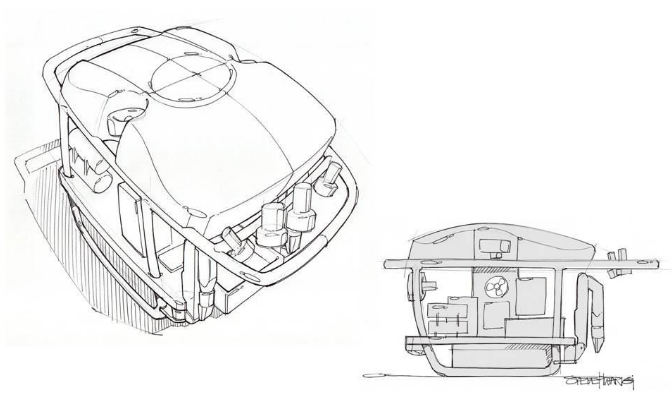
4,500m ROV
Science Mission Requirements



This report was compiled based on a survey of international deep ocean research community representatives

2015

Table of Contents

Executive Summary

Schmidt Ocean Institute (SOI) is a 501(c)(3) private non-profit operating foundation established in March 2009 to advance oceanographic research, discovery, and knowledge, and catalyze sharing of information about the oceans. SOI is developing a series of advanced undersea robotic research vehicles for use on SOI's research ship *Falkor*. The vehicles will support scientific research throughout the full range of ocean depths, including operations at hadal depths, thereby providing scientists with access to the deepest parts of the ocean. The vehicles will be outfitted with a suite of sensors and scientific equipment to support collection of a broad range of data and samples.

This document outlines the results of an independent survey conducted by SOI to elicit external input on science mission requirements for the 4,500m remotely operated vehicle (ROV) program SOI is developing. The survey collected input from a multidisciplinary group of the deep ocean scientific user community on the anticipated operational, scientific surveillance, and research capabilities for a new 4500m ROV. Through the survey SOI received advice that the vehicle should support a diverse set of oceanographic research activities, including:

- acquisition of high quality underwater video
- scientific data collection
- scientific sample collection
- object manipulation
- deployment and recovery of equipment
- seafloor surveying and photomosaicing

The survey also indicated that the vehicle should also be designed to acquire and record scientific data in a manner which is consistent with accepted oceanographic practices and standards.

The survey was completed by 28 representatives of the international oceanographic research community, 27 of whom have agreed to have their names shared as the SOI 4500m ROV Science Advisory Group.

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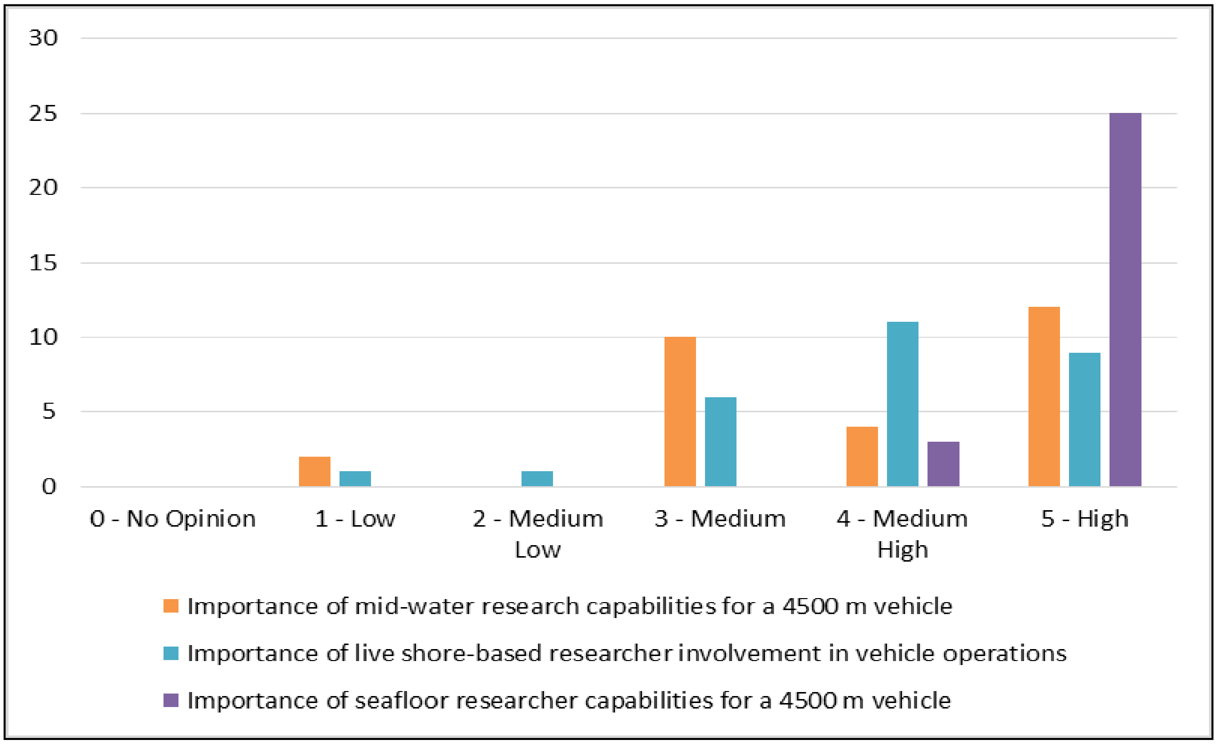
Grade Point Average Scores

The table below provides the average score for each question reflecting the priority value of each response from High (5), Medium High (4), Medium (3), Medium Low (2), and Low (1).

Level of Priority for Question or Equipment	Grade Point Average	Number of Responses (n)
General Science Mission Capabilities		
The importance of mid-water research capabilities for a vehicle with 4500m depth rating.	3.9	28
The importance of live shore-based researcher involvement in vehicle operations	3.9	28
The importance of seafloor research capabilities for a vehicle with 4500m depth rating	4.9	28
Scientific Sensors		
Conductivity, Temperature, Depth (CTD) Sensor	4.7	28
Turbidity Sensor	3.7	27
pCO2 Sensor	3.8	20
pO2 Sensor	4.4	22
High Temperature Water Sensor	4.2	27
Redox Potential Sensor	3.8	24
Fluorometer	3.2	20
Nitrate Sensor	2.2	20
Biomolecular Analyzer (e.g. Environmental Sample Processor or similar)	2.8	19
In situ Mass Spectrometer	3.5	26
Imaging Systems		
3DHD Video	3.3	25
4K Video	4.6	22
Pan / Tilt / Zoom capability	4.8	28
High Resolution Still Image Capture	4.8	28
Full Spectrum LED Lighting	4.8	24
Audio Recording Capability	3.2	21
Multi format / Codec capable video recording system	3.8	18
Frame Grabber	4.6	25

Level of Priority for Question or Equipment	Grade Point Average	Number of Responses (n)
Sampling Systems		
Water Sampler	4.1	28
Multi-Chamber Suction Sampler	4.7	26
Push Core	4.3	28
Rock Saw / Cutter / Splitter / Core	3.4	20
Multichamber Insulated Bioboxes (for fragile animals)	4.8	24
Pressurized Sampler for Deep Ocean	3.0	23
Seafloor Surveying Systems		
Forward Looking Sonar	4.7	24
Sidescan Sonar	3.1	21
Magnetometer	2.7	20
Sub-Bottom Profiler	3.0	19
Multibeam Mapping Sonar	3.9	25
Singlebeam 360° scanning sonar	2.9	15
Photographic Seafloor 3d/2d Mosaicing	4.6	24
Vehicle Instrument Interfaces		
RS-232 ports up to 115 Kbps	4.5	14
RS-485/RS-422 ports up to 2.5 Mbps	4.0	13
Ethernet 10/100 Mbps	4.9	14
Time-to-live (TTL) link	3.2	5
Optical fibres available for interfacing	3.9	14
Power 5 VDC, 12 VDC, 24 VDC, 115 VAC	5.00	16
Hydraulic rate functions	4.11	9
Hydraulic servo function	4.40	10
Navigation: Position and Trajectory Recording Sensors		
High Latitude Capable Ring Laser Gyro or Fiber Optic Gyro	4.8	9
Inertial Measurement Unit / Inertial Navigation System (IMU/INS)	4.5	16
Ultra-Short Baseline (USBL) beacon	4.9	20
Doppler Velocity Log (DVL)	4.8	19
Acoustic Doppler Current Profiler (ADCP)	3.7	21
Global Positioning System (GPS) antenna	3.4	18

General Science Mission Capability Responses



ROV to Ship to Shore Communication Responses

Directly Available Data Streams

Survey respondents provided significant input on the ROV parameters. They identified that having direct or live-stream access from both the vehicle to the ship and to shore would be beneficial. It was expressed that the entire suite of sensors should be capable of supporting remote participation with multiple live streams. For example, sonars (multibeam, forward-looking sonar), radars (sub-bottom profiles), other lower bandwidth, chemical and biological sensors for detecting plumes, video and still imagery, heading, depth, altitude, location (latitude and longitude), speed, temperature, salinity, audio from hydrophones, plus information from any custom sensors. Real time accurate navigation relative to a seabed feature (e.g. hydrothermal vent, canyon setting, seamount geomorphology at a variety of scales) would allow scientists to have a reference of position for the field of view. For mid-water research real time data on the physical environment with graphical representation (e.g. temperature, chlorophyll, turbidity) was stated as being useful for studying biological processes at micro-layers and thermoclines. Acoustic data of the wider area around the ROV was also identified as important for mid-water and upper pelagic work. Links to these streams should be available to all participating scientists on shore, not just scientists in a command center location.

