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Conducting Visual Surveys with a Small ROV in Shallow Water

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Abstract

Small remotely operated vehicles (ROVs), sometimes described as low-cost (<$150,000) ROVs, have become valuable tools in the study of marine organisms and their habitats. The versatility and relative simplicity of these vehicles is enabling scientists and fishery managers to develop a better understanding of the marine ecosystem that has not been possible using conventional survey methodologies. The ability to work at depths beyond the reach of scuba divers and in complex habitats inaccessible to trawl surveys is helping to "fill the information gap" between nearshore and deep offshore habitats, allowing for the development of more comprehensive management strategies of the ocean's resources.

Small ROVs are especially suited for use by natural resource agencies and academic institutions operating on limited budgets with minimal resources. In calm, nearshore conditions, a small ROV can be operated from vessels as small as 6 m with a minimum of equipment and crew. In contrast, conducting safe, quantitative surveys with a small ROV in more extreme marine environments increases the complexity of the operation and requires additional equipment and personnel to ensure success. This paper focuses on the technical aspects of designing and conducting shallow-water (<200 m) surveys with a small ROV, based on our experience using a Deep Ocean Engineering Phantom HD2+2 ROV in San Juan Channel, Washington. Topics addressed include equipment, navigation and tracking, deployment protocols, tether management, camera calibration, survey design, data collection, hazards and safety, transect length and width, and recent technological developments.

Introduction

Over the past decade, small remotely operated vehicles (ROVs) have seen increasing use in the study of marine organisms and their habitats, enabling scientists and fishery managers to gain a better understanding of the marine ecosystem that has not been possible using more conventional methods. Compared to large work-class ROVs (e.g., *ROPOS, VENTANA*) that are expensive to charter and require specialized teams to operate, the greater affordability, lower operating costs, and relative simplicity of small ROVs makes them especially suited for use by natural resource agencies and academic institutions operating on limited budgets and with minimal resources (i.e., vessels, personnel). Unlike large ROVs that typically require a large, dedicated support vessel, a small ROV can be deployed from a range of platforms that can be tailored to match the scale of operations and expected working conditions (e.g., Csepp 2005). Small ROVs are capable of working at depths beyond safe scuba limits (~25 m) and in complex habitats inaccessible to trawls and other nets, and can be transported quickly and deployed in response to acute or very short-term events such as hypoxic conditions (Grantham et al. 2004). Additionally, the ability to conduct non-destructive sampling makes the small ROV an excellent tool for surveying rare or fragile species.

Although small ROVs are relatively simple to operate, the vehicle and associated systems are complicated and thus prone to mechanical, electrical, and software problems. This requires the user to be familiar with the system components in order to operate them safely and efficiently. Literature presenting the results of small ROV studies seldom includes a detailed discussion of technical difficulties the author(s) may have encountered. Instead, many of these experiences are related among users by word-of-mouth or learned by trial and error. Training offered by companies that supply small ROVs typically provide a good introduction to individual systems (ROV, tracking, sonar, etc.), but are not specifically designed to address the general operational issues involved with the day-to-day use of the vehicle and other equipment (e.g., software setup, intersystem communications, tailoring systems to specific applications). In this paper we discuss many of the technical aspects associated with designing and conducting shallow-water (<200 m) visual surveys with a small ROV, based on our studies of benthic marine fishes in the San Juan archipelago in Washington state. The topics and examples presented herein are not unique to our work, but are illustrative of the challenges and problems that new users are likely to encounter when using this technology.

Table 1. Studies using small ROV in fishery and habitat investigations.

Reference	ROV	Manufacturer	Size (length × width × height)
Hardin et al. 1992	Phantom DS4[a]	Deep Ocean Engineering	1.73 m × 0.9 m × 0.7 m, 94 kg
Davis et al. 1997	Hydrobot[a]	Hydrobotics	1.1 m × 0.6 m × 0.5 m
Norcross and Mueter 1999	MiniROVER MKII[a]	Benthos	0.9 m × 0.5 m × 0.4 m, 41 kg
Norcross and Mueter 1999	Phantom S2[a]	Deep Ocean Engineering	1.5 m × 0.8 m × 0.6 m, weight unspecified
Amend et al. 2001	Phantom HD2	Deep Ocean Engineering	1.4 m × 0.7 m × 0.7 m, 91 kg
Parry et al. 2003	Phantom XTL[a]	Deep Ocean Engineering	1.1 m × 0.5 m × 0.5m, 45 kg
Csepp 2005	Phantom XTL[a]	Deep Ocean Engineering	1.1 m × 0.5 m × 0.5m, 45 kg
Martin et al. 2006	Falcon	Seaeye	1.0 m × 0.6 m × 0.5 m, 50 kg
Byerly (2005)	Phantom HD2	Deep Ocean Engineering	1.4 m × 0.7 m × 0.7 m, 91 kg

[a] Vehicles no longer in production.

Table 2. Owners of small ROVs used to conduct fishery or habitat investigations in Canada, Hawaii, and along on West Coast of the United States.

Agency/organization	ROV model(s)
Alaska Dept. of Fish and Game	DOE Phantom HD2+2
Bamfield Marine Science Center	DOE Phantom HD2
California Dept. of Fish and Game	DOE Phantom HD2+2
Cordell Bank Marine Sanctuary	DOE Phantom XTL
Dept. of Fisheries and Oceans Canada, Pacific Biological Station	HD2+2
King County (Washington) Dept. of Natural Resources	VideoRay Pro 3 XEGTO
Monterey Bay Aquarium Research Institute	DOE Phantom, unknown model
NOAA-NMFS, Auke Bay Laboratory	DOE Phantom XTL (2 vehicles)
NOAA-NMFS Hawaii	DOE Phantom DHD2+2
NOAA-Southwest Fisheries Science Center	DOE Phantom DS4
Oregon Dept. of Fish and Wildlife, Marine Resources	DOE Phantom HD2+2; VideoRay Explorer
Simon Fraser University, School of Resource and Environmental Management	DOE Phantom DHD2+2
University of Washington, Friday Harbor Laboratories	DOE Phantom HD2+2

What is a small ROV?

The terms small ROV and low-cost ROV (LCROV) have typically been used in reference to vehicles that do not require dedicated support platforms or crews to operate (e.g., Stewart and Auster 1989, Auster et al. 1989, Hardin et al. 1992, Sprunk et al. 1992, Norcross and Mueter 1999). The Remotely Operated Vehicle Committee of the Marine Technology Society describes small ROVs, which includes the majority of LCROVs, as vehicles designed to operate in water depths less than 300 m and costing between $10,000 and $100,000 (http://www.rov.org/info.cfm). The small ROV class can be subdivided into mini-class and light-work categories based on cost, size, and power. Lower-priced vehicles, commonly described as personal, micro-, or mini-ROVs, are typically very small (≤40 kg) and designed mainly for recreational use. The more expensive vehicles are typically several times larger than mini-class vehicles but generally weigh less than 100 kg, and are sometimes referred to as "inspection" class ROVs. Vehicles in both categories have been used to conduct quantitative fishery and habitat investigations (Table 1), and are owned by a number of natural resource agencies and academic institutions in Hawaii and along the West Coast of the United States and Canada (Table 2). Due to their greater power and payload capacities, larger vehicles tend to dominate the field, although recent improvements in thruster design coupled with rapid advances in component miniaturization (e.g., imaging, laser, and tracking systems) are providing mini-class ROVs with performance characteristics and capabilities rivaling or exceeding some inspection-class vehicles.

In U.S. dollars, purchase costs for a base model Deep Ocean Engineering (DOE) Phantom HD2+2 (Fig. 1A) can range from $85,000 (used) to $100,000 US (new) (Mike Chapman, Mecco Inc., Duvall, Washington, 2007, pers. comm.), while the slightly smaller Seaeye Falcon (Fig. 1B) can be purchased for between $125,000 and $150,000 (Chris

Figure 1. **Examples of light-work and mini-class ROVs. A: Deep Ocean Engineering Phantom HD2+2. B: Seaeye Falcon. C: VideoRay Pro 3 XEGTO microROV.**

Roper, Roper Resources Inc, Victoria, British Columbia, 2007, pers. comm.). The purchase price for a VideoRay Pro 3 (Fig. 1C), a high-performance mini-class ROV, is approximately $28,000 (http://www.videoray.com/). The above costs do not include ancillary equipment such as tracking and navigation systems, imaging sonars, or laser systems, which can easily add $15,000 to $150,000 or more to the initial ROV purchase price.

Background

Populations of rockfish (*Sebastes* spp.) and lingcod (*Ophiodon elongatus*) in Washington state are currently at historically low levels or in the early stages of recovery (PSAT 2007). Trawl surveys are the primary tool for conducting bottomfish population assessments by the Washington Department of Fish and Wildlife (WDFW) (Palsson 2002, Palsson et al. 2003), but are impractical for sampling the high-relief habitats inhabited by many rockfish species (Kreiger 1993, Krieger and Ito 1997, Jagielo et al. 2003). In the early 1990s WDFW developed a non-destructive drop-camera technique for sampling nearshore (≤40 m) high-relief habitats within the interior marine waters of Washington state. Drop-camera surveys conducted from 1993 to 2004 were successful in identifying habitats occupied by rockfish, lingcod, and other relief-oriented fish species, but were discontinued in 2005 due to budget and staff shortfalls. Results from WDFW drop-camera surveys were used to develop habitat maps of Puget Sound and to augment population assessments derived from WDFW trawl surveys. Since 1993, ongoing scuba surveys have been conducted by WDFW at fourteen index sites in Puget Sound to monitor trends in rockfish and lingcod populations, but are limited to a practicable working depth of 25 m.

