected potential obstructions combine to present a strong likelihood for entanglement, exceptional demands are placed on the concept of situational awareness during the deployment and operation of inspection-class ROVs in these environments.

On a recent project in a flooded mine in northern Canada, SeaView Systems and SeaVision Marine Services teamed with Nuytco Research Limited to develop a world-class inspection-class ROV solution to investigate the mine in water depths exceeding 1400 feet. By developing fully-georeferenced 2D and 3D models of the mine tunnel system and outfitting a SeaEye Falcon with a Doppler-velocity log-aided Inertial Navigation System, the team used this combination of models and real-time navigation inputs to successfully negotiate a complicated underwater tunnel geometry in order to penetrate approximately 450 feet from the launch point to investigate the tunnel conditions during two separate missions.

This strategy of 3D Modeling and aided-Inertial Navigation combined to provide a real-time navigation and operational solution that provided a dramatic improvement in situational awareness under harsh operating conditions. Though applied in an inshore setting, this approach can provide the foundation for similar low-visibility, confined access conditions in the offshore as well.

Blind man's bluff might be a fun children's game that can hold the attention of some youngsters for about an hour or so. Most anyone who has worked commercially as an ROV-pilot or diver, unfortunately, has had the experience of attempting to navigate through difficult surroundings with poor visibility.

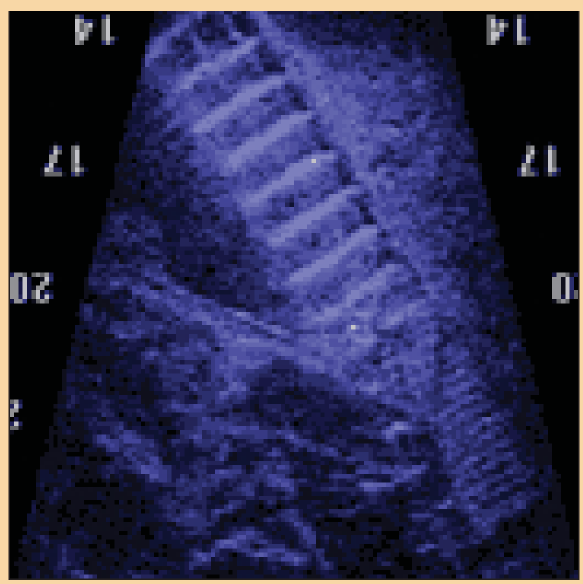
In some respects, divers have the advantage of utilizing tactile feedback to feel their way through a project site. Armed with an understanding of their surroundings prior to a dive, and communications with the surface during a dive, it is possible for divers to overcome poor visibility and use their hands (and feet, and knees, and heads) to navigate around a project site.

ROVs, however, do not afford the luxury of providing tactile feedback to the operators. Even if armed with a manipulator arm, it may not be possible for an ROV to "turn around, face your rig, and take up your slack as you come back" in order to free an entangled umbilical. Instead, ROV operators rely on operational strategies and a growing suite of technologies to improve or supplement their situational awareness and operate in poor visibility environments.

Low light cameras, improved subsea lighting systems, and visual enhancement technologies serve to improve the visual quality in video feeds available to ROV operators. Varying grades of high definition, high-resolution scanning/imaging sonars are common on ROVs from large work-class machines to small mini-ROVs, providing operators with improved awareness that is not impacted by the quality of visibility. Real-time positioning is often provided by acoustic positioning systems such as ultra-short baseline (USBL) and long-baseline (LBL) systems.