Telepresence

Live telepresence capabilities were viewed with mixed opinions. The concept of projecting the ROV video ashore was recognized as popular because it allows for wider participation by both scientists and the general public. Some responders shared experiences of the systems not working very well. It was found that the majority of these operations unfolded slowly and was

Students at the University of Western Australia connect live with RV *Falkor* during an ROV mission at Perth Canyon. Photo credit: SOI/ Malcolm McCulloch.

largely tedious; "live links" were only effective when rehearsed, and "live shows" provided a more scripted feel. There is a tremendous amount of context that is lost by just seeing screens of streaming data. Other respondents stated that they have found telepresence to be an extremely valuable tool for outreach. Live audio commentary from a shipboard dive leader is essential for shore-based participation in dives. Additional feeds to shore would enhance the role of shore-based investigators in dive operations and was noted as desirable; this includes subsea navigation screen, data from ROV-mounted sensors and updates on tasks completed/remaining in dive plan.

One responder suggested that there could be occasions where direct control of some ROV subsystems by a remote party would be helpful. For instance, where verbal communication to ROV pilots for a particular angle, lighting or effect is required, but is difficult to explain succinctly. This will not only be a scientific requirement but may also enable land-based professional photographers to gather stunning images (something that scientists and ROV pilots may not have the skills to do).

The EV *Nautilus* program was remarked as an effective outreach program supported by their website, which provides live feeds of multiple video streams as well as commentary by the scientific personnel onboard.

Other General Communication Link Comments

- Live streaming of 4K is very exciting, but not absolutely essential. When 4K poses challenges it can be done without; it should not be done if it compromises any other operational tasks.
- Spare dedicated fibers, and means to connect to them, in the cable to support even higher resolutions than 4k on occasion. This would allow the vehicle to achieve 4k by optically multiplexing over a limited amount of fibers.
- Headset communication and instant messaging capability between researchers at the ROV central station, other researchers on board *Falkor* (e.g. in laboratories) and researchers at shore.
- Gig Ethernet connectivity should also be available to connect and control cameras.
- In-water acoustic links to beacons, landers, homers and any sort of instrumentation deployed *in situ.* The ability to upload accumulated data from instrument packages, other vehicles, or observatories, in order to relay that data to the surface.

Payload Capacity Comments

Survey responders provided balanced input on the merits of payload capabilities, which are one of the most significant constraints on what an ROV can do. For many purposes, ROV's are not primarily observing tools but rather the "pack-horses" to carry sampling and monitoring equipment to depth, and as tools to conduct surgical sampling and complicated manipulations. While efforts are made to keep the sampling gear, and mission specific instruments light, the reality is that many of the new and novel sensors and tools are heavy and awkward. They also typically require traditional measurements to be made at the same time or site. Very large payloads on the vehicle itself always leads to compromises - you need large thrusters to compensate for the extra buoyancy or lift for the extra weight, this then means a thicker cable, heavier vehicle etc.

Rock samples from the Mariana Trench. Photo credit: SOI/Paul Yancey.

Overall, there was a range of recommendations from 95kg to 300kg. The majority recommended a capacity of 150kg or more. Biological research was suggested as not needing significant capacity whereas geological and vent work may need more for rock sampling. The heavy lift capacity (>500lbs) of ROPOS using an ROV winch was indicated as a nice innovation.

Recommendations

- Use of light syntactic foam was recommended to help maximize payload capacity.
- A modular floatation system could help adapt to special needs on demand.
- Use of an elevator system could help increase payload.

Dual Spatially Correspondent Manipulator Comments

Many respondents felt that it would be nice to have force-feedback manipulators on the ROV that a user on the surface could control. It was acknowledged that some operations do not use these manipulators to keep the complexity to a minimum (less complexity means less things to go wrong), however, for sensitive sampling (e.g. not crushing biological samples) having that control allows for useful applications such as picking up fragile samples like glass sponges. Devising at least one arm with force feedback was stated as critical.

General Recommendations

- At least one manipulator should be equipped with a "wrist-cam" to enable close-up examination of samples before collection, and precise, fine-scale positioning of sensors.
- Outfitting the manipulators with the grip style most commonly used would minimize retrofitting of equipment; or flexible grip. In the U.S., the most common grip style may be the t-handle, but if may be another for international users.
- Ability for the manipulators to insert microelectrodes for very fine-scale pH, O2, and chemical measurements.
- Assuming a 7-function manipulator is used, it should also have an array of interchangeable claws as well as cutters. Possibly a removable drill/corer for obtaining

sideways cores from rock faces and a rock saw, since often *in situ* rock is very difficult to simply break free.

- A swing arm on each side of the vehicle, for pushcores and other samplers.
- Two dexterous 7-function manipulators.
- An integrated electric or hydraulic ram for actuating samplers would be good.
- Make sure you get ROV-pilot input, because ease of use and maintenance is often as important as sampling capability with manipulator arms.
- If a camera will be mounted on the manipulators (even optionally), it might be nice to record the data about the position of the manipulator (6DOF) with respect to the vehicle reference frame so there is the potential to calibrate images for 3D reconstruction. This information could also be used to get more precise sample positions
- Two swing arms on the sides to hold samples and to mount lighting (e.g. on the ROV D2 or Doc Ricketts). It would be good if the arms could withstand moderate vibrations (e.g. from small vibrocorers to loosen slightly compacted volcaniclastics in front of a suction hose held by the manipulator).
- An "elevator" capability may be useful also - i.e., a separate system to transport instruments to the seabed and recover samples that may be too heavy for the ROV itself to transport. The manipulator would then need to be capable of extracting and placing objects within the elevator.
- Manipulator arms need to be both robust (rock collection, holding onto the seabed) and sensitive (collection of fragile organisms and operating seabed chambers).
- The manipulator should be able to: operate (turning) rotary switches and valves; hold and push in sediment push cores vertically into the seafloor; and grab fragile animals.
- Vacuum or "slurping" capabilities would be valuable, but perhaps this could be an add-on that is handled by the manipulator.
- Retractable bins that can be pushed out within easy reach of the manipulator arms then retracted a couple of feet back out of the way of the cameras and sensors while transecting, transiting, or working with seafloor experiments.

General Vehicle Science Mission Requirement Comments

General Video Capability

Several responders provided comments regarding visual capacities of the vehicle. It was noted that the ROV should be capable of (a) 4k video (or better), (b) excellent motion sensing (orientation, 3D-acceleration), (c) high-precision and (d) vehicle-wide time-stamping at the video frame-rate would be imperative for the ROV to conduct visual surveys. For visually mapping complex areas (volcanoes, reefs, landslides, hydrothermal vents, ship-wrecks, archaeological sites, fault breaks) high-precision navigation (good DVL and ring-laser-gyro) and good synchronicity via time-stamping were identified as pre-requisites. One important benefit to ROVs is their ability to look at things from the sides.

3D video has had differing (and often bad) opinions, but some scientists may find it helpful on occasion. Building video capture technology that would allow for creating virtual reality reconstructions of deep-sea habitats would add a great spatial analysis and teaching opportunity.

The vehicle will need to be equipped with plenty of light sources, including the possibility of swing arms equipped with lots of LED lights on the vehicle's brow. This would allow the vehicle the ability to collect images and video that's well lit. The vehicle should also include a ~24 MP stillframe camera. Stillframes from the 4K or 2K would not likely provide imagery up to scientific standards.

General Hydraulic vs Electric Drive System

Responders provided details on the benefits and detriments to both drive system operations. SOI was asked to consider whether opinions for sound suppression can be supported because of the large price to pay as electric vehicles are much less commercially available. Some indicated a preference for hydraulic drive because of superior power and reliability, especially for seafloor work. It was noted though that hydraulic systems may have a greater chance for minor spills, and that it is critical to have enough hydraulic capacity to provide high flow rates at high pressures.

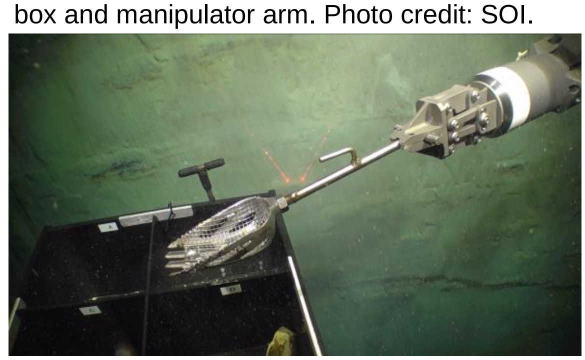
Others had a preference for electric drive systems because they are significantly quieter, which is beneficial for biological work as the loud noise does not drive mobile animals away. Electrical systems also allow for acoustic scientific payloads to be used. Additionally, because of noise concerns, there is benefit to having excellent ballast control that allows the vehicle to go neutral in midwater and heavy on the bottom without the use of thrusters. Several questions were raised that SOI would need to address internally to judge which systems would be ideal: *What does "quiet" means? How "quiet" would a vehicle have to be to have minimal effect? What frequencies are important and to what types of animals? Is it the propulsion system or the various pingers that are important?*

It was noted that maintaining an electric ROV could prove to be problematic, as it can be difficult to replace components and build/maintain software. It is also difficult for an electric vehicle to have the power and payload necessary for heavy geological and benthic needs. Some felt that the main system being hydraulic or electric was unimportant for many applications, and that there would need spare electric and hydraulic channels to power devices as well as digital and analog channels for instrument communication.

Payload

Responders recommended building a modular skid underneath the main vehicle with a centralized interface bay so that payloads can be exchanged quickly (e.g. bring the vehicle up, exchange a frame with a surveying package for one with specialized sampling baskets or a rotary container suction sampler) (HyBIS platform by HydroLek; modular skids for ROPOS and Ricketts). Such a design might drastically cut down installation times and keep the vehicle smaller. In addition to payload, a critical consideration is volume available for gear; an open design with lots of flexibility for payloads of different sizes and arrangements is key. A respondent cautioned that to have ROVs deliver gear for research is only one aspect of success, getting the weight right important, but physically maneuvering something on and off the tool tray is often hard.