Between 2000 and 2004, the WDFW investigated the utility of a small ROV for collecting quantitative data in high-relief outcrop and bank habitats, and concluded that the technique had the potential for improving WDFW's stock-assessment methodology and understanding of fish and habitat relationships. Consequently, we designed and conducted separate habitat-based visual surveys with a small ROV in San Juan Channel (SJC) (Fig. 2) in 2004 and 2005. The survey area was selected based on the availability of high-resolution multibeam bathymetric (Fig. 3) and backscatter data collected by the Center for Habitat Studies of Moss Landing Marine Laboratories and the Canadian

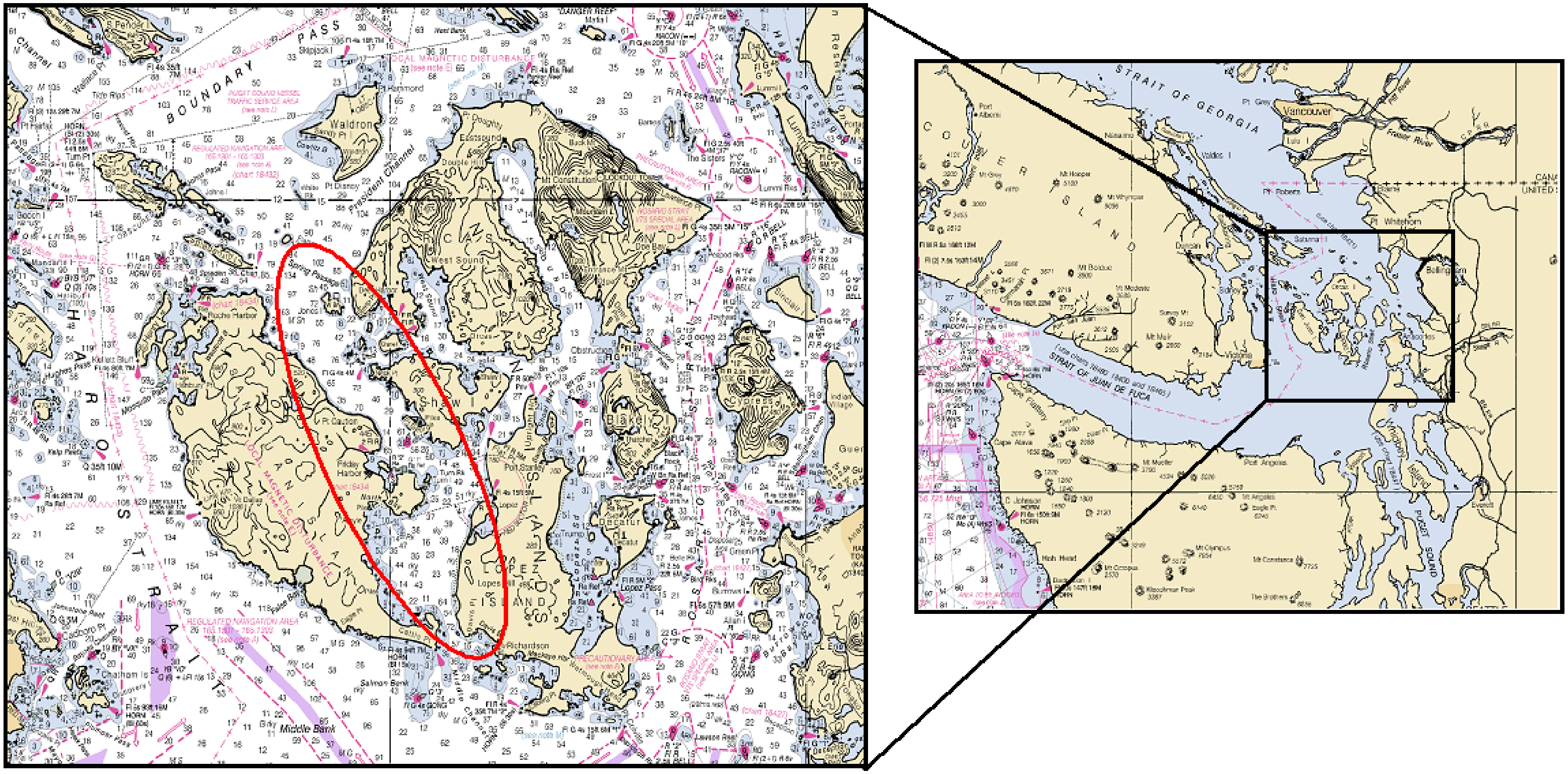

Figure 2. San Juan Channel study area (red oval) for the 2004 and 2005 ROV surveys.

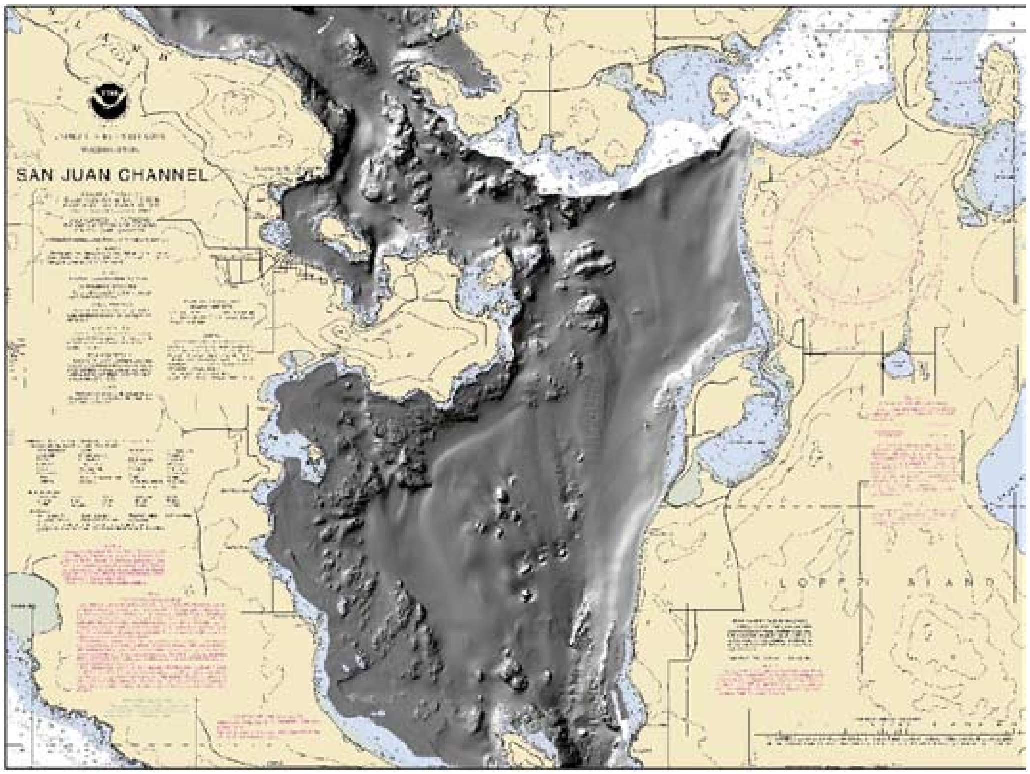

Figure 3. **High-resolution multibeam bathymetric imagery of San Juan Channel ROV study area.**

Hydrographic Survey. San Juan Channel is 18 km long and reaches a maximum depth of 166 m (91 fathoms), with current velocities reaching 2 m per second (4 knots) in some locations. The goals of the 2004 survey were to (1) collect fish density and habitat data for evaluating fish communities across all depths and habitats, and (2) visually groundtruth habitat maps derived from the multibeam and backscatter data (see "Survey design" section of this paper). Results of the 2004 survey provided valuable insight into the distribution and habitat utilization of several important rockfish species, and were used to refine the design of the 2005 survey, which focused only on fishes living in rocky habitats.

ROV system and configuration

The ROV used in both of our surveys was a DOE Phantom HD2+2, measuring 1.4 m long by 0.7 m wide by 0.7 high and weighing 120 kg (in air) (e.g., Fig. 1A). Power is supplied by four ½ hp horizontal thrusters, one ¼ hp vertical thruster, and one ¼ hp lateral thruster, providing 68 kg of forward thrust, 7 kg of vertical thrust, and 7 kg of lateral thrust, respectively. The Phantom is equipped with a Sony EVI-330 high-resolution color zoom camera that can be tilted up and down; the camera was fixed at 45° below horizontal when conducting transects, a position that maximized coverage of the seafloor for data collection while providing the ROV pilot with an adequate driving view. A pair of DeepSea Power and Light (DSPL) 15 milliWatt red lasers aligned in parallel at a separation distance of 10 cm were mounted on top of the camera housing to provide a frame of reference for estimating transect width (Caimi and Tusting 1987). The zoom function was used to examine substrate composition and make positive identifications of small organisms, but only when the ROV was stationary on the bottom. Two DSPL 250 W floodlights provided illumination of the visual field: one light was mounted in a fixed position on the ROV crash frame, with the second mounted on top of the laser bracket so that it could be tilted with the camera. A fluxgate compass and a pressure sensor within the ROV body provided accurate heading (±1°) and depth (±0.65 m) information to the ROV pilot. A 240 m long, 32 conductor, neutrally buoyant umbilical (tether) connected the ROV to the control console on board the support vessel, providing power and control for the ROV, camera, and lights while returning video, depth, and heading data to the console.

After the ROV had been configured to achieve the desired lighting characteristics and laser placement, it was trimmed for level flight using lead weights and floats constructed from 3.8 cm (1.5 inch) schedule 40 PVC pipe. The ROV was ballasted to obtain slightly positive buoyancy in order to (1) minimize the use of upward vertical thrust that can disturb bottom sediments and limit visibility, and (2) pro-

Figure 4. **The R/V *Molluscan*, owned and operated by the Washington Department of Fish and Wildlife.**

Figure 5. **The R/V *Elakha*, owned and operated by Oregon State University. Note Phantom HD2+2 on rear deck and umbilical on reel behind cabin.**

vide a failsafe measure that would allow the vehicle to float to the surface in case the umbilical was severed or power was interrupted for an extended period.