These improved visual and acoustic technologies are excellent options for providing better real-time, nearfield observations. Range limitations prevent them from providing an understanding of "big picture" situational awareness. This may be acceptable when the access and egress pathways are easily located and utilized. Open water projects often afford the opportunity to complement these observation systems with acoustic positioning from USBL and LBL systems which can aid the operators in understanding their immediate surroundings and help them to develop a strong sense of situational awareness. What do we do when a project demands remoteinspection or intervention, and poor visibility, complicated structural layouts, and challenging tasks combine to decimate any sense of situational awareness? How can we go beyond the information provided by visual inputs from cameras or sonar imagery and operate in areas where acoustic positioning is not available, so that we can successfully navigate an ROV in a poor-visibility, confined access environment? With a limited of amount of fundamental but

Visual enhancement technologies, such as those being developed by LYYN AB, help to improve visibility in turbid subsea environments. (Image from http://www.lyyn.com)



High resolution imaging sonars, such as the SoundMetrics DIDSON, provide excellent subsea imagery with surprising levels of detail. Pictured above is a collapsed oil rig. (Image from http://www.soundmetrics.com)

A view down Cigar Lake Mine Shaft 1. The actual floor to be investigated was 1500 feet below the ground surface; water had flooded to within 60-feet of the ground surface.

The SAAB SeaEye Falcon DR, outfitted for deployment in the Cigar Lake Mine. Note the SoundMetrics DIDSON sonar mounted below the primary camera, the additional DSPL Lights on the starboard side of the ROV, and the Teledyne-RDI DVL on the instrument skid. Also note the additional syntactic foam installed on the Falcon to maintain neutral buoyancy. The Outland Pan/Tilt cameras were installed immediately after this picture was taken.

accurate

structural layout information available, it is possible \ to develop useful three-dimensional concept models that can be managed, in real time, in order to provide a general understanding of the location and orientation of an ROV. These models can vary in complexity, from the custom full-physics training models that are becoming more popular in the ROV industry, to much more simple on-the-fly models that can be developed using off-the-shelf software. The technology exists, in the form of Doppler Velocity Log-aided inertial navigation systems, to provide adequate positioning and orientation information for the ROV that can be fed into the models; these models can then be utilized to supplement real-time inputs from video and sonar sensors to enhance overall situational awareness.

Flooded Mine: A Challenging Environ

For the purposes of this article, we shall focus on a confined access environment with poor visibility where water depths and access required remoteinvestigation: specifically, a flooded mine with water depths approaching 1500 feet. The Cameco Corporation is a large producer of uranium based in Canada. In October 2006, the main mine at their developmental Cigar Lake facility in northern Saskatchewan suffered a roof cave-in resulting in the mine flooding at a rate of approximately 15,000 to 20,000 gallons per minute.

The mine had been designed to contain such an event with the installation of two 12-foot diameter highpressure bulkhead doors located within the mine so that, when closed, the doors would isolate the ore body floors (in development) from the mill/production facility area (near completion), allowing the mine to flood, but to protect the mill/production assets. During evacuation, one door was closed successfully but the other failed to seal despite heroic efforts on the part of the miners. After several attempts, and with frigid water flooding through the door and increasing in volume at an alarming rate, it became apparent that the door was not going to able to be closed. Reluctantly, the miners evacuated the mine.

The failed bulkhead door was located approximately 1500 feet below ground surface. By the time flooding had stabilized, water had completely flooded the mine and risen within the single vertical access shaft to within 55-feet below ground surface.

Given the estimated $19 billion value of the mine, no time was spared by Cameco in starting on a recovery program. They decided upon a two pronged approach towards rehabilitation. The main rehabilitation plan was to bring in two land-based drill rigs which were to drill down to the site of the rockfall area, pump grout to form a large plug in the fall. Once set in place and proved to be sealing, the mine could be dewatered on the downstream side so that rehabilitation could proceed. The second approach involved Cameco contracting Nuytco Research, in Vancouver, BC, to provide a robotic option to perform a condition assessment of the mine in the region of the open bulkhead door and of the door itself. To support them in this undertaking, Nuytco contracted SeaView Systems to provide their SeaEye Falcon DR remotely-operated vehicle (ROV). Together the two companies took a 'white paper" development approach with the only restriction to the problem being the state-of-the-art of applicable underwater technology. As visibility was expected to be near zero, the need for the best available real-time remote imaging equipment and accurate navigation was identified as being a critical requirement for the successful completion of the project.