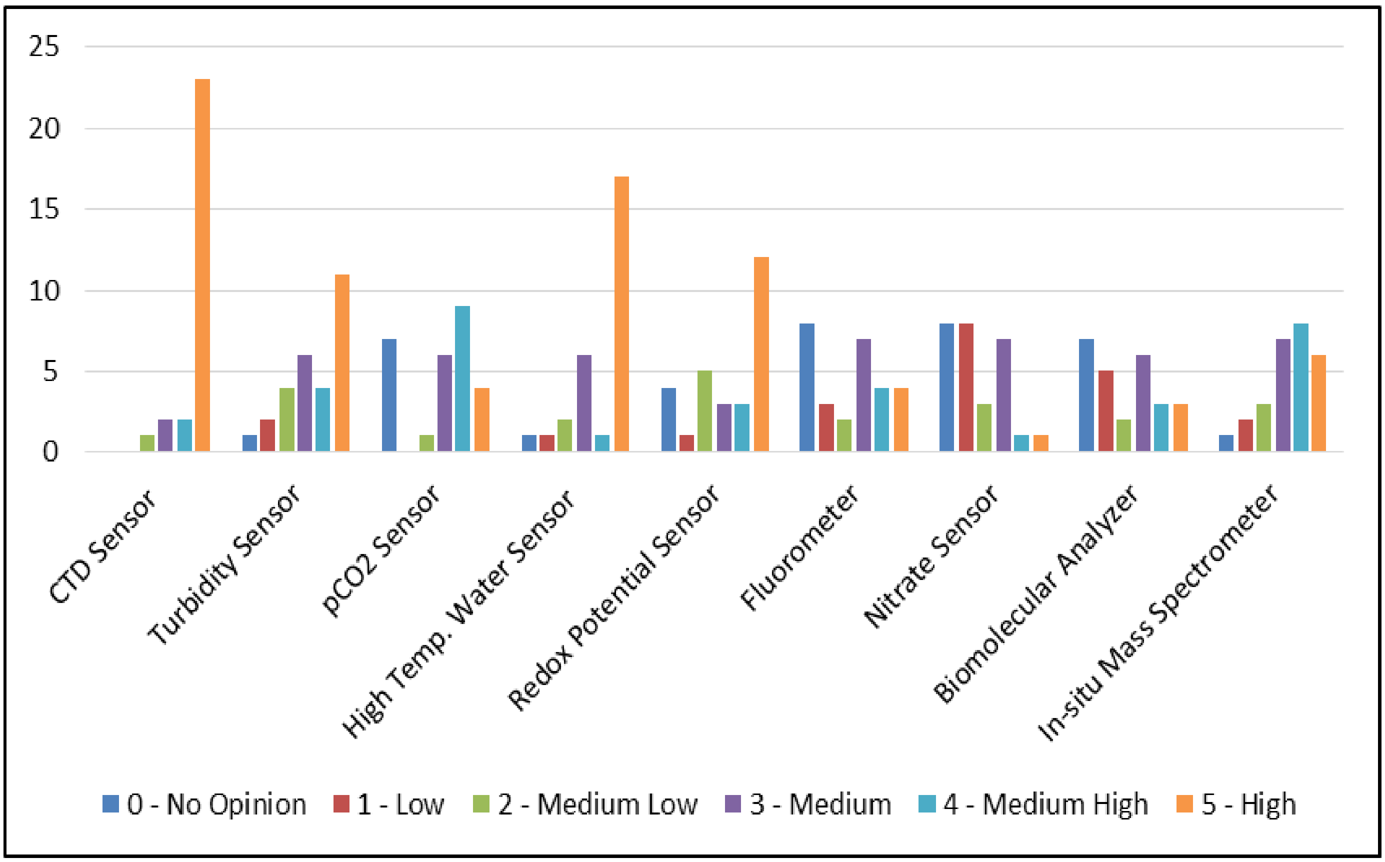
Exploration of Perth Canyon with a sampling box and manipulator arm. Photo credit: SOI.



Other General Vehicle Science Mission Requirements Comments
Responders provided additional comments regarding system considerations, including:

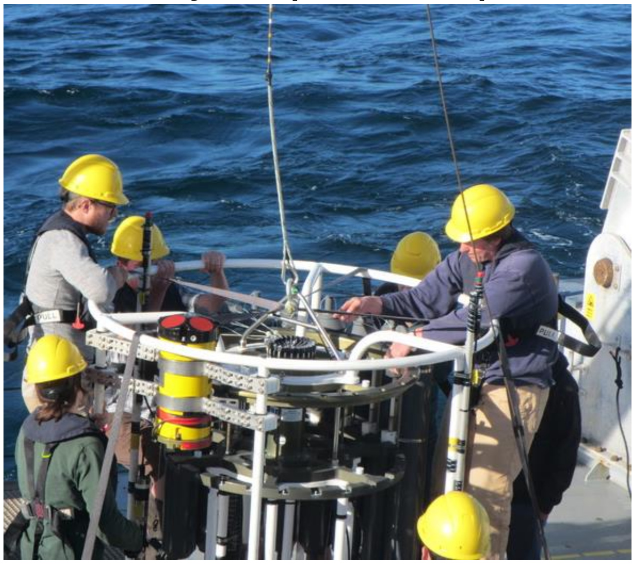
- Telecommunication is great for publicity but has low value to remote scientists.
- The vehicle should be designed to be a broadly capable ROV (not a battery-powered HROV) if it is to serve the needs of a broad range of users. A battery-powered ROV lacks the power, endurance and payload to meet many science mission requirements.
- A variable ballast system is a very important capability that no scientific ROV should lack. It allows the vehicle to go neutral, to add weight for rapid descent, or to add buoyancy as a lifting aid. The ability to repeatedly trim to neutral buoyancy is valuable.
- Biologists will find it extremely important to be able to sample animals from midwater or the bottom. A slurp gun sampler with multiple chambers is ideal. It should be equipped with a tube than can be easily picked up by a manipulator arm for benthic sampling or have an extension arm for midwater sampling.
- Easy maintenance and cycling of the vehicle (recovery and redeployment).
- Elevators to support the heavy lift sample and equipment support requirements.
- If the vehicle is built for live-boating it would be interesting to have telescoping light arms on the sides. Additionally, lights from different angles would be a tremendous asset.

Scientific Sensor Responses



Scientific Sensor Comments

Conductivity, Temperature, Depth Sensors



The science team working on the CTD Rosette onboard of Falkor. Photo credit: SOI/ Judy Lemus.

Conductivity, Temperature, Depth (CTD) measurements collect basic oceanographic information and were considered to be a standard for data collection by all surveyed. CTDs provide must-have baseline information and are considered of critical/highest priority, especially for calculating depth. Most deep-water science would require the use of such data and it would be great if the ROV could collect the CTD data while descending and ascending the water column, freeing up time that would otherwise be spent profiling with a conventional CTD if this were not a feature of the ROV.

The CTD sensor should be compatible with international standards and contain proper calibration metadata as part of its standard data package. One recommendation was to follow Standard Seabird or Scripps Institution of Oceanography data collection and processing protocols. Calibration needs to occur routinely, but the instrument should not require daily calibration (for example, annual factory calibration would be essential over daily calibration when often operators forget to calibrate).

The CTD should not contain a filter for dissolved oxygen sensors, which can clog with sediment upon touch down. Sensors that can be fixed or manipulated would be ideal, for assessing local conditions at precise locations. It would also be good to find a CTD that can push the boundary of communications technology from analog to digital. As such, real-time display of the data, particularly temperature, would be "awesome". Another feature that would be useful would be to have a track line display that allowed users to toggle between various water sensor observations in real-time.

Turbidity Sensor

Respondents had mixed comments regarding the usefulness of having a turbidity sensor on board. On the one hand, turbidity signals on an ROV can be interfered with by touching the bottom, i.e. vehicle thrusters stirring up sediment, so the data are often difficult to interpret and may be considered "suspect". However, a turbidity sensor can give good data in the water column and is considered critical for hydrothermal plume, particle flux, and seabed suspended particles studies. Additionally, turbidity sensors are very robust and easy-to-use solid state sensors. The most common ones that operate at these depths have only analog output. Nephelometer and transmissometer data allow one to quickly identify water column anomalies.

pCO2 Sensor

Respondents agreed that information from such a sensor would provide a good value added and would create an important dataset of CO2. There is a global need for vertical CO2 profiles that could be acquired during ROV descents and ascents. Respondents also noted that additional DIC measurements (pH, DIC, Alkalinity) may be needed to fully capture the CO_2/pH dynamics.

Additionally, pCO_2 sensors are still in their infancy and will likely require more frequent maintenance and calibration than other sensors in order to maintain data accuracy. The new optodes seem to be fairly effective, but are still in development. One respondent pointed out that pH sensors don't work in the deep sea, but it was mentioned that the new Durafet should work well, yet is not commercially available in a pressure housing; when available it should be a priority. The issue of frequent calibration is a concern, which may prove to be more work than can be routinely done by an ROV crew.

Overall, the priority for a pCO_2 sensor depends on the research question. If work is planned in areas of active hydrothermal venting or in the upper ocean, this sensor may be more of a priority due to its low-level investment. Perhaps making the instrument available on an as needed basis might be a better approach than one size fits all. Niskin bottles would also be needed to verify some of the measurements.

pO_2 Sensor

A pO_2 sensor is thought of as one of the highest priorities and one of the most important sensors on the ROV, especially if a CTD is thought of as "standard". This sensor is important for studies of bottom water oxygen concentrations, Oxygen Minimum Zones, fine scale zonation of fauna relative to quite small changes in oxygen and fine scale changes due to physical, biological, and chemical processes.

Several respondents noted the issue of optodes vs electrodes. One respondent noted the pO_2 sensor should use an optode system, rather than an electrode because the optode systems maintain calibration for weeks to months in comparison to the electrodes, which require continual maintenance and calibration for accurate results. However, another respondent noted that when experimenting with Aanderaa optodes in parallel with Seabird polarographic elecrodes, the polarographic electrodes were more accurate and reliable. Finally, another respondent is not convinced of the reliability of the newer optodes and iterated the need for water samples/ Niskin bottles to verify the measurements.

