

The skinny on SCINI



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Cazenave, Zook, Carroll, Flagg and Kim describe a compact, cost-effective ROV specifically designed for deployment through ice in remote regions.

Who should read this paper?

Anyone with an interest in under-ice environments, ROV manufacturers, and engineers developing instrumentation for remote, extreme environments such as Antarctica.

Why is it important?

This paper describes the development of an ROV for research under ice, and its deployment under the sea ice and ice shelf in Antarctica. SCINI (Submersible Capable of under Ice Navigation and Imaging) is a small, slender vehicle that can fit through a 20 cm hole in the ice, allowing for deployment without heavy drilling equipment and with minimal logistical support. SCINI was designed to be lightweight, rugged, reliable, easy to repair and inexpensive. For the most part, the vehicle was built using commercial off the shelf (COTS) components. The user interface was designed to enable ease of use by anyone with a small amount of training to carry out precise surveys in water depths of up to 300 metres. The long slender shape of the vehicle makes it particularly well suited to survey work, with forward speeds of up to 4 knots, good heading control and the ability to fly to working depth quickly. SCINI uses Ethernet over power on a 400 m long two-wire tether, giving a high immunity to damaged tether connectors and lower cost and greater durability than fiber optics. The SCINI navigation system uses a combination of two to four acoustic transducers hanging below the ice and a synchronized pinger on the vehicle. This system provides operation in complex under-ice environments with positional accuracy of better than 1 metre.

About the authors

François Cazenave is a mechanical engineer with expertise in underwater vehicles, oceanographic instrumentation and physical oceanography. Bob Zook is the chief engineer on the SCINI project, with 14 years of experience in engineering for extreme environments. Dustin Carroll is a physical oceanographer with an interest in ROV software engineering, scientific instrumentation, and polar oceanography. Marco Flagg is the CEO of Desert Star Systems LLC and also the company's chief architect of underwater acoustic systems. Stacy Kim is a research professor at Moss Landing Marine Laboratories with an interest in seafloor ecosystems in the Antarctic and other extreme environments.

DEVELOPMENT OF THE ROV SCINI AND DEPLOYMENT IN MCMURDO SOUND, ANTARCTICA

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ABSTRACT

Remotely Operated Vehicles (ROVs) are powerful tools whose use has become common in many aquatic systems, for many purposes, from commercial to research applications. Polar regions, because of ice cover and harsh conditions, remain difficult locations for ROV work. This paper outlines the development of an ROV designed to facilitate exploration and scientific research under sea ice, giving easier access to largely unexplored regions of the seafloor. The ROV SCINI (Submersible Capable of under Ice Navigation and Imaging) was developed at Moss Landing Marine Laboratories and deployed in Antarctica for four field seasons, from 2007 to 2011. Ice provides a convenient deployment platform but commercially available ROVs require a large hole in the ice and much logistic support, which restricts their use in polar regions. Unlike other ROVs, SCINI has a slender torpedo shape (length: 1.4 m, diameter: 15 cm), which allows it to be deployed through a 20 cm hole in the ice. This small hole can be drilled by two people, using a handheld drill. The entire SCINI system and personnel (three or more persons) can fit in one helicopter, thus giving easy and quick access to remote sites. SCINI is a modular vehicle that can easily be modified or serviced in the field. It is also rugged and designed for harsh polar conditions. SCINI is equipped with two video cameras, scanning lasers, and lights. Its maximum depth capability is 300 m. A long baseline acoustic positioning system is used for navigation. SCINI is a highly manoeuvrable vehicle, better suited for flying transects over the seafloor than most ROVs. Engineering tests and scientific surveys were based out of McMurdo Station, Antarctica, and carried out at various sites within a 100 km radius. Knowledge gained from these deployments led to numerous modifications and improvements to the vehicle. This paper provides details on the vehicle's most recent configuration, including mechanical design, electrical design, software, and navigation system. Deployment methods, vehicle behaviour, and results of field testing are described. Four scientific surveys are also briefly described as examples.