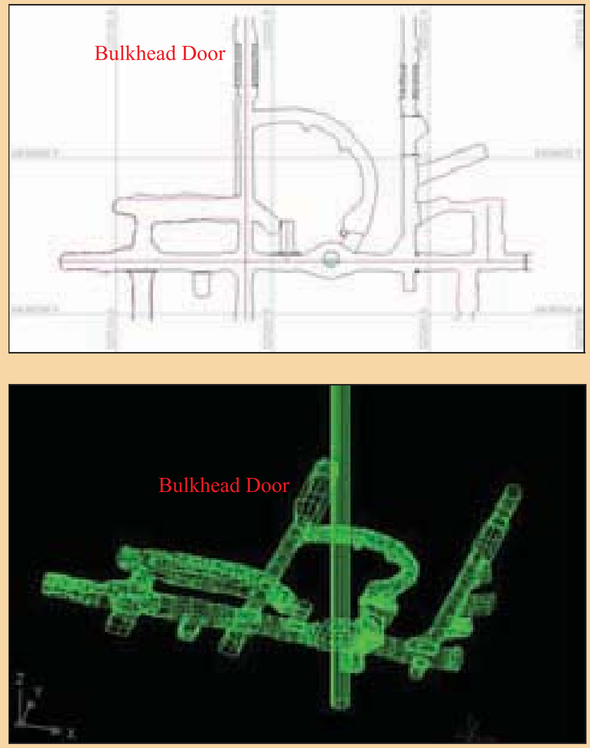
To address the issue of real-time imaging equipment in poor visibility situations, Nuytco and SeaView identified:

(1) A SoundMetrics DIDSON imaging multibeam sonar, mounted to on a tilt platform to track the primary Falcon camera
(2) A CDL MiniPulse profiling sonar
(3) An Imagenex 881a imaging sonar
(4) Two Outland Technology Pan & Tilt cameras
(5) Two 150W DeepSea Power and Light halogen lamps to be deployed in addition to the standard low light SeaEye Camera.

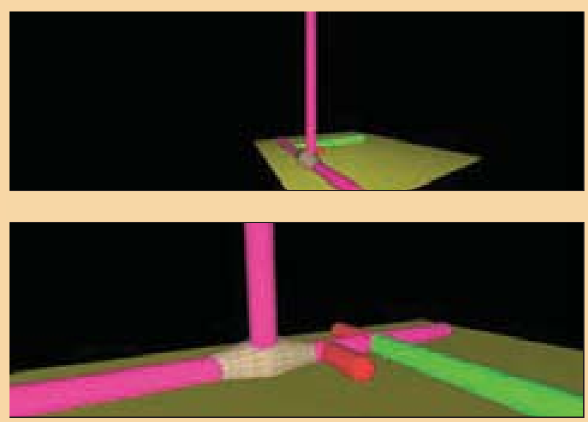
To address the issue of real-time navigation, an inertial navigation system was necessary. Having had earlier experience with deploying a Doppler-velocity log-aided Inertial Navigation System (INS) on the ROV, Mr. Matthew Cook at SeaView Systems recommended that the ROV be positioned using a CDL Minipos INS system and that Nuytco contract SeaView's historical partner in INS operations, SeaVision Marine Services LLC in Connecticut.

Aided Inertial Navigation

The CDL MiniPos is an INS that is built around a Kearfott T16 Ring Laser Gyroscope (RLG). A monolithic RLG provides highly accurate heading, pitch, and roll information in real time at a rate of nearly 20 Hz. This information, when paired with the data from linear accelerometers in three dimensions (x, y, and z) can produce an accurate dead-reckoning position for the INS in



The base plans for the mine tunnel complex in the vicinity of the shaft. The top image is a 2-D base plan view of the mine complex. The bottom is a 3-D oblique view of the same base plan. The long vertical shaft is the access Shaft 1.



SeaVision utilized the Hypack 3-D Terrain Viewer to develop the georeferenced conceptual model of the Cigar Lake Mine. The purple Shaft 1 descends to the gray shaft chamber. From there, an eastbound horizontal tunnel, or "drift" and a westbound drift depart the chamber. The bulkhead door was located at the end of the green horizontal drift in the model. Additional spurs off of the primary westbound drift were color-coded red so that we would avoid mistakenly turning down those drifts.