All video imagery in our surveys was recorded to Digital Hi-8 videotape for later analysis. A Pisces Design video-text overlay system was used to imprint the time, date, and calculated position of the ROV on the videotape, which allowed the positions of fishes and seafloor features to be georeferenced for examining patterns of fine-scale (<5 m) habitat use.

Support platform

Csepp (2005) demonstrated the ability to conduct safe and efficient ROV operations from a vessel as small as 6 m. Using a DOE Phantom XTL, a lower-powered version of the HD2+2, and limiting operations to shallow water (<76 m) and relatively calm seas (waves <0.6 m), Csepp (2005) eliminated the need for hydraulic capabilities and required only a small (2 kW) portable generator for power, thus minimizing the size and space requirements of the vessel. Because our surveys were conducted in deeper waters and higher sea-states that increased the demands on the vessel and the ROV, we required a larger platform to accommodate the additional equipment and crew necessitated by these conditions. Our vessel, the R/V *Molluscan*, is a 12 m fiberglass center-wheelhouse monohull design with a beam of 4.5 m, equipped with a hydraulic deck winch and stern mounted A-frame (Fig. 4). The inherent stability of the R/V *Molluscan* facilitated ROV piloting and simplified tether management, enabling operations to be conducted in more extreme weather conditions than those described by Csepp (2005). The large, open deck provided adequate space for efficient handling of the ROV and umbilical, and the removable transom boards expedited deployment and recovery of the ROV and other equipment. Because the San Juan Channel is a relatively small and protected geographic area, a lack of vessel speed and maneuverability were not liabilities in our surveys, although these characteristics may be important when operating across wider areas and/or in extreme weather conditions. For example, vessels operating in exposed coastal environments may be equipped with high-performance engines and dynamic positioning systems (e.g., R/V *Elakha*, Fig. 5), although these features may add considerably to vessel and operational costs.

During pilot studies we concluded that a 2 kW generator was insufficient for meeting the electrical demands of the ROV, tracking system, and peripheral equipment (VCRs, computers, monitors) needed for our surveys. Instead, power was supplied by an 8 kW generator delivering true sine wave 100-250 VAC at 60 Hz, mounted below decks to maximize workspace and dampen the effects of noise and exhaust fumes on the crew. The open-deck vessel employed by Csepp (2005) required the construction of a custom workstation to shield the electronics from weather and salt spray. In contrast, the enclosed cabin of our vessel provided complete protection of the equipment while greatly enhancing pilot and crew comfort, which had obvious positive effects on crew morale and productivity. The large galley area of the R/V *Molluscan* allowed the electronics to be configured ergonomically such that the pilot could operate the ROV, tracking system, video equipment, and computers without assistance if necessary. To improve the pilot's ability to operate in high light conditions, shades were affixed to the cabin windows to reduce the effects of backlighting and glare on the video monitor and computer screens.

Figure 6. ROV umbilical coiled on deck of the R/V *Molluscan*.

Figure 7. Motorized slip-ring and reel system for a Phantom umbilical. This unit is owned by the University of Washington Friday Harbor Laboratories.

All of our operations were conducted using a "live-boat" technique that required the support vessel to be operated at speeds closely matching those of the ROV. Working into the current and using the vessel's trolling clutch, the R/V *Molluscan* could be slowed to under 1 knot while maintaining steerage, allowing the pilot to minimize the separation distance between the ROV and support vessel and reduce the "leapfrog" effects that can complicate ROV navigation.

Umbilical storage and management

The most common and least expensive approach to storing the ROV umbilical on a small vessel is to figure-8 or coil it onto the deck or into a well. To maximize deck space, we opted to coil the umbilical during our surveys (Fig. 6), although this method requires the umbilical to be flipped under itself every second or third coil to maintain the natural twist of the conductors. In contrast, the figure-8 technique reduces handling time by eliminating the need for flipping, and is preferred when space is available. A more sophisticated but expensive method involves the use of a slip-ring and reel system. These systems can be manually or automatically controlled (Fig. 7), but can also be large and heavy, and may require the use of a larger and/or dedicated vessel.

Proper management of the ROV umbilical is an important element of all operations that can have significant impacts on vehicle piloting, and is critical for maintaining the integrity of the umbilical. We used two methods to manage the umbilical in our surveys, both of which required two people to accomplish effectively and efficiently. When operating at depths less than 30 m, the umbilical was paid-out and controlled by hand from the stern of the support vessel. This technique allows for rapid deployments of the ROV, but required the deck crew to constantly monitor and adjust umbilical tension to avoid hindering the vehicle's maneuverability. For operations conducted deeper than 30 m, we employed a clump (downweight) system modified after Stewart and Auster (1989) to reduce the umbilical's catenary and minimize the effects of vessel movement on the ROV (Fig. 8). Our clump system was composed of a 185 kg lead-filled scuba tank attached to 3/8 inch braided Kevlar Samson™ line (Fig. 9) spooled onto a deck-mounted hydraulic winch. The clump line was run through a block on the vessel's A-frame, which allowed the clump weight to be safely lifted and controlled during deployment and retrieval. As a safety precaution, the clump weight was connected to the Kevlar line with a breakaway cord that would allow the ROV to be recovered in case the clump became snagged on the bottom.

To deploy the ROV when using the clump system, the support vessel was positioned ~50 m downcurrent of the starting coordinate and powered into the current to maintain a stationary position. The ROV was launched and driven on the surface 35 m astern of the vessel and the clump weight lowered 1-2 m into the water. A brass snap-shackle on a loop of nylon twine was attached to the umbilical with a prussic loop at the 35 m mark, and clipped to a loop of nylon cord threaded through the Kevlar line 3 m above the clump weight. The ROV was then driven back to the vessel and down to the clump weight. As the clump was lowered, additional snap-shackles attached to the umbilical were clipped to nylon loops in the Kevlar line at conveniently spaced 15 m intervals. To prevent the ROV from becoming separated from the support vessel during descent, the pilot followed the clump until it had reached the desired depth, at which point the ROV was driven to the bottom and the vessel speed was increased to begin the transect. Floats attached to the umbilical between the ROV and the clump kept it suspended in the water column and prevented it from contacting the bottom. When

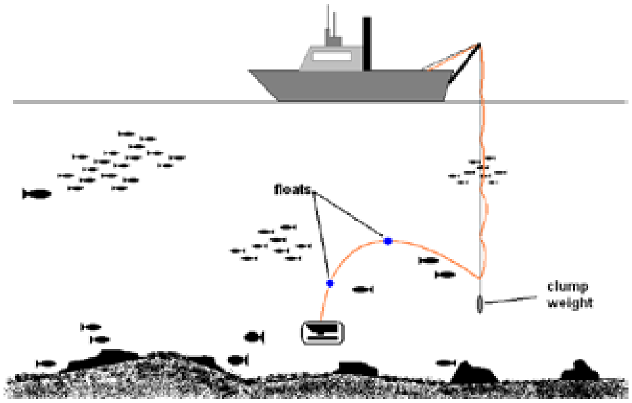

Figure 8. Schematic of clump weight system used in the 2004 and 2005 San Juan Channel ROV surveys.

Figure 9. Clump weight.

transects were conducted on flat bottoms or gradual slopes, the clump was maintained between 3 m and 5 m above the bottom. When work was being done in high relief (>3 m) or steep-walled habitats, the clump weight was kept 5 m to 10 m above bottom to allow for sufficient time to raise it if necessary, although this reduced the operating envelope of the ROV and required the pilot to maintain closer contact with the support vessel.

ROV positioning and navigation

Establishing the position of the ROV during operations is essential for safe piloting, as well as for obtaining accurate estimates of distance traveled necessary for calculating area swept estimates for each transect. Fine-scale navigational accuracy (<3 m) is always desirable, and can be especially important in studies examining organism-habitat relationships. Positioning of the ROV in our surveys was achieved with an ORE Offshore® Trackpoint II Ultra-Short Baseline (USBL) system, which utilizes a directional hydrophone mounted on the support vessel to communicate acoustically with a transponder attached to the ROV. The hydrophone was mounted on a 3.8 cm (1.5 inch) galvanized steel pole affixed to a pivot bracket amidships on the port side of the vessel, which allowed the unit to be raised for transit between deployment sites. In the lowered position the hydrophone was suspended 1.5 m below the keel of the vessel. The hydrophone was maintained in a perpendicular orientation by lines running fore and aft from the hydrophone to cleats on the bow and stern, and was prevented from swinging laterally by lashing the top of the hydrophone pole to the vessel's handrail. We used two different transponders during our surveys, alternating between an ORE 4330B and an Applied Acoustic Technologies (ATT) model 219. The ORE 4330B is manually activated via a grounding pin on the transponder body, whereas the ATT model 219 is activated automatically upon immersion. The transponder was mounted on the forward, vertical, portside support of the ROV crash frame with stainless steel hose clamps, and secured with a safety lanyard in case of a clamp failure.

The georeferenced position of the ROV was calculated with Hypack® Max navigational software linked to a WAAS enabled Northstar 952 DGPS and KVH Azimuth® 1000 digital fluxgate compass, and displayed in real-time on a computer screen registered to a bathymetric map of the bottom. In our application, the hydrophone was mounted almost directly under the DGPS antenna (<1 m); thus Hypack required no sensor position offsets for correctly locating the ROV's position. Tracking data was acquired at 2-second intervals at an accuracy ±3 m. It should be noted that a number of USBL tracking and navigation systems are commercially available (e.g., Fugro WinFrog, LinkQuest TrackLink, Desert Star Pilot), all operating on the same basic principle.