The STOX sensor, which goes beyond the standard O_2 sensor (it is very sensitive), may be useful. A design that can be put on a tee-handle and held at a location by a manipulator would be useful, as too many sensors are permanently mounted to the vehicle when they could be more useful if they were movable. Clips and magnets could be used to affix sensors to a vehicle that could easily be removed by the manipulator for flexibility in placement.

High Temperature Water Sensor

This probe is very specialized for work conducted in hydrothermal vents and/or volcanoes. However, it is considered to be essential for characterizing hydrothermal vent habitats and selecting vents for sampling, as well as measuring the temperature of fluids coming from the seafloor. While this is an important instrument for hydrothermal science, it does not need to be on the vehicle all the time. Having a "hand-held" available on an as-needed basis is an option, as it does not need to be considered as "core ROV" gear. One responder noted that having a low temperature sensor would also be important. Another indicated that having a high temperature water sampler could be more valuable given technological limitations to sensors.

Where the electronics for this high temperature sensor are located on the vehicle is important; as you may not want to be moving the ROV body into damaging heat. Be careful to control its internal temperature too.

Redox Potential Sensor

This is another sensor that provides a unique and important measurement for deep-sea reducing environments sampling (vents, seeps), etc. and is considered a "must have" for hydrothermal vent studies but may not need to be a part of "core ROV" gear. However, these types of sensors are subject to considerable drift and require frequent calibration.

SOI should be mindful of the calibration and maintenance issues. Depending on the model used, this instrument needs maintenance. The Seabird one is good to 1000m, Koichi Nakamura has retired and the PMEL instrument needs maintenance. However, results from PMEL suggest that the ORP sensors that PMEL has built are more sensitive to hydrothermal vent emissions than temperature or optical sensors, emphasizing the importance of this sensor when exploring for hydrothermal vents. Additionally, real-time display of this in map view would make it very useful for finding vents. Temperature and Redox are very convenient to scout for hydrothermalism in unknown terrains.

Fluorometer

Fluorometer measurements are not useful for deep-water work below the photic zone and are better suited for upper ocean micro-layer and thermocline studies. As such, ship-deployed CTD-Fluorometer profiles or specialty ROVs are a more sensible way of collecting the data. However, it could be useful for biological investigations, or hydrocarbon specific fluorometers could prove use near seeps or oil spills.

Nitrate Sensor

Nitrate sensors are another sensor suite that are not useful for deep-water work; ship-deployed CTD-nitrate profiles are a more sensible way of acquiring these data. Also, slower response time of these sensors detracts from their usefulness on a moving platform.

Respondents generally agreed that if reliable measurements were possible, the sensor may have a high priority as nitrate is a nice parameter to measure. However, optical nitrate sensors are easily overwhelmed by CDOM in the coastal zone and therefore aren't reliable and most are biosensors, meaning they need a microbial culture in order to operate which would require someone on board to permanently take care of the microbial culture to avoid sensor failure. These sensors also do not have a long lifetime. Perhaps this sensor should only be installed when researchers with the expertise to operate them are on board and are necessary for the project. Respondents were also unsure of their usefulness in regards to a ROV program.

Biomolecular Analyzer

Current technology is not ready for the ROV world – it is bulky, heavy, slow and limited to shallow depths and is very expensive. Some respondents mentioned alternative approaches, such as supporting development of additional microbial sensors, including an in situ preservation system for microbes (rather than an analyzer), as there may not be a case to do PCR in situ. H, and having an ROV that can plug and play rather than one that is too specified in its suite of sensors. Development in this area remains rapid, and there are good low-cost alternatives. Most respondents agreed this is not a necessary component and that taking care to preserve the samples before bringing them on deck may be a more suitable solution.

In-situ Mass Spectrometer

An *in situ* mass spectrometer seems at present to be the best way forward to characterize the chemical environment in the deep sea – most single-component sensors are too accurate to do this and *in situ* mass spectrometers are more advanced than the ESP-biomolecular analyzers. Having an *in situ* mass spectrometer would provide a unique opportunity for deep-sea/vent/seep analysis; it also has other important and interesting applications, and seems to be gaining traction in the community for its variety of uses.

Although this is not considered "core gear" for the ROV, as it certainly is mission-specific, this may be the future of *in situ* marine analyses and SOI should definitely have one to continue to be at the front of research. It would especially be an outstanding tool if it could be tuned to a variety of different mass sizes. It was noted that most of the meaningful measurements made require pH as well. This is very expensive equipment but would be useful.

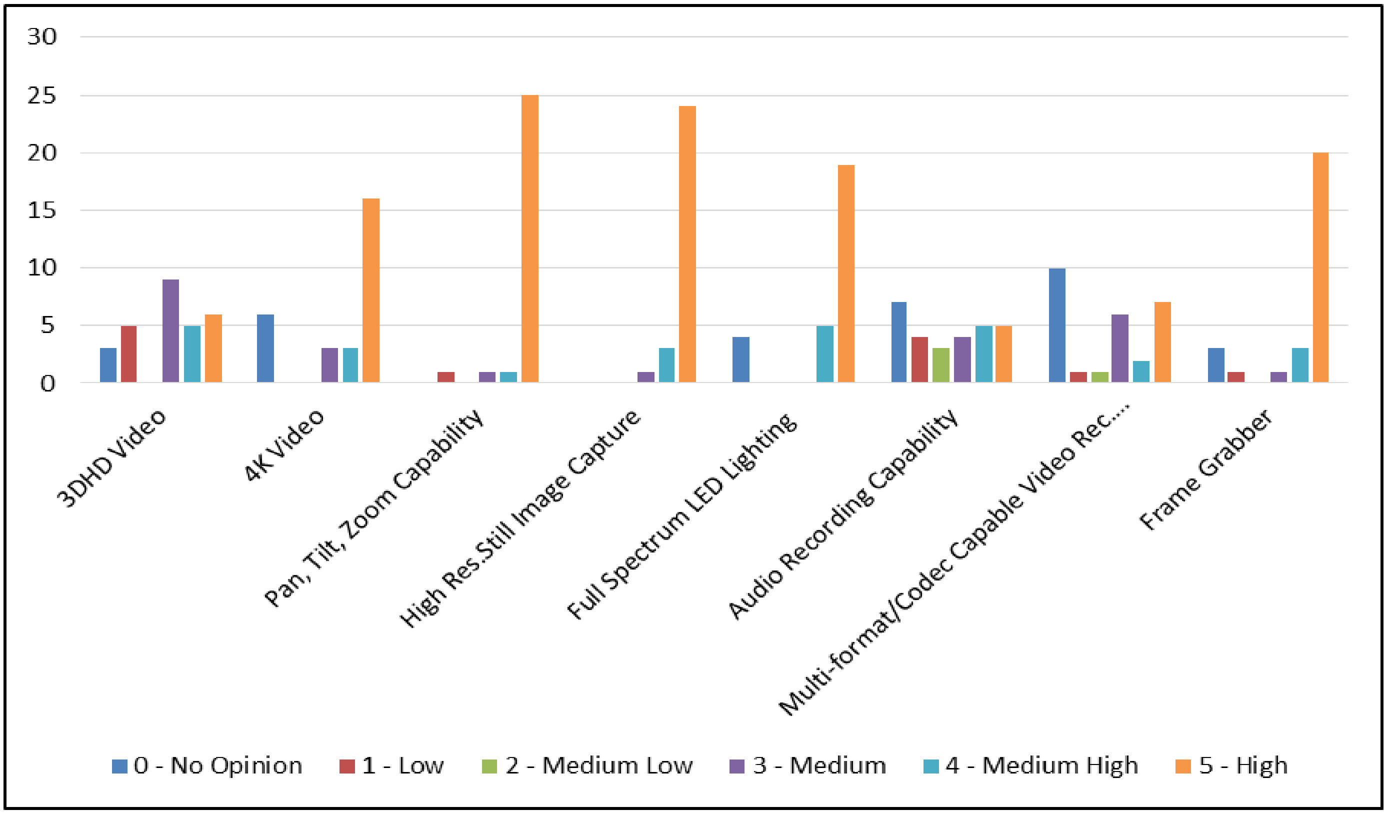
Other Scientific Sensing Systems

Many of the above listed sensors will be important for some missions, but considering them all as core vehicle sensors would be a mistake. Room should also be made on the vehicle frame for occasional deployment of other; experimental scientific sensing systems and providing easy connectivity would make sense. Another key component to have easy communications systems for user-supplied equipment and empty ports for PI provided sensors or equipment to be plugged into the ROV via various pin configurations and Ethernet.

Other important systems to have on an ROV:

- Multibeam sonar for deep-water low-light applications/sub bottom profiler/side-looking sonar
- Photomosiaking capability to be part of a downward looking video/still image package. Downward looking video with a complete overlay showing depth, heading, position, and perhaps CTD info as well as a timestamp.
- ADCP package. They have some high frequency models specifically designed for use on moving vehicles and for looking down at the bottom from a short height above it to measure bottom current speed and direction. This is another instrument that could set your ROV apart from the pack and make it extremely useful for deep-water coral and sponge research as well as many other types of oceanographic research.
- Diverse sampling systems like micro-suction syringes
- High-volume filtration support
- SUPR sampler
- NOAA Hydrothermal Fluid and Particle Sampler
- Sensors that quantify the visibility underwater
- Bioluminescence
- Acoustic multiple frequencies
- Downwelling light
- Underwater microscope (Jaffe lab)
- pH Sensor (Wendy Schmidt X-Prize)

Imaging Systems Responses



Imaging Systems Comments

3DHD Video

The majority of respondents stated that they do not find an advantage to having 3D video capabilities. It was seen as imagery that few would be able to exploit for research or education purposes. Complexity, data storage size, and lack of use/market for the video content led many responders to suggest that they were doubtful of the use of the technology for the vehicle. There were benefits to the technology suggested for the ROV operators for navigation, sampling and manipulator use. Some responders indicated a benefit for outreach and education purposes. It was recommended that time should be allowed until a commercial vendor comes out with a very robust model.