A view from the perspective of the Falcon, from within the Shaft 1 chamber alongside the elevator that carried the deployment garage to the 480-meter level. SeaVision color-coded the different spurs off of the primary drift so that the SeaView's ROV operator knew which tunnel was the target. The spur tunnels do not actually come into the interior of the main drift; rather, that is an artifact of the 3DTV shapes used to develop the concept model for the project.

Approaching the bulkhead door and an abandoned scoop loader.

three dimensions. The inner-workings of an INS can seem a bit "blackbox". However, if we think back to our college-level physics, an instantaneous measured acceleration can be integrated with respect to time to generate a velocity. Removing the calculus notation, the equation is:

$v_t = v_0 + (a_t \cdot \Delta t)$

This is read as: the velocity at any time t is equal to a starting velocity plus change in velocity due to an acceleration applied over an incremental change in time t. A second integration can generate a displacement.

$x_t = x_0 + (v_t \cdot \Delta t)$

such that the location x at time t is equal to a starting location plus a change in location due to the velocity over an incremental change in time t.

Unfortunately, a stand-alone INS has a tendency to drift because it does not sense constant velocity drift. Without aiding from an external source, an INS can only generate its own values for the constant velocity (the v0 member of the equation above). The INS struggles to accommodate three-dimensional longterm drift, so Kearfott aides the INS in the MiniPos by providing it with a Teledyne-RD Instruments Doppler Velocity Log (DVL) and, in this case, a DigiQuartz pressure/depth sensor. The DVL provides real-time constant velocity measurements that aid the INS to account for horizontal (xy) drift. The DigiQuartz pressure sensor, accurate to nearly 0.01% of actual depth, provides a vertical correction to aid the INS. These inputs, combined with the dead-reckoning solution from the RLG and linear accelerometers, are fed through onboard hardware and firmware that run a series of Kalman filtering algorithms that generate the aided inertial navigation solution.

The pairing (the INS and the DVL) mounted to an ROV instrument skid are run through a "training" or calibration routine prior to the actual survey so that the Kalman filters can be taught how to combine the information from the INS and the DVL to generate a highly accurate positioning solution. For this project, SeaVision teamed with Nuytco to accept delivery of the instrumentation at Nuytco's offices in Vancouver, install the MiniPOS INS and the Teledyne-RDI DVL to the tooling skid, and perform the training calibration routines from a survey vessel near Port Coquitlam, British Columbia.

After calibration, the result was an instrument skid that was ready to be mounted to the underside of the ROV (in our case, the SeaEye Falcon), powered from the ROV, and capable of outputting a single data stream that contains the x,y,z positioning, the heading, pitch, and roll and the velocity of the ROV in real-time at an update rate of between 10 Hz and 20 Hz.

So long as we could know the real-world location (in coordinates) of our starting point, we would be able to use the aided INS to generate a displacement from the start-point that takes into consideration the entire course traveled, because each position solution is a function of the previously recorded position. The added benefit of the aided INS is that, with an RLG at its core, it could provide very accurate heading and attitude referencing to correct for the attitude of the ROV.

INS Combined with 3D Model

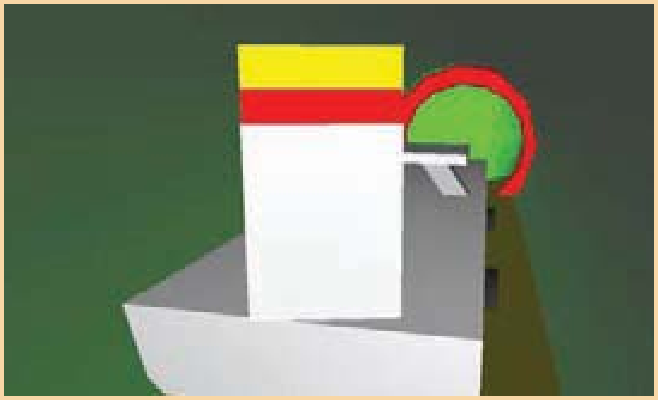
Due to the low visibility anticipated in the Cigar Lake Mine, it was necessary that a means of navigating the ROV be developed that would not only position the ROV in real-time but also provide an expedient means of mapping any debris or obstructions as they were identified in order to minimize the risk of entrapment.