Due to our initial lack of familiarity with the Trackpoint II system, we experienced several problems that produced less than desirable tracking results. The most common problem we encountered early in the 2004 survey was neglecting to update the depth parameter needed by Trackpoint to calculate accurate ROV position estimates. Fortunately, position estimates did not appear to be adversely affected when the ROV was operating within ±20 m of the input depth, but became increasingly inaccurate as ROV depth exceeded this range. The update frequency varied with the rate of change in depth, with flatter transects seldom requiring more than an initial depth input at the start of the transect, whereas transects conducted along steep walls or pinnacles often required six or more updates over a 20-minute transect. The Trackpoint system can be configured to update the depth parameter automatically, although our system lacked this capability, and it was not until the latter part of the 2004 survey that entering the ROV depth became a consistent process.

A less common but more perplexing problem appeared to be the result of multipath errors in the acoustic signal,

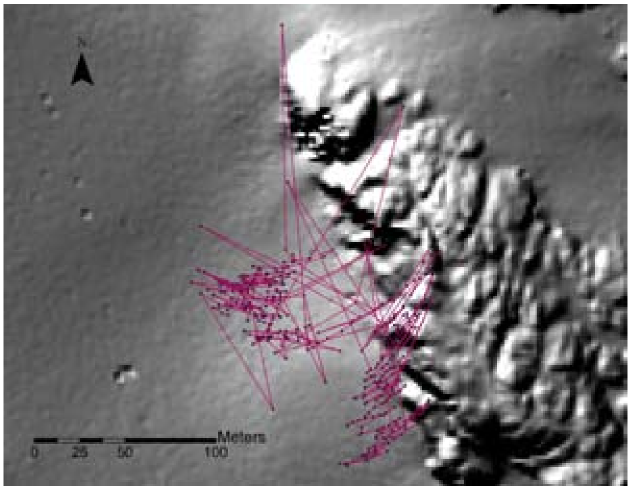

Figure 10. **Example of poor tracking due to multipath errors in the transponder return signal when operating in steep, rocky habitat. Note large jumps (>100 m) in trackline.**

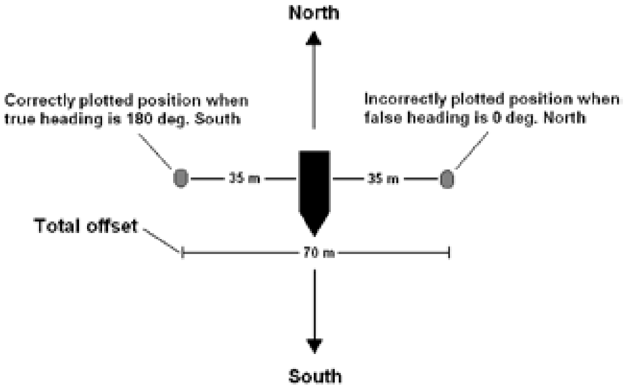

Figure 11. **Example of maximum offset error in ROV positioning due to incorrect Hypack® software driver.**

which were easily recognized by large jumps (tens to hundreds of meters) in the tracking data (Fig. 10). At best, only portions of the ROV trackline would be affected, but in some cases the data were completely unusable for estimating track length. This situation was most apparent when the ROV was operated in steep or highly rugose rock habitats, and may have been related to the placement of the transponder on the ROV. As we gained experience with Trackpoint, we were able to minimize the occurrence of this problem by mounting the transponder as high on the ROV as possible and maintaining a clear transmission path between the transponder and hydrophone (e.g., vessel offshore of ROV on steep walls).

The most significant and pervasive problem affecting our tracking success was the result of an incorrect software driver for the KVH compass, which provides the heading data needed by Hypack® for calculating the ROV's georeferenced position. This problem went undetected until the third day of the 2005 survey; thus all of the position estimates collected to that point (including all of the 2004 data) were calculated based on a vessel heading of 0°. The positional error associated with this problem is minimized when the vessel heading is maintained at due north or when the ROV is directly under the hydrophone, neither of which were typical conditions in our surveys. As vessel/ROV distance increases and vessel heading approaches 180°, the positional error increases systematically until reaching a maximum error of 70 m in our surveys (twice the maximum free umbilical length) (Fig. 11). We discovered this problem after completing a transect where the ROV had been visually tracked continuously from the surface. Despite knowing that the ROV was always shoreward of the vessel, Hypack® plotted the vehicle offshore of the vessel and with a consistent position offset, whereas Trackpoint plotted the correct relative position of the vehicle throughout the transect. This contradiction was clearly indicative of a problem with the heading input, which we were able to confirm in two ways. First, by changing the vessel heading while keeping the ROV stationary on the bottom, we could "force" Hypack® to plot the ROV's true position, which only occurred at a vessel heading of 0°. Second, an examination of the KVH data string and the Hypack data file revealed that even though the vessel heading was displayed correctly in Hypack®, the navigation file recorded a constant heading of 0°, which implied a problem with the software driver. After installing the correct driver, the problem was completely resolved, resulting in an immediate improvement in ROV tracking. This problem was noted several times in 2004 (always when transects were run in a northerly to southerly direction), but did not occur at a frequency that seemed to warrant further scrutiny, and was dismissed as a random software glitch. Because the ROV pilot tended to use the relative position display from Trackpoint for navigating the ROV, there was never any suspicion that this problem existed. However, had we conducted more extensive testing with the tracking system prior to the 2004 survey, or had the pilot been using the georeferenced position display from Hypack® as the primary navigational aid (which became the norm after this experience), the problem likely would have been discovered much earlier.

We would occasionally lose the GPS signal when operating in close proximity (<50 m) to steep shorelines, although this problem was typically short-lived (<30 seconds) and self-correcting. On several occasions the battery in the ORE 4330B transponder dropped below the required voltage (18 VDC), usually as a result of leaving the unit activated between deployments, but in one instance was due to a bad charging unit. This condition was recognizable by poor or missing position estimates, but was easily resolved by switching to the ATT transponder. The only major problem we experienced with a transponder was a spontaneous O-ring failure, resulting in a complete flooding of the unit and loss of the acoustic return signal. Bubbles produced around the hydrophone due to rapid changes in vessel heading or current velocity would occasionally result in degradation or loss of the acoustic signal, but were of short duration (<10 seconds) and had no serious effects on tracking.

Working in 24-29 m of water with a Trackpoint II USBL system, Karpov et al. (2006) reported tracked ROV distances approximately 3% longer than actual distance by comparing obvious geological features from the video record to the tracked position of the ROV overlain on the detailed bathymetry map. Given the tracking problems experienced in 2004, it is unlikely that we achieved a similar level of accuracy in our transect length estimates; over half of the fifty-eight transects conducted in 2004 had gaps or other data errors that accounted for more than 20% of the overall track length, and the data collected on 18% of transects were completely unusable for establishing the ROV's path. However, a preliminary examination of the 2005 tracking data showed that 71% of transects were missing data accounting for less than 10% of the overall transect length, and less than 4% of transects were comprised of unusable data. This substantial improvement in tracking success should allow us to use the methods of Karpov et al. (2006) to test the accuracy of our track length estimates.

The accuracy and precision of ROV tracking could be improved through the use of long baseline (LBL) or GPS intelligent buoy (GIB) acoustic tracking systems, although these systems are expensive and more commonly employed in operations using large ROVs and manned submersibles. Doppler aided inertial navigation systems (INSs) mounted on the ROV can provide highly accurate measurements of the vehicle's path, but are subject to error (Whitcomb et al. 1999) and may cost as much or more than the ROV system itself.

Survey design

Our surveys utilized a habitat-based, random-stratified design based primarily on high-resolution (2-5 m gridded) multibeam bathymetric and backscatter data that were interpreted to characterize the geomorphology of San Juan Channel (SJC) and produce habitat maps using the methods of Greene et al. (2007). For nearshore areas where no multibeam bathymetric data were available, habitat maps were created from coarse-scale (1-2 km) drop-camera video data collected by the WDFW. The two data sources were integrated in ArcGIS 9.0 and polygons created for the four broad-scale habitat types used as the initial stratification for the 2004 survey: Complex, Smooth Rock, and Coarse habitats occurred at the scale of tens of meters up to 5 km, and were imbedded in the Soft habitat that dominated the survey area (Fig. 12). The four habitat strata were stratified by depth (<40 m and ≥40 m) to allow for comparisons to WDFW drop-camera surveys, with each habitat-depth pair stratified by geographic location in the channel (north and south) to distribute sampling effort throughout the survey area. This design resulted in a total of 16 possible strata (4 habitats × 2 depth zones × 2 locations), although two of the strata (Course, Deep, North; Course, Deep South) were not represented in SJC.

Based on WDFW scuba and drop-camera surveys, rockfish populations within the Complex stratum were expected to be patchy and randomly distributed. Having no a priori knowledge of rockfish distributions in SJC at depths over 25 m, we hoped to strike a balance between survey efficiency and maximizing the encounter rate of rockfish by conducting transects that were neither too short nor too long. Based on the time required to deploy and retrieve the ROV and an average transect speed of 0.5 m per second, we concluded that a transect distance of 400 m would allow us to conduct a minimum of three transects per stratum over the planned 16 day survey period. Hawth's Tools extension for ArcMap 9.0 was used to generate random points within each stratum that were originally designed to serve as starting locations for each transect. However, when hydrographic conditions prevented the ROV from reaching the bottom within 100 m of the designated starting point, the transect was conducted to pass as close to the point as possible while remaining within the stratum polygon. In 2004, 45 of 58 transects (78%) started, ended, or passed within 100 m of the preselected starting locations.