4K Video

Responders were overwhelmingly favorable of have 4K video as the standard video quality for the vehicle. 4K video was stated as rapidly becoming a broadcast and video documentary standard and will soon be widespread in the consumer market. A concern was raised regarding data volume, ease of use, and storage for science users.

Pan / Tilt / Zoom capability

All respondents felt that it is critical that at least one video camera should have all of these capabilities to allow for expanded observation while maintaining the vehicle on a steady course or in a given location; zoom for biology.

General Recommendations

- The system be designed so that the scientists have control over at least one of the primary cameras.
- Record quantitative information about this so imagery can be calibrated.
- The zoom should be reported back accurately, preferably in a digital form.
- A 4k large field of view camera and a separate camera that allows zooming into details while the overview of the main camera remain untouched.
- Maximum-resolution camera as a 3D reconstruction can be made from the video in many cases.
- A low light sensitivity high-resolution camera. For imaging bioluminescence you need 10E-5 lux. Also red light illuminators with cut off filters to illuminate wavelengths below 695 to 700 nm so the ROV can be used in stealth mode and see without being seen.
- Strongly consider how the video is it annotated and archived.
- GoPros in pressure housings deployed all over the vehicle.
- Priority on high resolution and large field of view.

High Resolution Still Image Capture

All respondents stated this to be essential for the vehicle. Its use in resolving fine scale biological features *in situ*, outreach, and publications, together with video in critical.

There were mixed opinion on the ability for software extracting high-res still images from high-res (4K) video (frame grabbing), this explicit technology could be de-emphasized if a trade-off decision is required. Detailed particulars were provided stating that working with video in machine vision application suffers from interlaced footage, motion blur, and various compression artifacts. Codecs compress in the poorly lit regions creating double trouble to work with these areas of an image. A raw recording high-resolution still camera with a well-calibrated fixed focal length lens (preferably a wide angle), together with a powerful flash unit, would be a great asset. One respondent stated that for one system in particular a stand-alone digital still camera is no longer used because they get equivalent quality images from our video frame grabs.

Full Spectrum LED Lighting

Respondents provided a variety of opinions on this topic, including:

- A capability for some on-the-fly adjustments of lighting field configuration (intensity, projection angle) would be highly desirable, especially when switching between close-up work and video surveys and reconnaissance.
- It is not sufficient to have 695 or 700nm LEDS because the tail into the short wavelengths is visible to many deep-sea inhabitants. You need cut off filters to be able to block out these shorter wavelengths. Also for fluorescence imaging besides the deep blue illumination you will need yellow filters for the cameras.
- All of the photo and videography work requires the best illumination possible and illumination is not hard to do, so yes, a high priority or all other imaging investments are wasted.
- If you are going LED, you must use full spectrum.
- Tunable lights would be ideal. Take into consideration recent research based on the different wavelengths that some of the deep-water species can see.
- The most important thing is that the color temperature of the lights installed does not get mixed up, i.e. all lights are the same. Mixing temperatures creates patchy images. The

LEDs should be optimized towards blue to reach as far as possible.

- Some, working in mid-water faunal surveys do require infrared light to conduct noninvasive studies.
- This may be the most energy saving way to generate a high light output for the vehicle.
- It reduces heating problems from the lighting source.
- A variety of lighting angles should be provided, including floodlights on a bar above and lights to the sides, which can be turned on or off to expand the field of view of the main and task cameras. More direct downward lights to illuminate the sampling basket are also important. These lights should all be dimmable. The light arrangements on the Tiburon (now gone) and Doc Ricketts are good models.

Audio Recording Capability

Some respondents stated a general interest and that it could be of great interest because there has been so little done in this regard to date. It was generally agreed that the value could only be realized if the vehicle can be made quiet so the microphone can truly listen, if the vehicle has a central hydraulic power pack the recording would be dominated by its noise. It was noted that it would be good to have a wider recording spectrum than just human audio band (a bandwidth of at least 200 kHz). Many respondents stated that they do not have a use for audio data.

Multi format / Codec capable video recording system

The respondents provided mixed feedback on this subject. Many felt it would be critical to have multiple format/codec options so that file sizes and data volumes can be chosen appropriately for various uses. Others stated that it is important to establish a high-quality standard to ensure that high quality video is consistently recorded but that there are many formats and codecs currently on the market so that it would be sensible to offer a standard format and point users to conversion tools.

Two case studies were suggested as learning opportunities: WHOI, who experienced headache from this, and; Bill Lange’s detailed study for Alvin upgrade video. Technology advancement happens rapidly and future-proof planning should be prioritized.

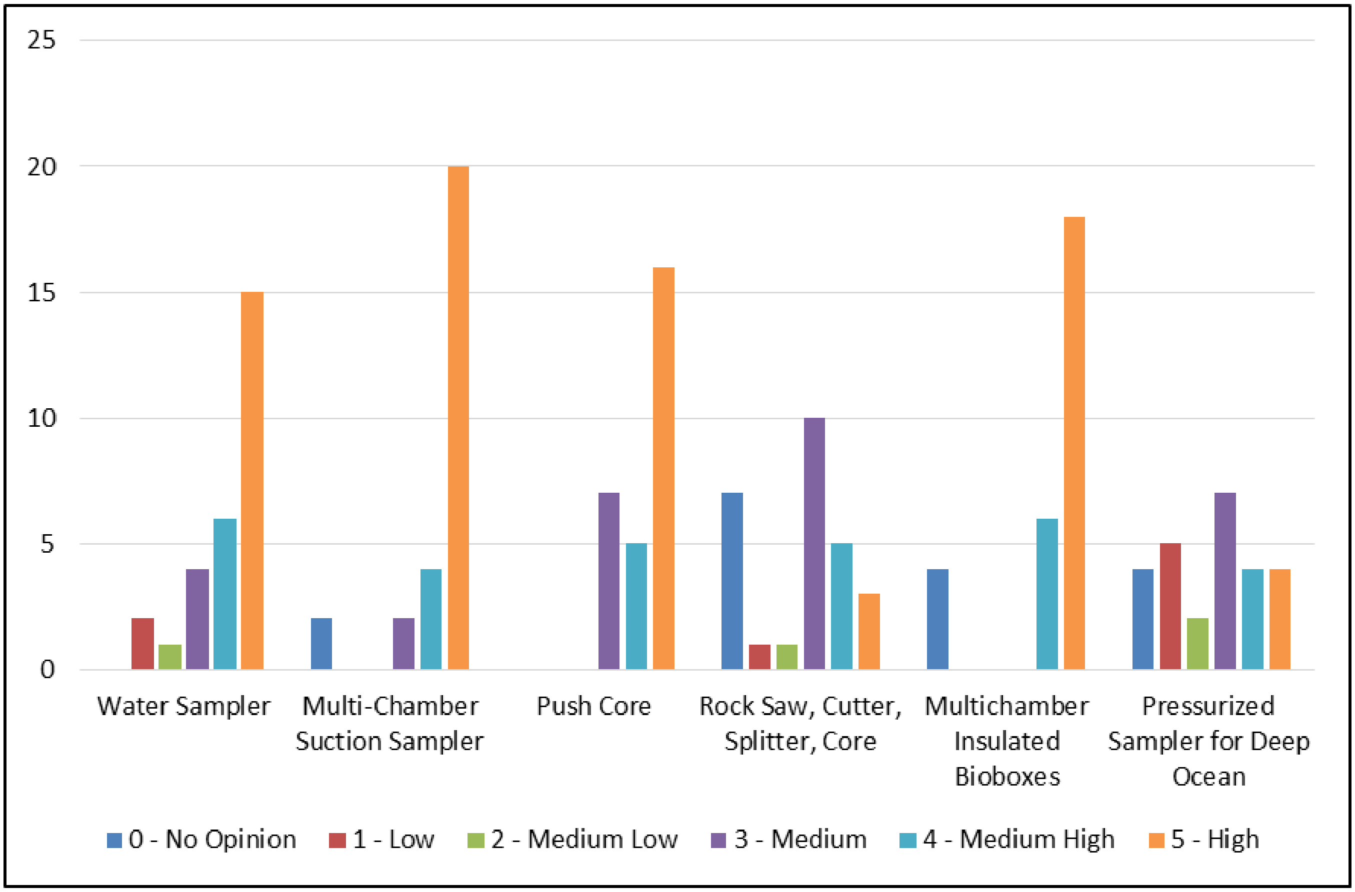
Frame Grabber

All respondents stated that this was a high priority, excellent tool. It can be used for generating automatic visual summaries of dive activities, publication images, websites, press, and cataloguing dive activities afterwards. Several mentioned the benefit of not having the complexity of setting up a digital still camera to capture an image. A suggestion was made to ensure there is documentary software to accompany the system so that pictures can have comments accompany them. It was also mentioned that manual frame grabbing also useful, especially for on-the-fly recording of sample collections and instrument deployments being followed by the video camera. One respondent stated that this leads to an individual doing this back on shore, thus creating double work.

General Comments on Imaging Systems

- The best video is "just" pretty pictures unless you can very accurately position it and so empower post-dive reconstructions
- A down-looking camera with matched lighting should be used as a removable payload for grid surveys. Shipboard support for GIS-based video mosaicking would be desirable.
- Many science users do not have the means to convert video observations in digital mosaics. Delivering a turn-key process for collecting and rapidly and systematically processing photomosaics for selected targets would transform our ability to visualize and communicate. With overlays of sensor data and navigation.
- Get the best possible imaging systems with the most features that you can.
- Imaging is perhaps the most important function of the sensors system on an ROV. There needs to be a reassurance that the imaging suite is brilliant (lots of light). HD or 3D can become awkward or unmanageable once it has been stored.
- This will be the featured capability of the system. Make the imagery and video as useful to science as possible. The end results should be geospatially referenced, easily aligned with dive logs, and discoverable to users who are not aware of the contents.
- Go big here. The only way to tell your story is through the imagery.
- In sourcing a camera for mosaicking, it should be one that has no moving parts. The sensor particularly for a mosaicking/surveying camera should be very sensitive to bridge passages where the vehicle is high or far away. It is also important to have a high repetition rate of 1 Hz or better (-> flash system!) in order to guarantee that the images have enough overlap (300-400%) for photogrammetry and not just mosaicking.
- It would be really great to source a system that can block the LED flash from the view of the other cameras in order not to distract the pilots on hour-long surveys.
- All cameras must be calibrated for their intrinsic (ok, difficult with zoom) and extrinsic parameters in order to facilitate quantitative measurements.
- Careful thought needs to be given to imaging payloads that will yield scientifically valuable information. Nice looking video may not be sufficient to extract quantitative information about the environments such a vehicle will be visiting. It is also important for the main imaging system to have a pair (or more) of scaling lasers.