KEY WORDS

Remotely operated vehicle; ROV; SCINI

INTRODUCTION

Remotely Operated Vehicle (ROV) use has proliferated in recent years to support ocean resource extraction, scientific research, and education. Advantages in research situations include the ability of ROVs to work much deeper than scuba divers, increased working time at any depth, and increased safety under hazardous conditions. The imaging capabilities of ROVs allow for realtime control of the vehicle from a surface station, and provide invaluable situational awareness and responsiveness. Vehicles range in size from a few kilograms (micro class ROVs) to several tons (heavy workclass and cable-burial ROVs), and are available in a wide variety of configurations. Most vehicles used for scientific research weigh hundreds to thousands of kilograms and require a substantial investment in support for deployment and recovery. Smaller ROVs are sensitive to surge, current, and tether drag. However, the ease and simplicity of deployment of small ROVs makes them valuable initial reconnaissance and work tools. When the limits of the small ROV have been reached, further research can be conducted by the more expensive, intensive deployment effort for a larger, more capable ROV.

Only a few underwater vehicles have been used in Antarctica [Stone et al., 2009; Nicholls et al., 2008; Montes-Hugo et al., 2009; Stoker et al., 1995; Hobson et al., 2010]. The ice cover makes deployment of large ROVs particularly challenging and costly, as a hole must be made large enough to accommodate the size of the vehicle. This has limited the use of ROVs for scientific research in both the Arctic and especially the Antarctic, where ice cover is more persistent. Extremely low air

temperature and -2°C water temperature are also a challenge for equipment and operators. Standard daily transportation methods (tracked vehicle, helicopter) are vibration-rich and frequently damage equipment. Finally, even with the best preparation, limited access to supplies and technical support can impact polar research efforts. One advantage of working in ice-covered seas is that surge and wave motion are severely damped to non-existent, making station keeping much easier even for a light vehicle.

The design constraints for a polar ROV are thus:

- 1) Small diameter for deployment through a hole in the ice.
- 2) Rugged enough to operate under polar conditions, including temperature extremes and variability.
- 3) Easy to troubleshoot and repair quickly in the field.
- 4) Inexpensive to repair or replace due to the high risk of damage or loss during polar work.

We have developed an ROV system that meets these constraints. The Submersible Capable of under Ice Navigation and Imaging (SCINI) can be deployed through a 20 cm diameter hole in the ice. In ice that is 8 metres or less in thickness, this size hole can be drilled with a hand-held power auger, requiring minimal logistical support and cost. Many holes can be drilled, allowing a continuous ROV survey of the seafloor from the ice surface. In four Antarctic field seasons, SCINI has proven to be reliable and robust under polar conditions, simple to maintain even in extreme settings, and economical. The cost of the vehicle is approximately \$45,000 (USD).

In an Antarctic coastal region like McMurdo Sound, fast ice covers the shallowest seafloor to water depths of hundreds of metres. This ice cover, pack ice, and icebergs preclude safe ship operations by anything other than an icebreaker. However, it also provides a convenient work and travel surface for nine to ten months of the year. Shallow areas to 40 metres water depth in this region have been explored and studied by research divers since the early 1960s [Brueggeman, 2003]. However, despite the proximity to the largest research base on the continent, very little is known of the seafloor at depths greater than 40 metres. SCINI opens up this and other more remote polar marine regions to scientists interested in ecology, biology, geology and other fields.

VEHICLE DESIGN

Mechanical Design

SCINI's main design requirements were to fit through a 20 cm hole in the ice, and to be easily deployed and serviceable in polar field conditions. The size limitation was set by the diameter of commercially available drill bits for the hand-held "Jiffy" drills (Model: 30, Jiffy Ice Drills) stocked by the U.S. and other national Antarctic programs. Therefore we opted for a torpedo shape, and a modular design. In its most basic configuration (only one camera), SCINI's diameter does not exceed 15 cm. With a dual camera housing, the outer diameter is under 18 cm. SCINI is 1.4 m long, weighs 18.5 kg, and can easily be carried and launched by one person.