Based on the spatial distribution of rockfish and lingcod observed in 2004, the 2005 survey was conducted entirely within the Complex stratum using the same depth strata as the 2004 survey. Prior to the 2005 survey we acquired additional multibeam and backscatter data for some of the nearshore areas that lacked this information in 2004, allowing us to update our habitat map by removing non-rocky habitats previously classified as Complex, and conversely, to include rock habitats classified as non-rock in 2004. To explore patterns of habitat use by rockfish and lingcod, the 2005 survey was also stratified by habitat slope (<30° = shallow; ≥30° = steep) as calculated from the multibeam data using the Spatial Analysis extension for ArcMap 9.0. With only four strata, the design of the 2005 survey was much simpler than the previous year, but was comprised of many smaller and more fragmented polygons than the 2004 survey design (Fig. 13).

Based on the variance of rockfish and lingcod densities observed in 2004, we concluded that 10 to 20 transects per stratum would be needed to improve survey precision and obtain acceptable population estimates for these species (±30% CV). To distribute sampling effort throughout the channel and to provide more opportunities for working if conditions were unfavorable in a particular location, we chose to conduct 20 transects per stratum with a minimum transect distance of 200 m. Hawth's Tools (ArcMap 9.0) was used to generate random points within each stratum that served as reference locations for the individual

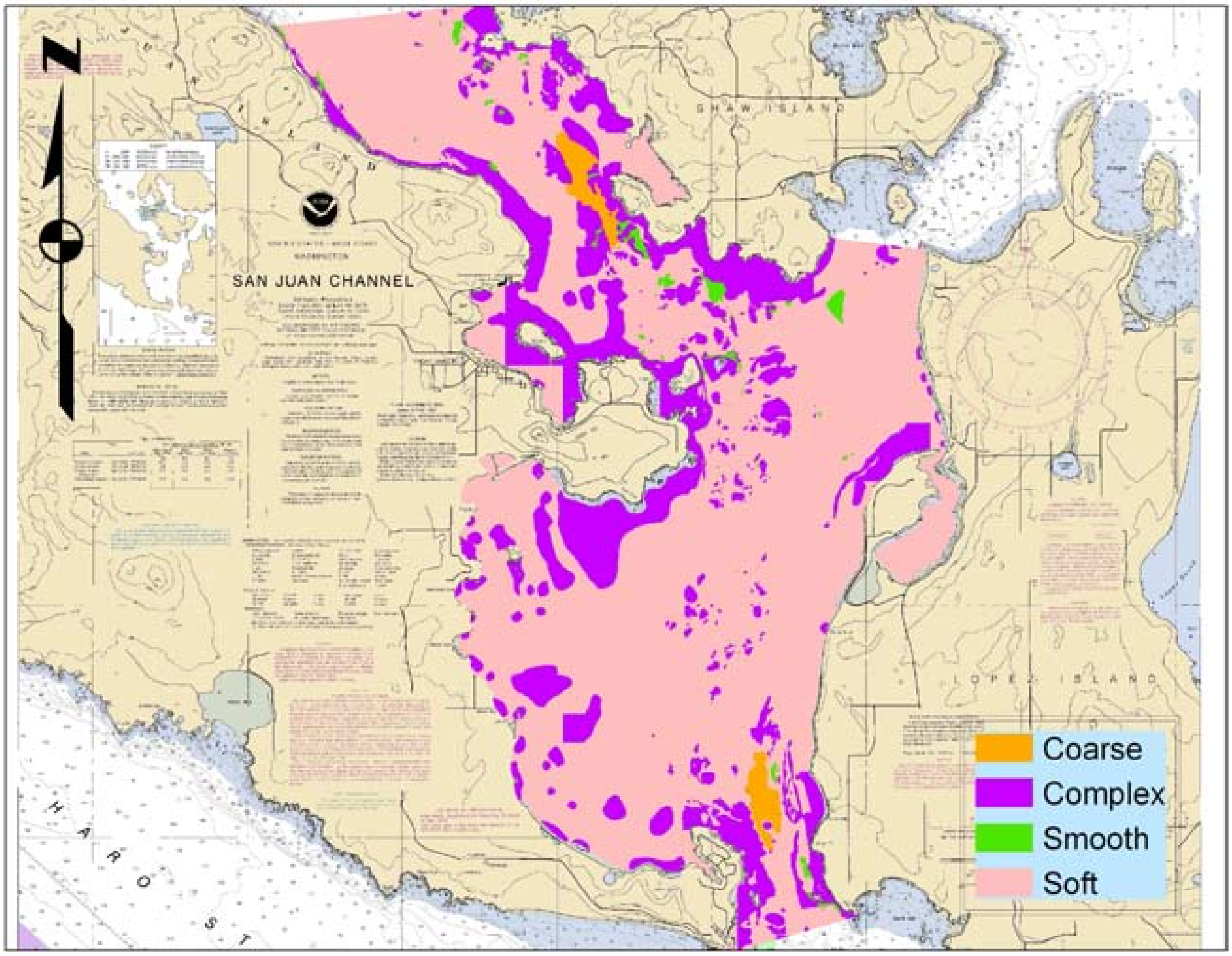

Figure 12. Broadscale habitat stratification used in the 2004 ROV survey of San Juan Channel.

transects. Of the 78 transects completed in 2005, 64 (82%) passed within 50 m of the preselected transect point, a substantial improvement over the 2004 survey that reflects the increased experience and skill of the vessel captain and the ROV pilot from one year to the next.

Transect strategy

A variety of transect strategies has been proposed or employed in studies using small ROVs, each having their advantages and disadvantages. Csepp (2005) and Byerly (2005) conducted transects perpendicular to the shoreline, working offshore to onshore, an approach that optimizes the collection of video data by maximizing (in theory) the amount of time the bottom is in view. However, operating windows may be severely limited when working in locations with strong, alongshore tidal currents, resulting in decreased operational efficiency. Also, because perpendicular transects may be very short when surveying steep, shallow water habitats (e.g., <30 m), many transects may be required to collect sufficient data for conducting statistical analyses.

Stewart and Auster (1989) proposed flying the ROV away from a clump weight on a known length of tether, with the clump serving as the starting position and the transect ending when forward progress is impeded, although this method is not practicable for conducting transects longer than about 100 m due to the amount of umbilical the ROV must pull behind it. Under some conditions, the preceding technique could be expanded to conduct radial transects by returning to the clump weight and changing the heading of the ROV (Fig. 14). Alternatively, the ROV could be towed like a sled, although this technique is not particularly well suited for working in highly rugose environments.

In high current areas, Stewart and Auster (1989) propose anchoring the support vessel with the ROV attached to the clump weight on a very short tether (<5 m) and oriented downcurrent, then paying out the anchor warp to allow the ROV to progress along the transect. When working on smaller vessels (<15 m) with short anchor lines (<100 m), this method is limited to very shallow water (<30 m)

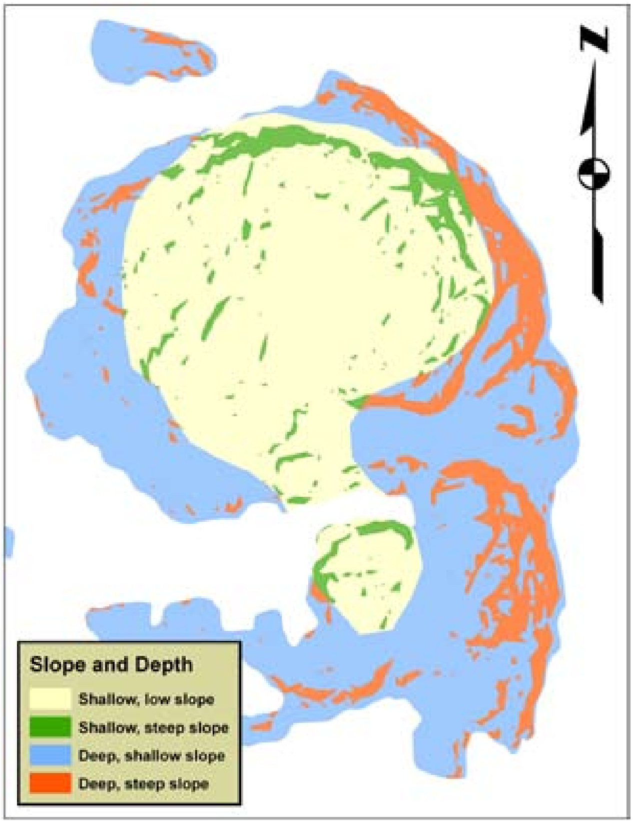

Figure 13. Example of depth and slope stratification used in the 2005 ROV survey of San Juan Channel.

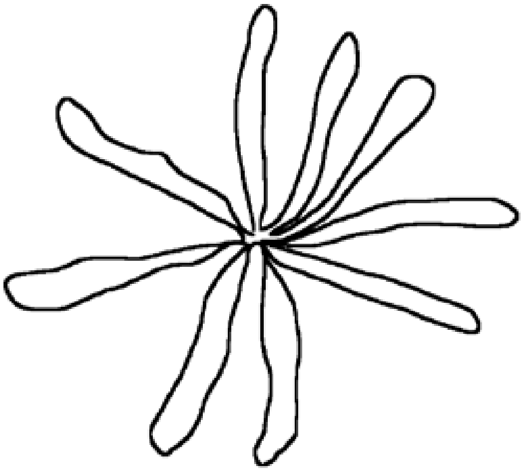

Figure 14. Example of radial transect pattern.

and results in short transects. Also, it has been our experience that anchoring the support vessel directly over a precise location is difficult and an inefficient use of survey time, and should be avoided except in cases where no other option exists for accomplishing a transect.