Sampling Systems Responses



Sampling Systems Comments

Water Sampler

All respondents stated that water sampling will be very important for a number of missions, but that there is a delicate balance as to how much emphasis to place on this. To get good science from the samples, this sampler must be water- and gas-tight, non-reactive, and may need temperature control. Niskin Bottles have utility for some applications, those that ride on the side of the ROV quickly get dirty and even being in the water which is entrained with the ROV inherently deteriorates that validity of these samples. Titanium samplers for hot water fluids are also important to include.

Specific Comments on Water Sampler

- Many people may bring their own, favorite, sampler.
- Sampling fluids/gases emanating from the seafloor will be very desirable. However, to get a good sample requires placing the inlet system in the flow. This is hard to do. There can be issues with gas hydrate forming in the sampler.
- A capacity to collect small-volume (<10 litres) samples of ambient seawater, using ROV-mounted Niskin bottles is important. Collection of precisely positioned water samples adjacent to benthic organisms is also important to many studies. The ROV's sampling tools should also include standard 750ml titanium syringes for the collection of high temperature hydrothermal fluids and the vehicle would need an actuator to trigger

these syringes and a place to store collected syringe samples (at least two per dive).

- A readily available set of tools to collect water samples would be good. Some of the automated ones similar to or better than the PMEL HFS system or the WHOI SUPR sampler would be good. The basic ones, like the WHOI titanium syringe, the Lupton gas tight, and the like would be good to have as well. The only one that is easily maintained by an ROV crew would be the Titanium syringes. Other samplers would have to be made as simple as possible so that both the user and the supplier (*Falkor*/ROV/SOI) could easily work together to maintain and use such a system.
- This could mean a lot of things. A sampler for ambient water (Niskin-type sampler)? Or the capability of using titanium Major and Gastight sample bottles (requiring a hydraulic ram on one of the manipulator arms) for vent sampling? Or a more integrated system like the NOAA HFS (which includes pumps and sensors and multiple sample bottles for fluids with and without filters for microbial DNA). A sampler like that is the most efficient and useful, but takes an expert to use and maintain it. I would say the SOI vehicle should at least be capable of carrying and using a sampler like that (for example if it was brought on a cruise), and the ROV should also be capable of using Major & Gastight samplers. In fact, it would be valuable if SOI bought a suite of Major & Gastight sample bottles to keep on the ship to use with the ROV.

ROV read to collect coral samples. Photo Credit: SOI/ Cordelia Moore

Multi-Chamber Suction Sampler

Respondents were overwhelmingly in favor of having this sampler available as a regular attachment to the vehicle. It has general utility and would be missed by many research groups if it was not available, particularly biologists. It would be very useful for collection small organisms and particulate materials. Several respondents expected that it would get significant use and it was noted that its one of the most frequently used tool for JASON. The maltese-cross advance mechanism that is employed by MBARI was remarked as being very impressive and that their system as a whole could be a good model.

Specific Multi-Chamber Suction Sampler Comments

- The chambers should be around the size of a liter or half a liter at least, but there should also be 20 or more compartments - sampling sediments, e.g. from a volcanic stratigraphic sequence, will require this many to be effective.
- Consider having an excenter or vibrating chisel at the inlet of the hose in order to loosen compacted material, though this will not work for solid rock.

Push Core

All respondents indicated that this would be an inexpensive piece of equipment that would be expected as a part of the compliment of samplers that can be connected to the vehicle. They indicated that many researchers would find utility in this equipment and that it is a very commonly used tool and critical for any soft sediment work.

Specific Push Core Comments

- The vehicle should have a bay for installation of a quiver of 4-6 push core tubes.
- A lower lid mechanism (as in a box corer) would be a clever innovation.
- Make sure the push cores have a solid rack system with bottom stoppers that can be removed from the rack after recovery.
- Ideally the push cores should be in racks of 12 and configurable on the front basket - more or less cores - to accommodate varying scientific dive needs.

Rock Saw / Cutter / Splitter / Core

Responders were mostly critical of the need for this equipment, however a few indicated that it would be very useful; a specific reference was made to cutting carbonates. There has been very limited success with using *in situ* "saws". Simply put, they jam easily and every deployment is different. The implication for payload and dive time is enormous. Possibly as a future add-on option or a mission specific effort. The initial vehicle design should at least consider the necessary payload capacity and auxiliary hydraulic power to operated heavy-duty science tools such as rock saws. It was stated that it would be a major advance if such a system was successfully built, however if it proved unreliable then it would be a disappointment to the research community. A chisel and suction hose could be designed to accomplish this task.

MBARI's Vibracoring system has been a terrific success. This has opened up new avenues in science by enabling multiple long sediment cores to be collected on individual dives. This has enabled a new level of surgical sampling possible. Such systems are being built for the British ISIS and Taiwanese ROVs.

Critical Considerations for Rock Saw / Cutter Splitter /Core

- How to keep constant pressure on bit (i.e. how do you "anchor" the ROV or drill tool)?
- How do you get the core out of the rock (Assuming you do not drill right through but need to break it off inside the rock-face?
- How do you deal with dead vehicle whilst drilling (because if ROV and drill are solidly connected, the drill then acts as an awesome anchor)?
- How do you keep everything aligned whilst drilling? Look at how builders make circular holes through concrete walls when retro-fitting new heating pipes etc. and think of how you would do that under water.

Multichamber Insulated Bioboxes (for fragile animals)

Many respondents were supportive of having this equipment available for missions as a high priority. It was recommended that the system be easily configured in to a variety of shapes and sizes for researchers who want fewer bigger specimens. This equipment is critical for any live animal work, and most proper preservation for genetic work. Deep-sea sampling would require the bioboxes to be well insulated. In addition to bioboxes for bottom samples there may also be a need for a detritus sampler for midwater samples.

Pressurized Sampler for Deep Ocean

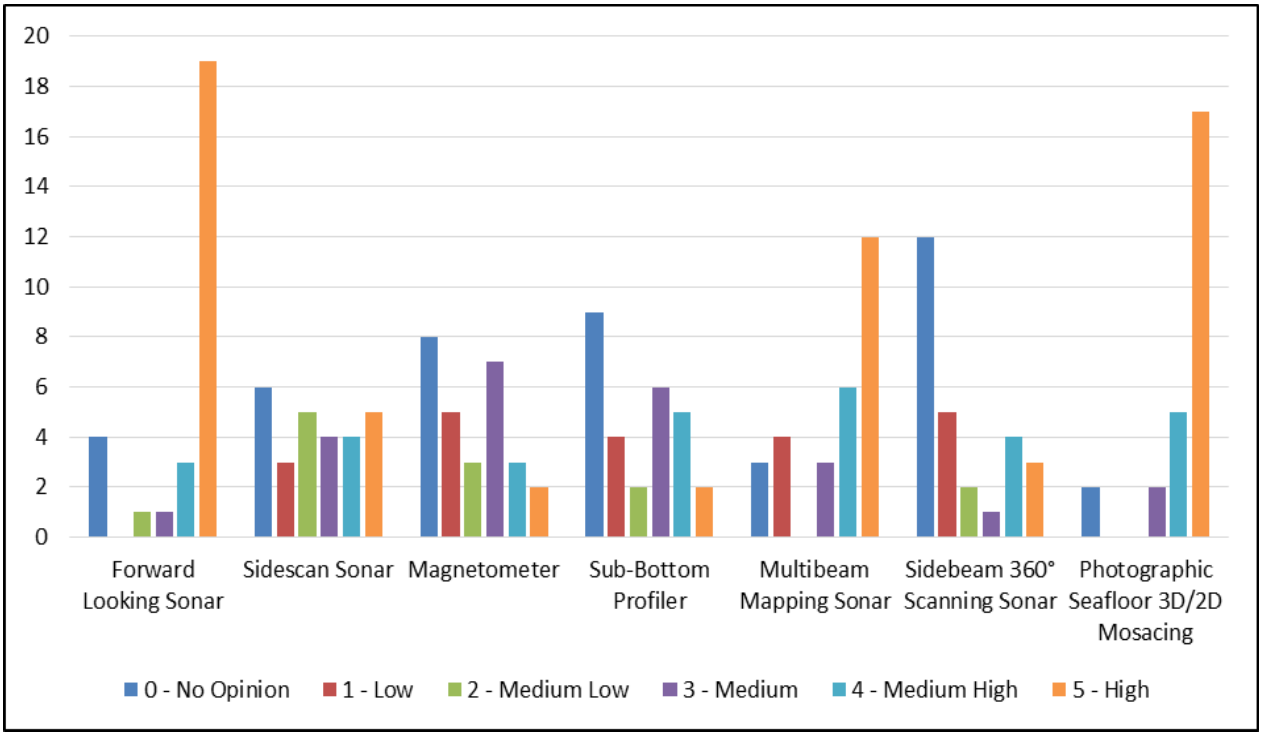
The respondents generally felt that this would be a nice addition if the technology was available to build one reliably and within acceptable risk tolerance, but that it is not currently the case and not worth the risk of having it. They all indicated that it would provide a great value, but that the risks of the system imploding under pressure doesn't balance the benefit of the samples it could collect or warrant the investment into having it. Unique opportunities such as pressurized sampling for microbes below about 2000m and sampling gas hydrates were described. A system would also need to be designed to handle samples once they were returned to the surface.