SCINI's modular design allows the vehicle to be disassembled and reassembled in less than 30 minutes. This allows for easy maintenance in the field. If a component fails, it can easily

be replaced on site. The five main modules include, from front to back, the camera housing with its lighting system and scaling lasers, the front manoeuvring thrusters module, the main electronics housing, the rear manoeuvring thrusters module, and the main thruster module (Figure 1). The five modules fit into each other and are held together by a strap system running from the main thruster module to the camera module.

The camera module (Figure 1, A) is a 10.2 cm diameter 1-atmosphere aluminum housing with a polycarbonate dome port at one end for the forward looking camera, and a polycarbonate vertical port for the downward looking camera. The camera housing is rated to 350 m depth. Inside the housing, an electronics tray with the two cameras and several printed circuit boards is attached to the end cap of the housing, which serves as a heat sink for the power supplies. The vertical port is a flat window that provides an undistorted downward view, ideal for video transects of the seafloor. The hemispherical shape of the dome port allows for the use of a tilting mount for the forward-looking camera. The downward-looking camera has an 84° lens (about 65° in water), while the forward-looking camera has a 180° lens which provides good situational awareness for the pilot.

Two sets of lights with scaling lasers were custom made to meet the space requirements. One set faces forward, for the pilot camera, and the other faces down, for the science camera. The forward light is a ring composed of two scaling lasers (Model: PPA6501F3PA, LaserMate) and 20 Luxeon Rebel high efficiency LEDs (Model: LXM7-PW40, Philips Luxeon Rebel). The lack of space did

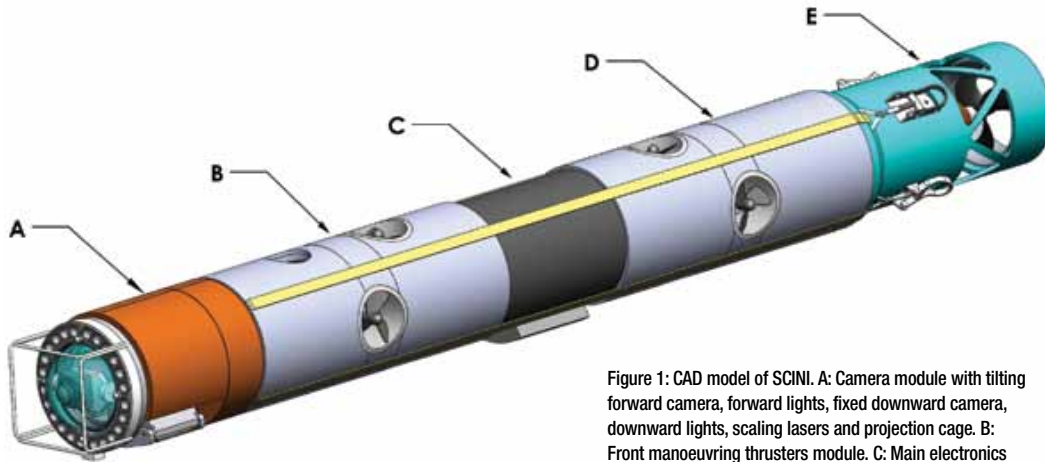


Figure 1: CAD model of SCINI. A: Camera module with tilting forward camera, forward lights, fixed downward camera, downward lights, scaling lasers and projection cage. B: Front manoeuvring thrusters module. C: Main electronics housing. D: Rear manoeuvring thrusters module. E: Main thruster module and tether attachment point. Length 140 cm, diameter 15 cm, weight 18.5 kg.

not allow for the use of a 1-atmosphere dry housing, and the laser diode cannot be flooded with liquids, so a pressure-compensated housing could not be utilized. The LEDs and laser are cast in two layers of epoxy resin. The bottom layer is a thermally conductive polyurethane resin that draws the heat away from the LEDs, underneath the metal core PC board. The top layer is clear epoxy to let the light through. The light ring provides 70 lumens per watt for 75 W in total, and has been tested to 330 m. The downward facing light is composed of two 1-atmosphere housings that accommodate two Luxeon Rebel Star LED modules each (Model: 7007-PWC-08-3, Luxeon Star). Off-the-shelf waterproof connectors were too large for the housings so custom feed-throughs were manufactured for the light cables.