The consistent tidal currents in San Juan Channel and planned depth of many of our transects (>75 m) precluded the use of the above strategies, thus we determined that working into the prevailing surface current (generally parallel to the channel axis) would yield the most productive results. The principal drawback of this approach occurs when working in highly rugose or steep-walled habitats, where the probability of losing visual contact with the bottom is increased. Also, because our method of calculating transect width assumes a level substrate (see below), a condition that may not be met when the ROV is flown parallel to a slope, transect area estimates may be significantly biased depending on the degree of the slope.

All of our transects were conducted at current speeds ≤2 knots, which typically occurred within a two hour window around the predicted slack tide or current for a particular location. Prior to each transect, the support vessel was stationed ~400 m upwind or upcurrent of the starting location and allowed to drift for several minutes. The speed and vector of the drift were used by the captain to reposition and orient the vessel in order to minimize potential course corrections needed by the ROV along the transect. Weather conditions in the survey region were typically mild, with seas up to 0.5 m and winds under 10 knots. If necessary, we were capable of conducting operations in seas up to 1 m and winds up to 20 knots, although these conditions complicated deployment and retrieval of the ROV and clump weight, and were not well tolerated by the ROV pilot.

We utilized strip transects in our surveys, with the assumption that all organisms within the strip were detected with equal probability (Barry and Baxter 1993). A pair of DOE 15 mW red diode lasers mounted in parallel at 10 cm apart were projected into the center of the camera's field-of-view to provide reference points for estimating transect width and measuring organisms (Tusting and Davis 1992). Transect width (W_t) in meters was estimated using the relationship:

$$W_t \equiv W_m{}^{*}0.10/W_l$$

where W_m is the width of the video monitor (m), W_l is the laser width (m) measured on the video monitor, and 0.10 is the fixed laser separation distance in meters. During videotape review, laser measurements were taken at 60 second (±10 second) intervals along each transect and averaged to

Figure 15. ROV calibration grid. Note laser dots for scale (10 cm separation).

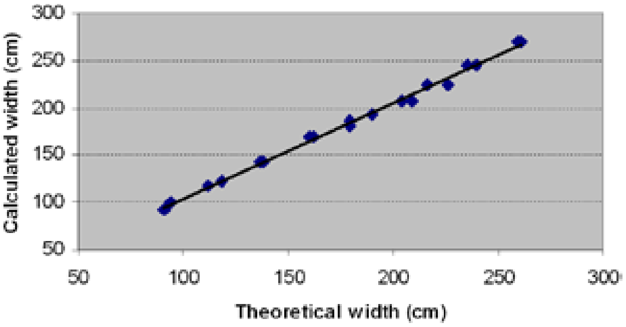

Figure 16. Relationship of theoretical transect width to calculated transect width, from grid calibration tests.

obtain a mean transect width. All measurements assumed a flat substrate with the ROV flying a level attitude. The accuracy of this method was tested by driving the ROV at different altitudes over a measured grid deployed on a flat bottom (Fig. 15). The regression of estimated transect width to the measured width on the video monitor was nearly perfect, with an R^2 of 99% (Fig. 16).

Line transects have been proposed for surveying demersal communities with ROVs as long as certain assumptions are met (Butler et al. 1991), although a review of the literature did not find any studies using this method in benthic ROV surveys. Large changes in camera height can produce significant bias in line transect density estimates (Jachmann 2002), thus line transects may not be appropriate for conducting ROV surveys in high-relief habitats. In surveys that focus on large benthic organisms that are readily visible when the ROV is flying close to the bottom, it may be reasonable to assume that the detection function is at or very close to unity within the field of view, thereby allowing the simpler strip transect method to be employed. However, improvements in low-light recording, laser-ranging tools, and software technology may facilitate the use of line transect methods by allowing the ROV to be flown higher above the bottom to increase the field of view.

Navigation data and ROV speed

The raw navigation data in our surveys were acquired at 2 second intervals, resulting in a "sawtooth" line that required editing and smoothing prior to calculating transect length (Fig. 17). Initial data editing was done in Hypack® to identify and remove outliers and data with point-to-point distances over 10 m, then the data were imported to ArcMap 9.0 for final editing and smoothing. In cases where the tracking data contained large (>10 seconds) jumps, the videotape data were used to construct a plausible ROV path. Where the ROV track could not be reasonably approximated or was otherwise unusable (e.g., multipath errors), the vessel trackline was used as a proxy for the ROV. The tracking difficulties we experienced in 2004 resulted in tracklines that contained numerous "blind" loops and dead-end "spurs," which hampered the use of line generalization algorithms for smoothing the data. Instead, the raw data points were interpolated by eye and smoothed tracklines were hand-digitized in ArcInfo 9.0. Substantially improved tracking in 2005 allowed us to use the Smooth Line tool in ArcInfo 9.0 to generalize the data and improve the precision of our track length estimates. 2D lengths of the smoothed lines were calculated with Hawth's Tools (ArcMap 9.0) and used to calculate organism densities. 3D track lengths were calculated for transects with underlying multibeam bathymetry coverage, and could be used to revise the density estimates in future analyses.

Average transect speeds in the 2004 survey ranged from 0.14 to 0.60 m per second (mean = 0.33 m per second). Based on the videotape reviews, we determined that ROV speeds between 0.25 and 0.75 m per second were optimal for identifying the larger (>10 cm) benthic fishes that are the focus of our studies. At speeds greater than 0.75 m per second it was difficult to image or identify cryptic fishes, and we were concerned that fish might avoid the ROV before they could be imaged and thus bias the survey. Slower ROV speeds did not appear to produce any increase in the number of fish encountered, and resulted in long transect times that increased videotape processing time.

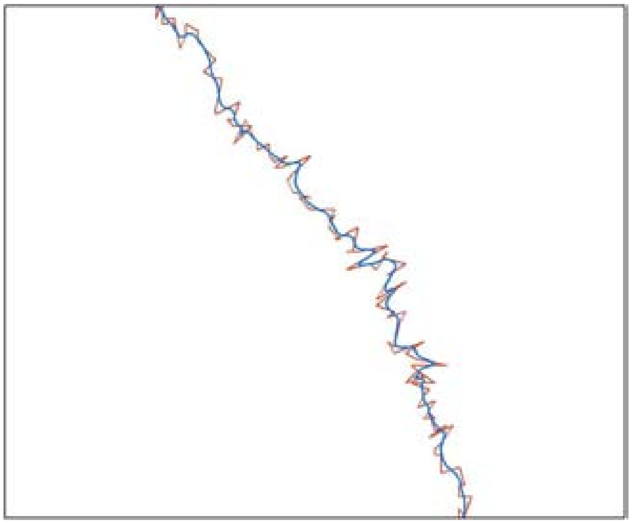

Figure 17. **Raw navigation data (red line) and smoothed trackline (blue line) after removal of outlying data points.**

Fish response to the ROV

The response of fishes to the ROV can positively or negatively bias estimates of abundance, depending upon whether they are attracted to or avoid the vehicle, and may vary considerably between species. Spanier et al. (1994) described the impacts of ROVs on the behavior of American lobster, but the quantitative effects of small ROVs on benthic marine fishes has not been studied. Based on observations from WDFW scuba and drop-camera studies, benthic rockfishes typically exhibited either no response or a "startle" response when approached by divers or the drop camera, retreating to a nearby crevice or moving just far enough to avoid physical contact. Lingcod tended to remain stationary or swam slowly away from the divers or camera, although some fish exhibited "burst" avoidance, rapidly departing the immediate vicinity. Our observations of benthic rockfishes and lingcod during ROV pilot studies and the San Juan Channel surveys suggest that these fishes exhibit similar responses to the ROV; thus we assumed that distributions of these species were not significantly affected by the vehicle. Kelp greenling, *Hexagrammos decagrammus*, often appeared to be attracted to the drop camera, but generally showed little or no response to the divers. It is unclear what effect the ROV had on kelp greenling in our surveys, as this species was observed just as commonly swimming through the habitat as resting motionless on the bottom. To develop a better understanding of response behavior, the reaction of all rockfish, lingcod, and kelp greenling observed in the 2005 ROV survey were coded for statistical analysis.

During WDFW drop-camera surveys, we have observed flatfishes and kelp greenling "attacking" the laser dots as if they were potential prey items, generally when the laser was moved over very short distances (<0.25 m) with repeated stops and starts. Conversely, rockfish and lingcod rarely exhibited a response that we could attribute to the lasers, even when they were pointed directly at the fish for measuring. We did not observe any apparent response of fishes to the lasers during the ROV surveys, possibly because the vehicle is moving continuously and the laser spots pass by before fish can visually detect them on the substrate.

ROV and equipment maintenance

The Phantom HD2+2 is a robust vehicle that requires only periodic maintenance. DOE recommends an annual inspection of all components, although if the vehicle is used consistently on a long-term daily basis, the inspection frequency should be increased appropriately. Visual inspections of the vehicle before and after every dive are highly recommended and should prevent most problems from occurring. The most common wear-related components on the Phantom are the thruster shaft O-rings, which are part of an oil-filled seal assembly that can be visually inspected to determine when O-ring replacement is required. Propellers may show uneven wear, usually as a result of an out-of-alignment thruster shaft allowing contact with the thruster guard or ROV body. If not detected early, this condition can develop into a serious problem resulting in rapidly failing O-rings and/or a damaged thruster motor. If the shaft is not badly out of alignment, it may be possible to work without affecting major repairs; otherwise, the motor will require disassembly to replace the shaft. Leak detectors installed in each of the Phantom's thrusters and in the ROV body will alert the pilot in the event of water intrusion, which in most cases should allow for sufficient time to remove the vehicle from the water before serious flooding occurs. Unfortunately, unless it is clearly obvious where the leak has occurred (e.g., failed thruster due to significant flooding), each detector will need to be checked to locate the path of intrusion. Following any leak detection it is imperative that all water is completely removed prior to replacing the detector pad(s). In the case of a flooded thruster, the unit will need to be disassembled and rebuilt. If flooding occurs in the ROV body, it is likely that many, if not all, of the internal electronics will be destroyed, in which case the vehicle will probably require shipment to the factory or an authorized service center for repair and calibration.