Multiple responders referred to such a system as the ROV carrying a bomb. It was noted that building the system to keep the container open on decent would remove implosion risks. Upon ascent minor burping might need to be accounted for but because of water's near-incompressibility the risk would be minimal.

General Sampling System Comments

- Most people will bring their own sampling equipment. Things that need to be integrated into the ROV system are what you should focus on (suction sampler, saw/splitter) and don't try to second-guess specialized sampling requirements.
- Need midwater detritus samplers.
- Except for the pressurized sampler, these are standard on ROVs, HOVs.
- This will evolve, don't try to do everything in advance if it means making trade-offs you might regret later.
- Many of the items listed here would be nice to have, however many of the complex ones may not be so important to have immediately.
- Syringe samplers have become important recently for the sampling of microbial mats and sediments. Various designs have been made from simple to complex. Some use a hydraulic ram on an arm to actuate (like the Major and Gastight samplers), while others use hydraulic functions, pumps and/or computer control to operate. Jason has a system at the low end of the complexity range, and Western Washington University has a system at the higher end.
- Filling compartments can take a very long time and cross contamination is always an issue. Maybe a system of consecutively opening bags on a spring-loaded frame would be an innovation, similar to a multinet.
- Passive detritus samplers, originally designed by HBOI, are extremely useful and should be part of any suite of samplers you develop.
- You should include a pressurized gas sampler with tubing and a collection funnel. This can be attached to the ROV frame similar to the water sampler.

Seafloor Surveying Systems Responses



Seafloor Surveying Systems Comments

Forward Looking Sonar
Respondents all felt this would be important to include and critical for navigating in rough terrain and in the benthos. It would also be good for finding targets underwater and useful for vehicle safety. It should also be to detect and represent acoustic beacons so you can go back to somewhere where you placed a beacon. It will be necessary to find instruments or structures on the seafloor that are beyond the light range.

Specific Forward Looking Sonar Comments
- 2D imaging sonar would be great.
- An ADCP could provide interesting data on fluid expulsions (hot springs, for example) or ocean current flow over bottom features (e.g., deep bed forms).

Sidescan Sonar
Most respondents commented that sidescan sonar would be better on an AUV than a ROV and thereby free up more time for ROV to do its specialties. Additionally, given the altitude that most ROVs fly, other imaging resources are out there that would do a better job.
It was stated that it could be quite useful when looking for wrecks when you want to use your ROV in mapping mode, 20-40 m off the bottom.

Magnetometer
Most respondents commented that a magnetometer would be better suited to an AUV. It was noted that if could useful to have on board for very specific purposes (i.e. hydrothermal sulfide

exploration), but generally better fit to an AUV. A possible problem may occur with magnetic field issues between the metal and motors on the vehicle.

Sub-Bottom Profiler
Most respondents commented that a sub-bottom profiler would be better suited to an AUV. It was noted that a really high-power system could have utility but would have handling problems with size and weight.

Some respondents provided comments regarding specific systems and utilities for it. A system with Chirp processing and low acoustic frequency (2-5 kHz, for example) would be best. The Tobi system (towed at 500 m typically) had a higher frequency profiler but it was unable to produce much information because of limited penetration. Data would need to be provided in SEG-Y format for broad use. This could be a useful tool in tracing volcanic ash layers, predicting the outcome of pushcores or finding sediment pockets for push cores on volcanic terrain.

Multibeam Mapping Sonar
The majority of respondents agreed that high-res mapping of new deep-sea environments may be interesting, but the priority here depends on what can be achieved using tows and other platforms versus this ROV and that an AUV would be better suited to this type of work. Many respondents stated that it is an excellent tool that would allow great high-resolution maps to be made of study areas particularly if other onboard systems were integrated with the data.

Specific Multibeam Mapping Sonar Comments
High-quality vertical reference unit for use with multibeam sonars and for accurate acoustic positioning of the ROV would be needed.
Data need to be provided in one of the formats read by the multibeam system to be of broad use. (http://www.ldeo.columbia.edu/res/pi/MB-System/)

Singlebeam 360° scanning sonar
A few respondents felt it would be very useful for general orientation and obstacle avoidance with respect to seafloor geological features during exploration and survey dives. It will need to be mounted such that it has unobstructed view in all directions.

Photographic Seafloor 3d/2d Mosaicing
Most respondents commented that this would be very useful and that it is becoming a more popular technique. It is very useful geologists and biologists for habitat mapping.

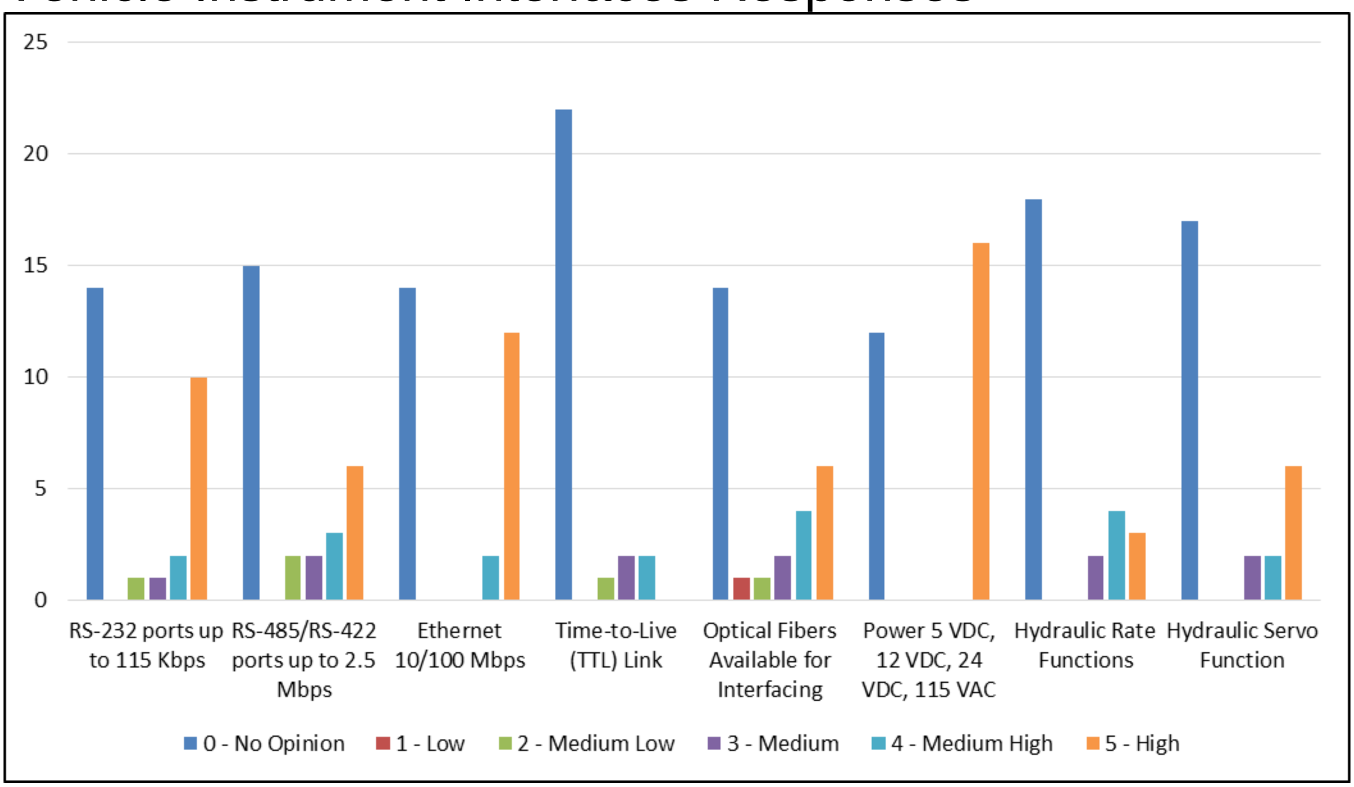
Specific Photographic Seafloor 3d/2d Mosaicing Comments

- Make sure it is a video as well as a still camera package. Downward looking video could be just as important as downward looking still images for photomosaicing.
- Great in combination with the high res maps and the chemical sensor data. And a nice time-series tool.
- It would be great to have automated mosiaicing. If it was available it would be very useful to the community.
- There may be an important software / processing side to having this capability.

General Seafloor Survey System Comments

- Build an ROV that excels in its strong points and utilize AUVs when and where needed.
- Shipboard integration of ROV navigation with existing bathymetric maps will enhance the ability of the science party and ROV operators to orient themselves with respect to seafloor features, making the dives more productive.
- Delivery of integrated shipboard products would be ideal. Merging of photomosaic, mapping, sensor data would be great, and if centralized on the ship this would be a major advance. Figuring out how to visualize and publicly archive full data sets from operations would be a terrific investment and major advancement. Collecting the data is one thing. Using the data, something else entirely, and incredibly important. Multi-terabytes of information is never accessed from researcher's ROV work because they don't have the funds to hire experts to process the data.
- If you want one vehicle that you can use for all types of different activities then load it up. However, perhaps you can have the various components as modules that you can swap in and out so you aren't creating wear and tear for some parts unnecessarily.
- Remain flexible to future needs as science and technology evolve.
- Consider Synthetic Aperture Sonar = sidescan with bathymetry.
- Using an ROV to map the seafloor is very wasteful of time. Far better to do your initial surveys with an AUV then come back to sites of specific interest with the ROV.
- Maybe it is a good idea to first build a great survey vehicle, then an even greater survey and sample vehicle, and then take it to great depths.

Vehicle Instrument Interfaces Responses



Vehicle Instrument Interfaces Comments

RS-232 ports up to 115 Kbps
Respondents suggest giving priority to RS-232 ports to support user-supplied legacy instruments, and Ethernet for the rest. It was stated that they would be necessary to accommodate most of the user-supplied gear. Probably 2-3 would be most helpful.
Additionally, it would be easy to use an A to D to get analog channels by this route as well.