To this end, SeaVision set to developing a virtual 3D model of the mine system based on drawings provided by Cameco. SeaVision selected Hypack, a hydrographic survey software popular throughout North America, as the platform for developing this model. As a survey software, it would provide userfriendly inputs for importing the real-time positioning and attitude information from the INS on the SeaEye Falcon ROV. A recently added feature to the software, the 3-D Terrain Viewer (3DTV) would provide the ability to view the real-time position of the ROV in plan-view as well as in a 3-Dimensional Viewer.

Fortunately, Cameco had developed very accurate three-dimensional survey drawings of the subterranean mine well before the flooding accident. These drawings had been geographically referenced to a coordinate system directly related to the Universal Transverse Mercator (UTM) grid, so that simple translations could bring these electronic drawings (in AutoCad format) into the UTM geographic coordinate grid.

Using the drawings as background information, SeaVision utilized the Hypack 3DTV Utility to develop a conceptual, fully georeferenced model of the principle features of the mine that would be encountered during the ROV missions to the open bulkhead door. Using simple geometric shapes like pipes and shells, SeaVision matched the general three-dimensional layout of the mine and generate a conceptual model of the mine.

Hypack can be configured to accept the position and attitude inputs, in real-time, from the INS so that the ROV can be displayed within both the 2-D plan view lay-



A view of the SeaEye Falcon (yellow, red, and white rectangular prism) navigating within the 3-D conceptual model of the tunnel. The object under the ROV is a concept of a scoop loader, which had been abandoned directly adjacent to the narrowed sidewalls that lead to the bulkhead door (marked in the background as the red toroid). Note that the ROV is hovering above the scoop loader and that a roof over the scoop loader operator station may be either an obstacle or an entanglement hazard.

A second view of the scoop loader in the vicinity of the bulkhead door, look back to the south towards the main drift (purple).

out and the 3-D concept model. The 3-D inertial positioning, as well as the heading, pitch, and roll information, our output directly from the subseahoused INS to a fiber-optic multiplexer on the ROV and transmitted topside across the umbilical. From the topside fiber-optic multiplexer, text strings of data from the INS are transmitted across an RS-232 port which can be easily read into Hypack and parsed according to the respective data fields. SeaVision also developed a simple representative model of the SeaEye Falcon with the reference point set to match the reference point of the INS. Prior to the missions, SeaVision also developed conceptual models of known large obstructions in the tunnel, particularly a scoop loader (a low-profile front-end loader) and a bobcat skid-steer and a scissor lift. Using this information, the ROV was to be flown through the virtual space much like a video game, using sonar primarily for obstacle avoidance and tunnel mapping duties. The 2-D and 3-D models could be viewed by the ROV pilot, in real-time, in order to navigate safely from the access shaft to the bulkhead door and back to the access shaft.

ROV Ops in a Flooded Mine

The portion of mine to be investigated, at the 480 m level (480 m below ground surface, or approximately 464 m in depth), had been near completion. As such, it was full of utility lines along the ceiling and sidewalls. During the evacuation that followed the accidental rock fall and subsequent flooding, the miners (all of whom escaped safely) abandoned toolboxes and heavy equipment. The exact location of these items was not known. Access could only be gained from the vertical access Shaft 1, which would require that the SeaEye Falcon DR be lowered within a deployment garage to the level to be investigated. By integrating the deployment garage into the elevator system, the Falcon and the garage could be lowered to the elevator shaft chamber at the deployment level. The positioning and orientation of the garage required that, upon arrival at the deployment level, the entire system (the ROV with all auxiliary systems and the garage) was required to remain in place foe a period of time (less than 30 minutes) in order to allow the INS to settle and to program the INS with the starting coordinates of assumed at the center of the garage within the shaft.