The straps suspending the ROV body within the crash frame should be checked periodically for damage and to ensure that the body is in proper alignment. Likewise, the umbilical and all cables and connections should be inspected regularly for nicks, cuts or other wear, especially when it is suspected that a component has been subjected to extreme stress (e.g., snagged on bottom, twisted, etc.). Transponders should be inspected for damage before and after each deployment and mounting clamps tightened as needed. The ORE 4330B is powered by a rechargeable battery and should not require opening under normal operating conditions, whereas the ATT Model 219 uses a 9 V battery that requires regular replacement. When it is necessary to open a transponder, it is critical that the unit be completely dry to avoid the entry of even the smallest amount of seawater that can easily damage or destroy component circuitry. It is relatively uncommon for the Phantom's control unit to experience a problem; in the 200+ dives we have conducted since 2000, the only failure we experienced was an overheated thruster power supply board, which required less than an hour to replace.

Safety considerations

Due to the amount of equipment, lines, and electrical connections on the vessel, crew safety was of paramount importance during all operations. Safety checklists were developed and strictly adhered to and all crewmembers were instructed in the safe handling of the equipment. Two of the biggest safety concerns in our operation were the ROV thruster propellers, which are very sharp and can easily mangle or sever fingers, and the lasers, which have the potential to cause retinal damage or blindness. To ensure maximum safety for the crew, the ROV was only powered up after launching, and was powered down prior to retrieval. When it was necessary to operate the ROV on deck, safety measures were in place to minimize or eliminate the potential for injury. Other significant safety hazards included the clump weight and the ROV, both of which are heavy and could cause serious injury if dropped on a hand or foot, and the ROV control box, which had a number of exposed high-voltage electrical components. One of the more common minor hazards we encountered was jellyfish tentacles clinging to the umbilical, which can cause mild to serious discomfort depending on the species and amount of exposure. As protection from these and other potential hazards, personal flotation devices were required during all on-deck operations, and work gloves, steel-toed boots, and ear-protection were available if needed. If overhead work is anticipated, we recommend the use of hard-hats.

Our surveys were conducted in an area continuously trafficked by ferries, commercial vessels, and recreational boaters, increasing the potential for vessel conflicts and adding another logistical and safety element to our operations. Commercial and recreational VHF traffic was monitored at all times, and the vessel was equipped with a loudspeaker to hail vessels not monitoring or responding to the radio. Per United States Coast Guard regulations, the appropriate dayshapes and lights were displayed during all deployments. Because recreational boaters seldom recognize these official signals, we also displayed the international alpha flag to alert boaters of our activities. Despite these precautions, the captain and crew had to remain vigilant, and on several occasions it was necessary to wave off oncoming boaters to avoid them damaging the umbilical or ROV when they were on or near the surface.

The captain and pilot should be familiar with any potential hazards to safe navigation of the vessel and ROV by consulting the most up-to-date nautical charts. In our particular case, San Juan Channel is heavily used for recreational and commercial fishing and crabbing activities, hence the ROV pilot must always be alert for the presence of derelict gear (e.g., gillnets, crab pots, submerged floating lines) that could entangle the ROV or umbilical. Power within the San Juan archipelago is distributed via electrical cables laid across the bottom and marked on the local nautical charts. These cables are typically buried and/or armored with rock to avoid disturbance by anchoring or fishing activities, but can be exposed where they cross high relief features, creating the potential for ROV damage or entanglement. When operating in high relief rock habitats, the ROV pilot must constantly be aware of overhangs and deep crevices. The use of a high definition imaging sonar can greatly increase the detection distance of underwater obstacles and hazards, allowing the pilot more time to initiate avoidance measures as opposed to the last-second maneuvers that are typical when relying solely on visual detection methods.

We did not conduct operations under canopy kelps (e.g., *Nereocystis luetkeana*) due to the potential for ROV and/or umbilical entanglement. Because understory kelps (e.g., *Pterygophora* spp.), algal drift mats, and sea whips (order *Pennatulacia*) can quickly foul the thrusters and prevent the shaft from turning, the height of the ROV above the bottom was increased when we were operating in areas where these hazards were present. While this occasionally resulted in a larger than desired field of view and decreased the probability of detecting small and/or cryptic fishes, it eliminated the need to retrieve the ROV during a transect in order to remove obstructions from the thrusters. Other potential fouling hazards include fishing line, plastic and wood debris, anemones (order Actinaria), and small crabs (order Decapoda). Fitting the thrusters with mesh netting may increase the ability of the ROV to be operated in areas where the potential for fouling is high, but we have not explored this option.

Communication

Successful deployments require coordinated teamwork that hinges on effective communication between the ROV pilot, skipper, and deck crew. It is therefore essential that communication pathways are clearly established and maintained throughout the deployment to minimize the possibility of damaging or losing the ROV. We found this to be particularly important when working in highly rugose habitats where the clump weight may be raised and lowered numerous times during a deployment, often on very short (<10 seconds) notice. The center-wheelhouse design of the R/V *Molluscan* provided the captain with an unobstructed view of all operations and allowed for clear, effective, and nearly instantaneous voice communications among survey personnel without the aid of a portable two-way radio. When working on vessels where communication paths are obstructed or when noise levels prohibit effective voice communication, a voice-activated radio can greatly facilitate on-board conversations between the ROV pilot and vessel crew.

Minimizing problems and improving efficiency

The key to achieving maximum efficiency in our surveys revolved around a coordinated and consistent approach to all aspects of the operation. By developing and posting equipment schematics (Fig. 18) and checklists for the various procedures in our surveys (e.g., equipment startup, hydrophone, and ROV deployment), we were able to minimize mistakes and maintain safe working conditions. A troubleshooting table was developed for identifying and correcting some of the more common problems we encountered before they could have serious impacts on our operations (Table 3). The use of logbooks to document ROV and equipment use, service, and repairs is highly recommended. We consistently documented problems in as much detail as possible, which proved invaluable in the diagnosis and resolution of new and recurring problems.

The importance of backup equipment and spare components cannot be overstated, especially when operating in remote or difficult to access locations. A basic spares kit for the ROV system should include a thruster rebuild kit (motor, shaft, wiring harness), shaft seal repair kit (seal, O-rings, oil), console power supply board(s), thruster and body O-rings, O-ring grease, propellers, and replacement pads for each leak detector. Also, because computers crash, transponders flood, video recorders malfunction, lightbulbs burn out, plugs short out, and connections fail, having replacements for as many of these items as possible is highly recommended. In the event that equipment repair or replacement is required, it is essential that the operator be familiar with the user and technical manuals of all the system equipment. Further, an operator with the ability to diagnose electrical and electronic problems, solder connections, and repair cables, can save valuable survey time and money.

Piloting the ROV can be a tedious and stressful activity that requires full concentration from the pilot, especially when operating in less than ideal weather and sea conditions or running long transects. For this reason, it is helpful to have another ROV pilot on board to relieve the primary operator if the need arises. We were able to quickly train several crew members to operate the ROV with enough proficiency to allow the primary pilot to take a short (<5 min) break to stretch, eat, monitor equipment, troubleshoot problems, etc.

The ROV and associated electronic systems can be highly susceptible to voltage and cycle fluctuations in electrical power (i.e., dirty power), thus true sine-wave AC (i.e., clean power) is recommended whenever possible. Fortunately, most newer portable and vessel-mounted generators are capable of producing clean power, as are some DC-AC inverters, although these may cost as much or more than a generator with a comparable volt-watt-amp rating. Surge protectors should be connected to all electronic components to shield them from potential power fluctuations.

Careful attention should be paid to the configuration of electrical system connections in order to avoid unexpected results. As an example, on several occasions the main power circuit to the ROV control console would trip for no apparent reason, resulting in a complete loss of power to the vehicle at depth. By documenting each occurrence, we determined that this problem only occurred when the ROV was operated at maximum nominal thrust (not boost) for more than about thirty seconds. As this was suggestive of an excessive load in the power supply, we traced the topside electrical connections and found that the Trackpoint system had inadvertently been connected to the same circuit as the ROV power transformer. After transferring the Trackpoint system to a dedicated circuit, the problem was permanently resolved.

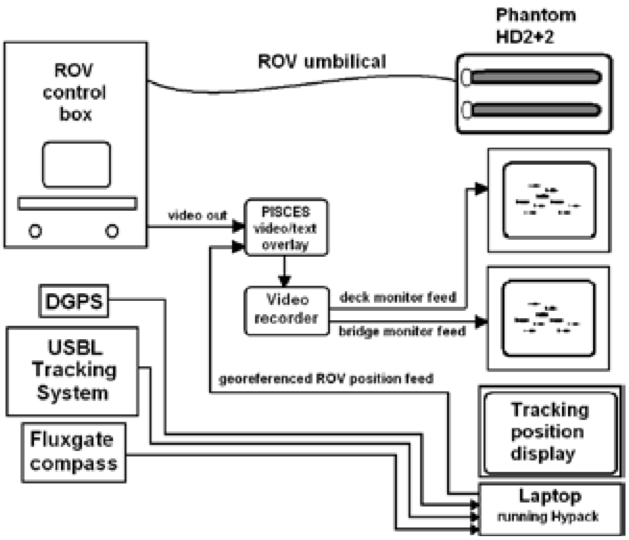

Figure 18. Equipment schematic for ROV system used in 2004 and 2005 San Juan Channel surveys.