RS-485/RS-422 ports up to 2.5 Mbps
Respondents suggest giving priority to RS-232 ports to support user-supplied legacy instruments, and Ethernet for the rest. It was stated that they are an important user interface for third-party equipment.

Ethernet 10/100 Mbps
Respondents suggest giving priority to RS-232 ports to support user-supplied legacy instruments, and Ethernet for the rest. They stated that many instruments are moving towards IP based data acquisition and that they would likely replace older interfaces. Ethernet allows users serial to Ethernet converters to accomplish RS-232 and RS-485/422 communications.
GigE was suggested for cameras.

Time-to-live (TTL) link
Certainly, centralized time stamping of all data and imagery collected by the ROV will be essential. Otherwise, there may be little advantage in supporting TTL.

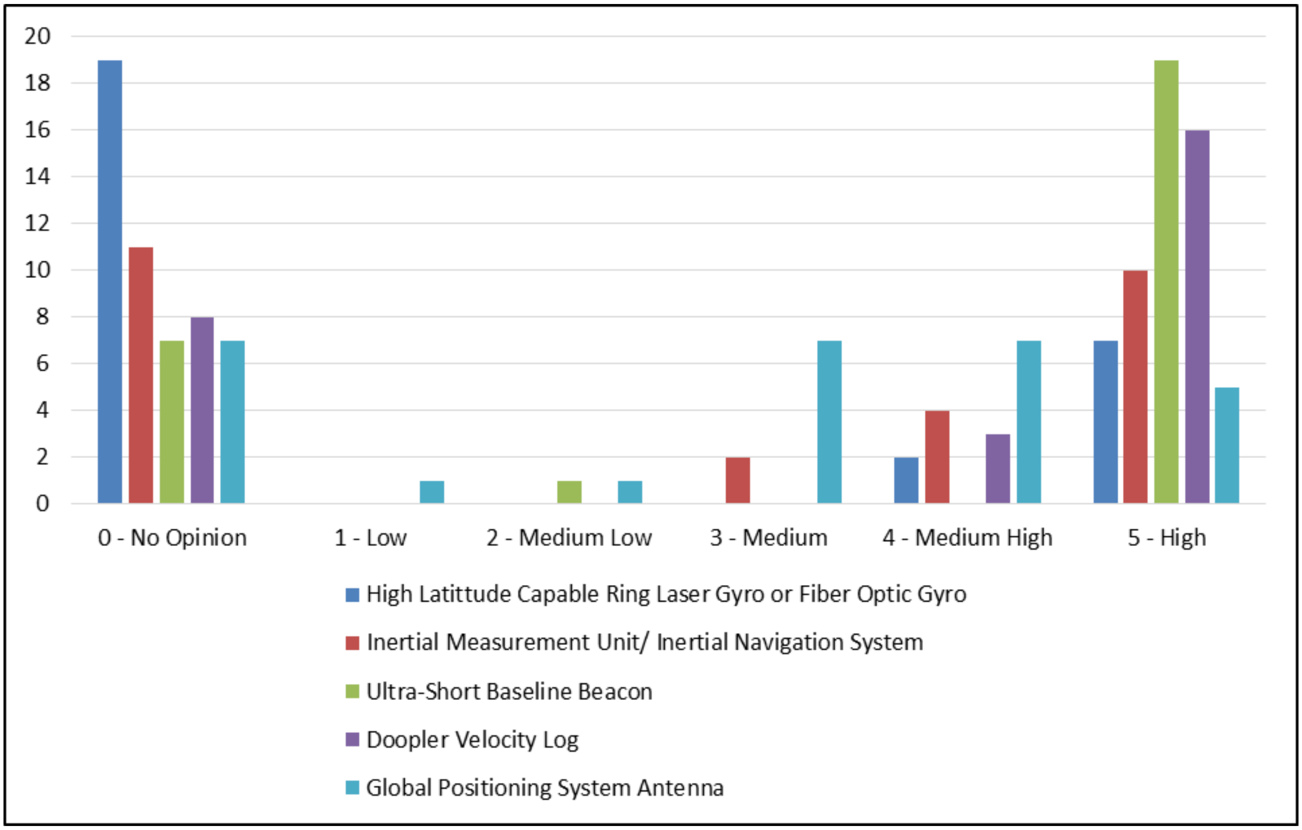
Optical fibers available for interfacing
One or two ports dedicated optical interfaces would be a real asset. This is likely an emerging requirement and would allow the vehicle to stay ahead of the curve. Optical fiber is generally considered to be the best you can have for video transmission.

Power 5 VDC, 12 VDC, 24 VDC, 115 VAC
Multiple 5, 12 and 24 VDC ports make sense. There may be little interest in providing a lot of AC power ports since most scientific sensors use lower voltage DC. Providing these connections would save your pilots a lot of headache in wiring user instruments. Adequate amperage would have to be provided.

Hydraulic rate functions
Some user-supplied scientific sampling tools (drills, saws, etc.) will require hydraulic power and it is difficult to add at later stages. It would be beneficial to be able to control the hydraulic pressure beyond off/on. It will need an acceptable level of ruggedness to support the sampling tools it would likely support.

Hydraulic servo function
Hydraulic functionality would be good to operate sampling motors and to actuate samplers. Electronic (magnetically couples) versions might even be better.

Navigation: Position & Trajectory Recording Sensors Responses



Navigation: Position and Trajectory Recording Sensors Comments

Gyros
If SOI decides to work at high latitudes this could be important. Although even in lower latitudes, laser ring and fiber optic gyros improve navigation. However, it might be adding on a lot of rarely or never used options.

IMU/INS
Having accurate navigation is critical and having multiple means of navigation improves redundancy. However, whether an inertial system is the way to go is less clear. When operating near the bottom a bottom track DVL is much more useful and considerably lighter. When operating mid-water, it seems more important to track ones position relative to the surrounding water mass.

An important piece of multi-component navigation system, especially in deep-water or other applications where acoustic navigation is less reliable. INS based navigation is crucial for Multibeam operations and just as well for the estimate of the online coverage of optical surveys. USBL and DVL can be used to get a good track after the fact, but INS is a fast commercially available solution to get a really accurate online position estimate.

USBL
Many respondents stated that this would be an essential navigation system for operations for the 4500m vehicle, although performance will deteriorate near maximum vehicle depth.

DVL
All respondents indicated that this is a standard important piece of multi-component navigation system, especially in deep-water or other applications where acoustic navigation is less reliable. Additionally it is more accurate than USBL once you are nav-ed in on the seafloor, great for running parallel lines. Having it run in tandem with other navigation sensors is best.


ADCP mounted onto the CTD Rosette, Photo Credit: SOI/Judy Lemus.

ADCP
An ROV based ADCP would be used in selective applications, such as mid-water operations. It would be helpful to know the currents and would greatly add to many studies. Utility on a moving platform may be limited. It would be best as an add-on sensor and not part of the standards suite. One respondent strongly recommended having an ADCP and stated they are pretty much standard.

GPS
Given the depths and the possible availability of USBL, GPS may not be particularly important for an ROV like this.

General Comments on Positioning Sensors

- Do not skimp on navigation sensors. They need to be as good as you can get otherwise your observations are severely compromised and the data will never be as useful as it could be. As things like INU, DVL are intimately integrated into the vehicle when it is being built, these need to be good right from the start - retro-fitting is very difficult. Note that the time-stamping of everything is an integral part of navigation - most vehicle manufacturers will try to make you accept 1 second time stamps, this is WAY TOO SLOW. An ROV can rotate 60-90 degrees in 1 second or cover a couple of meters of ground. Time-stamps need AT LEAST the video frame rate frequency so that you know exactly where and in what orientation the vehicle was when each frame was taken.
- An integrated, multi-component navigation system is essential to ensuring navigational accuracy, especially during deep dives where acoustic navigation is less reliable.
- All navigation should be associated with measurements as geospatially referenced information. National Deep Submergence Facility has struggled with X-Y coordinate grid systems being translated. Users will want inter-comparable navigation information.
- You have listed several forms of navigation. All of them likely rely on having a GPS antenna, so that is a must. USBL beacon would probably be good for both navigation and for tracking elevators, and other independent pieces of instrumentation left on or moving way from the seafloor. Most of these things are incremental, so I place the highest priority on a system that knows exactly where the ROV is and from there you can figure out how far it has gone. Barring that the USBL system with DVL is a standard that has worked fairly well so far.
- Navigation is essential and should be seen as one package; 3D navigation is a must.
- You need a system to know exactly where your ROV is, this is usually achieved by a pinger system that acoustically communicates with the ship. It is best if you connect your tracking system with maps and enable them to add notes and symbols while the ROV is *in situ*.

Glossary of Acronyms

3DHD – Three Dimension High Definition
4K – 4,000 pixel resolution (horizontal)
ADCP – Acoustic Doppler Current Profiler
CDOM – Colored Dissolved Organic Matter
CTD – Conductivity, Temperature, Depth Sensor
DIC – Dissolved Inorganic Carbon
DOF – Degrees of Freedom
DVL – Doppler Velocity Log
GIS – Global Information System
GPS – Global Positioning System
HFS – Hot Fluid Sampler
(H)ROV – (Hybrid) Remotely Operated Vehicle
IMU – Inertial Measurement Unit
INU – Inertial Navigation Unit
INS – Inertial Navigation System
Kbps – Kilobytes per second
LED – Light Emitting Diode
Mbps – Megabytes per second
MP – Megapixel
ORP – Oxygen Reduction Potential
PCR – Polymerase Chain Reaction
PI – Principal Investigator
PMEL – Pacific Marine Environmental Laboratory
RS – Radio Sector
SOI – Schmidt Ocean Institute
TTL – Time to Live
USBL – Ultra-Short Baseline
VAC – Volts Alternating Current
VDC – Volts Direct Current
WHOI – Woods Hole Oceanographic Institutions