Each of the two manoeuvring thruster modules (Figure 1, B and D) is composed of a PVC fairing, and two thrusters (vertical and

horizontal). The PVC fairing is made of two 5 inch PVC pipe couplers that are machined down and glued together, a very sturdy and economical design. The fairing has several holes for letting water in and air bubbles out. The thruster tunnels are also made of PVC pipe. The thruster motor housings are made of aluminum and are pressure compensated with silicon oil. The thruster power cables are also filled with oil and serve as compensation bladders. Thrust is provided by a 20 mm brushless motor manufactured by Neutronic, a radio-controlled (RC) airplane supplier (Model: RZ-1000, Neutronics). The motors are coupled with a 4.4:1 ratio Maxon gearbox (Model: GP 16K, Mazon). Custom made, spring-loaded lip seals (Bal Seal Engineering) are used for the propeller shaft. The two vertical thrusters are used for heave (when running in the same direction) and pitch control (when running in opposite directions). The horizontal thrusters are used for sway (when running in the same direction) and

yaw control (when running in opposite directions). Standard 60 mm RC boat propellers were used for the tunnel thrusters (Model: PRB2464, ProBoat). They are inexpensive but have poor efficiency when running in reverse. The thrust is approximately 20 N forward, and 12 N in reverse. SCINI's sway velocity is approximately 0.3 m/s, and it can complete a 360° turn in 20 seconds.

The main electronics housing (Figure 1C) is a 14.3 cm diameter 1-atmosphere, 2000 m rated aluminum housing with two flat end caps. End caps are drilled for three connectors and a pressure sensor. Inside the housing, an electronics tray is attached to one end cap. Two heat sinks transfer heat from the power supplies to the housing, which in turn transfers it to the ocean.

The main thruster (Figure 1E) is a modified VideoRay thruster (Model: PRO 3 GTO ROV thruster, Video Ray), rated to 350 m. The nozzle is also adapted from the VideoRay ROV. This thruster propels SCINI at up to 2 m/s in the forward direction.

Expanded polyurethane foam (General Plastics R-3318) with a depth rating of 400 m was used for floatation. The camera housing and the aft thruster are enclosed in floatation blocks. There are also four floatation blocks fitted between the five modules.

SCINI is maintained level in the water by a 1.5 kg lead keel weight, which is attached below the main housing. This weight provides a righting moment to counteract the torque of the main thruster.

The tether is attached to cables extending from the end of the aft thruster module, using a

locking mechanism that has been tested to 2000 N. This allows SCINI to be pulled out of the water through the ice hole for rapid and safe recovery. The tether developed for this project has a polyurethane jacket and is filled with a water blocking gel that prevents its buoyancy from changing at depth. This negatively buoyant tether is then made neutrally buoyant by attaching small custom-made syntactic foam floats at about 1.5 m intervals.

On the surface, an adapted garden hose spool is used for the tether reel. It has a motor winder and can accommodate 300 m of tether.

Electrical Design

Flexibility, simplicity and low cost were the main requirements for the electrical design. Therefore we chose to use commercial off the shelf (COTS) technologies when available; COTS devices offer state-of-the-art technology with short integration time, proven reliability and low cost. SCINI's most efficient use of COTS technology is the Ethernet over power (ENOP) devices, chosen for their ability to transmit 60 to 80 Mbps across 400 m of 18 gauge twisted pair tether. This two-wire tether eliminates many of the reliability problems associated with multi-pair tethers. The Ethernet tether also allows the use of a 5 megapixel Ethernet camera by Elphel (Model: 353, Elphel, Inc); this open source hardware and software platform has grown with the project to include some useful tools [McPike, 2010]. Another central COTS device is the Sidewinder (Model: Sidewinder, Castle Creations) brushless motor controller. Optimized by hobby enthusiasts and competitive manufacturing, this complex controller enables smooth motor response in a constantly reversing and low RPM environment.

Finally, in order to easily expand future functionalities of the ROV, RS-485 was chosen for the internal communications data bus. RS-485 communications are based on differential signaling, and are simple to implement in a reliable multi-node distributed processing network. For a few specific sensors and control operations, an I²C (inter-integrated circuit) bus was used for local interconnections.