We experienced some problems with video signal degradation and noise, which were attributed to the quality of the video cables and order of connections between the control console, video recorder, and deck monitors. As a result, we recommend the use of high-quality video cables and connectors with cable lengths minimized to avoid signal attenuation and the effects of electromagnetic interference. When connecting multiple video devices in series, the signal can be systematically degraded as it passes from component to component, thus the video recorder should be placed first in the series to obtain the strongest possible signal. When recording video directly to digital media, we highly recommend the use of a videotape recorder as a backup data collection device. On two occasions in recent equipment trials we experienced unexplained failures of different digital conversion boxes, resulting in a loss of recorded video. On another occasion the portable hard drive recording the data was inadvertently disconnected, also resulting in a loss of data.

Data storage and backup is an important consideration that cannot be overlooked. Given the expense of mount-

Table 3. Troubleshooting table for potential problems encountered during ROV operations.

Problem	Possible cause	Resolution
Poor/missing tracking	Transponder battery low	Replace/charge battery
	Transponder mounted too low on ROV	Raise transponder
	Incorrect Trackpoint depth setting	Update depth input
	Transducer mounted improperly	Check orientation
	Transducer mounted too shallow	Increase mounting depth
	Obstructed acoustic pathway	Maintain clear path between vessel and ROV
	Incorrect transponder settings	Check settings and retest system
	Transponder not activated	Check battery, turn on transponder
Loss of ROV maneuverability	Fouled thruster	Remove obstruction, check for damage
	Failed thruster	Repair or replace thruster
	Umbilical snagged	Drift downstream to clear obstruction; drive ROV back along umbilical and away from obstruction
	Clump snagged or dragging	Raise clump
	Failed control console power supply board	Replace board
Leak detected	Failed O-rings	Replace O-rings
	Purge plug(s) not installed	Reinstall plug(s)
Missing/incorrect heading input	Compass disconnected/turned off	Reconnect/turn on power
	Incorrect software driver	Install correct driver
Tripped circuit in power supply or control console	Overloaded circuit(s)	Install components on dedicated circuit
	Shorting in plug/cable/umbilical due to water intrusion	Check for damage, repair/replace components as needed
	Leak detected	See Leak detected (above, left column)
Collapsed thruster shaft seal	Failing O-rings due to wear or misaligned shaft	Install new O-rings and refill with oil
		Replace thruster shaft(s) as needed
Loss of video signal at control console	Camera disconnected on ROV	Check connector
	Short in camera connector	Replace connector
	Break or short in umbilical	Repair or replace umbilical
Video signal noise or degradation	Poor quality cables or connectors	Upgrade cables/connectors
	Electromagnetic interference in system	Minimize cable lengths, shield video equipment from EM source(s)

ing an ROV survey, it is imperative that data are collected and safeguarded using appropriate quality controls. The use of consistent naming and numbering conventions must be enforced to ensure the data are uniquely identified for later analysis. Each videotape in our survey was labeled with permanent marker and the recording tab removed to prevent accidental erasure. The advantage of videotapes is that they are robust and provide a permanent physical record of the collected video data. In contrast, no physical copy of the data exists if they are collected and stored digitally to a computer hard drive, making it critical that the data are backed up at regular intervals to avoid loss due to a hard drive failure. To prevent an accidental and potentially unrecoverable loss of data, we recommend the use of an uninterruptible power supply when collecting data directly to digital media.

The ability to conduct operations in rougher sea conditions than those described by Csepp (2005) allowed us to reduce survey costs by minimizing vessel and crew down time. Also, as we gained proficiency and confidence in our methodology, we were able to improve operational efficiency by streamlining or eliminating tasks when conditions allowed. For example, when the starting location of a transect lay within 0.25 km of the endpoint of a completed transect, we were able to reduce recovery and deployment times by up to 30 minutes by leaving the ROV in the water and following the clump weight as the support vessel transited to the next starting location. This technique was also used to return the ROV to a transect starting location when the vessel was blown off station by strong winds or current fluxes, and to reestablish contact with the support vessel when the tracking system "lost" the ROV.

By conducting transects into the current, the support vessel could be allowed to drift downwind or downcurrent if the umbilical became snagged or entangled on an obstruction. We employed this procedure several times in our surveys, enabling us to safely recover the ROV with no damage to the vehicle or umbilical. On the few occasions when this technique was unsuccessful, the ROV was driven back along the free portion of the umbilical to locate the affected section, and then maneuvered until the obstruction was cleared. Had this approach failed, it would have been necessary to unplug the umbilical from the control console and waterproof the connector by wrapping it in plastic, cut the clump line, attach a buoy to the umbilical, and leave the ROV in place on the bottom until a recovery effort (e.g., second ROV, commercial diver) could be mounted.

As the pilot gained experience with the handling dynamics of the ROV, we identified an area within the ROV's operating envelope where the umbilical had minimal effect on the handling and maneuverability of the vehicle (dubbed the "neutral zone"). In our case, the neutral zone was identified as a 3-4 m radius around a point 12 m forward and 7 m port of the clump weight. By keeping the ROV within this zone, we could reduce transect times by minimizing the number of course corrections needed by the ROV, producing "straighter" tracklines.

Pilot comfort is an important consideration, and anything that can be done (within financial reason) to improve working conditions and productivity are strongly recommended (comfortable chair, back support, equipment harness for controls, etc.). In our operations it was possible for the ROV pilot to control all of the electronics without help, although this was not an ideal situation given the number of components and overall complexity of the system. During the course of a transect it was often necessary to update the depth parameters of the tracking system, adjust the tracking and navigation displays, turn on or pause the video recorder, etc., all of which distracted from effective piloting of the ROV. Whenever possible, a crewmember was designated to assist with these tasks, thereby improving efficiency and minimizing pilot stress.

The ROV and tracking system used in our studies were leased units, which had several negative impacts on our efficiency. First and foremost, because we had no access to the equipment prior to pickup from the vendor, several days of survey time were lost in both years in order to transport and set up the equipment, install the tracking system, and configure and ballast the ROV. Secondly, two different ROVs were used in successive surveys, and because the vendor could not assure us that the camera specifications for both vehicles were the same, it was necessary to conduct another series of camera calibrations, resulting in the loss of a half-day of survey time in 2005. The advantage of using owned equipment in this case is clear, as the majority of these issues could have been resolved prior to starting the surveys. The use of a dedicated vessel can improve efficiency by allowing equipment to remain on board (if owned), or to be set up more quickly when mobilizing for an operation.

Technological improvements

In 2002, the WDFW used the manned submersible DSV *Delta* (Delta Oceanographics) to conduct sea-trials of a 3-beam laser system designed to improve the accuracy of density estimates obtained from in situ video surveys (Kocak et al. 2004). The system incorporates two lasers mounted in parallel with a third laser crossing at an oblique angle through the parallel beams. A roll/pitch sensor is integrated with a custom software package that identifies the positions of the laser spots on the video image to accurately calculate the area viewed (Kocak et al. 2002). In 2006, the 3-beam system was adapted to fit on a small ROV (Phantom HD2+2) and sea-trials were conducted in January 2007. The system performed as expected although several technical issues need to be resolved before the system can be fully implemented, including shielding of the camera from electromagnetic interference induced by the thrusters, and integration of the Doppler velocity log (DVL) aided inertial navigation system (INS).

Summary

Our work successfully demonstrated the ability of a small ROV to collect quantitative data for analyzing marine communities in depths up to 160 m, but required a substantial learning curve to reach a level of proficiency where transects could be conducted reliably and efficiently. In our case, the 2004 survey presented a number of technical obstacles that negatively impacted our success, the majority of which were due to our unfamiliarity with the tracking and navigation systems, but were eventually resolved as we gained experience with the software and equipment. This experience translated into fewer problems in 2005, and those that did arise were quickly identified and resolved before they could have major impacts on the survey. As the ROV pilot and vessel captain became attuned to each other's abilities, our skill and confidence improved to a level that enabled us to conduct operations more smoothly and in more extreme conditions than we would have attempted in 2004. As the deck crew gained experience, deployment and retrieval of the ROV and clump weight became second nature, improving survey efficiency to the point where we could accomplish 8 to 10 transects per day by the end of the survey as opposed to 3 to 4 transects per day at survey onset. Constant communication among crewmembers was vital to the identification and resolution of potential problems, and resulted in sequential improvements in operational safety, efficiency, and productivity. Through a coordinated effort of teamwork, trial and error, practice, and perseverance, our surveys evolved from the clumsy and disjointed approach that marked the beginning of the 2004 survey, to a streamlined and efficient production level operation by the end of the 2005 survey.

One of the primary advantages of conducting surveys with small ROVs is the reduced operating costs compared to manned submersible or large-ROV surveys, which may cost $10,000 per day or more (Farron Wallace, WDFW, 2007, pers. comm.). We were able to conduct our surveys for between

$2,500 and $3,000 per day; equipment lease costs were $1,000 per day and vessel and crew costs ranged between $1,500 and $2,000 per day. Further cost reductions could be achieved by purchasing some or all of the ROV and tracking system components, and though the initial purchase costs appear prohibitive in the short-term, the long-term benefits of ownership tend to outweigh this concern.

The capabilities of small ROVs will continue to increase as new technologies are developed for these versatile machines. With improvements and miniaturization of the electronic components designed for them, the purchase and operating costs of small ROVs have declined. As a result, these vehicles are becoming increasingly common in both the commercial and government sectors, providing scientists with affordable, first-hand knowledge of the seafloor and marine organisms for many avenues of endeavor. However, as with any tool, it will always remain that experience and testing will be required before using this technology for quantitative scientific purposes.

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