After calibrating the INS, positioning and orientation required that the ROV back out from the garage towards eastbound drift, circle 180 degrees around the garage, and then navigate to the westbound drift. After 100-ft. of penetration down the westbound drift, passing an oversized tool storage closet and arriving at an intersection of tunnels, the ROV had to turn 90-degrees to the north and perform an additional 230-feet penetration to get to the bulkhead door to be inspected.

Accomplishing this required that the ROV negotiate past a Bobcat skid steer tractor, a number of cables, pipelines and other infrastructure hanging from the tunnel ceiling, and finally maneuver past a scoop loader (low profiler tractor used in mines) that the miners had been using to try to pull the bulkhead door shut immediately prior to evacuation from the flooding mine. Finally, the ROV was to take a video survey of the bulkhead door which, due to the poor visibility, required that the camera be positioned very close to the door and associated slings.

In approximately 1525-ft. of water, with near zero visibility, the imaging sonars were necessary for general obstacle avoidance, and the additional pan/tilt cameras provided improved field of vision, but the 2D and 3D models in Hypack, with the real-time navigation input from the INS, provided the SeaView Systems' ROV operator with a real-time global picture of the progress of the venture from the deployment garage to the targeted bulkhead door. Leaving the garage, it soon became apparent that the 3-D virtual guidance was a great aid to the pilot and lived up to its promise in allowing the mission to be flown in virtual space as the ROV traveled in real space. The navigation and obstacle avoidance was complimented by the three sonars also carried aboard the ROV.

Hypack's 3-D Terrain Viewer also added the flexibility of changing the viewing perspective, such that you can view progress in the 3-D environment from several different camera settings. We found that operating from within the survey vessel (in this case, the ROV), or from just behind and above the ROV, to observe challenging, precise maneuvering, to be the most valuable approaches.

Also, to avoid entanglement, SeaVision was able to maintain the overall tunnel in two critical ways: first, to place concept models of large obstructions into the model so that they could be avoided during egress, and second, to record the track taken into the tunnel in order to develop a "Hansel-and-Gretel" trail that could mimicked on egress. Both capabilities provided specific additional means of umbilical management to complement the overall dramatic improvement in situational awareness in this confined access situation fraught with entanglement hazards.

Continued improvements in video and sonar technology are helping to improve the quality of visual feedback in low-visibility subsea environments. Low light cameras, better lighting systems, and visual enhancement technologies, as well as high-resolution multibeam imaging sonars, provide exciting new options for performing nearfield visual observations when visibility is poor. However, certain scenarios demand much more "big picture" situational awareness due to complex structures and entanglement hazards that are exacerbated by poor visibility. In such circumstances, a real-time 3-D model can be fed high-quality position and attitude information from an inertial navigation system to provide a real-time, virtual world that an ROV operator can utilize to supplement his/her suite of sensory inputs. In the case of a flooded mine in northern Canada, we encountered a confined-access, low visibility environment with a high likelihood of misguidance or entanglement. The deep waters and confined access disqualified the utility of positioning through acoustic methods, and the need for a robust, real-time, integrated positioning and attitude system demanded that a high quality inertial navigation system be used. The obstacles and entanglement risk required that the data from that navigation solution be fed into a 3-D model for real-time monitoring.

In the project, we demonstrated that we could pull together a host of off-the-shelf hardware and software to develop a unique, high-value navigation solution and a real-time, adaptive 3-D virtual environment to maximize the situational awareness for the ROV operational team. The solution, combined with advanced video and sonar observational tools, provides a comprehensive approach to avoiding a game of blind man's bluff with an ROV asset.

The Authors extend special thanks to:

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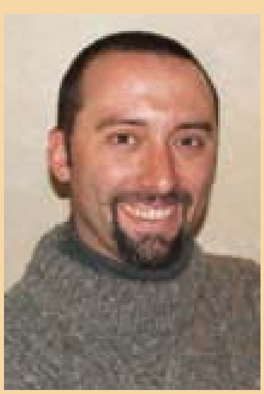
- *LYYN AB, for allowing us to use a sample image of video that has been enhanced with their LYYN T38 Video Enhancement Tool.*

About the Author



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