Top side electrical system

Figure 2 depicts the power supply and data transmission paths from the surface elements to SCINI. A 350 m two-wire tether (Manufacturer: Falmat) links SCINI to the surface. This tether conducts 220 V AC as well as a 75 Mbps Ethernet stream to the ROV. We found that using high voltage and high frequency to transmit video and control signals dramatically improved the reliability of the transmission. The AC power supply is provided by a portable 1 kW generator, a UPS unit, and a 220 V step-up transformer. An ENOP (Model: PLK200, Cisco-Linksys) uses the self-healing HomePlug AV2 protocol [HPPA, 2005] to modulate Ethernet data across the tether to SCINI.

Using Ethernet to transmit video eliminated the extreme sensitivity to dirty connector pins that plagues the more conventional method of using twisted pair for transmitting analog video over a tether. The downside to using Ethernet for video is the inherent delay, as Ethernet cameras have to compress and packetize their data. We were able to optimize the system to achieve video latencies of less than 200 ms, which was sufficient to fly the ROV effectively in a scientific survey environment.

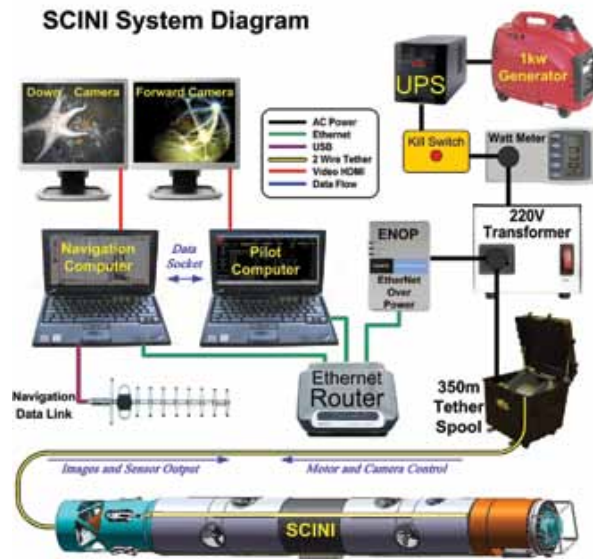


Figure 2: SCINI system diagram showing paths of power, Ethernet, USB, and data flow.

The control interface is provided by two laptop computers running custom software to control the ROV, provide imaging, and process navigation data. Details on software designs and the navigation system are provided under **Software** and **Navigation System** below.

Vehicle electrical design

Figure 3 depicts the ROV's electronic block diagram. The main electronics housing is dedicated to power and command distribution, as well as motion control and position sensing. Control is performed by the brushless motor controllers, and the attitude and depth are measured by the Inertial Measurement Unit (IMU) and the pressure sensor. This main housing is placed at the centre of the ROV while the camera housing is placed at the front of the ROV (Figure 1). The camera housing, as its name states, is dedicated to image capture performed by the two Elphel cameras and the lighting system. Details on these subsystems are given below.

Main electronics housing

Inside the main electronics housing, the AC power is routed to the primary module of a two-module high density Vicor power system. This primary module, a Filtered Auto-Ranging Rectifier Module (FARM), converts the 220 V AC to 330 V DC, which is thereafter routed to the HoldUp (HUB) capacitors. The HUB provides additional filtering and sustains the secondary module through transient demands. This secondary module converts the 330 V DC to regulated 15 V DC at 250 W. For noise isolation purposes, this power supply only provides power for the potentially noisy motor controllers.

The Ethernet over power (ENOP) demodulates an Ethernet signal that is then passed to an X-port adaptor and converted into an RS-485 data stream. Thus the command and control data are separated from the image data, and are then distributed to the device controllers within the main housing, as well as to the camera housing.

Two micro controller units (MCUs) are the core elements for the ROV motion control. First of all, one of the MCUs generates five pulse width modulation (PWM) signals to command the five Sidewinder brushless motor controllers. Secondly, by monitoring the IMU (Model: ADXL203, Sparkfun), which

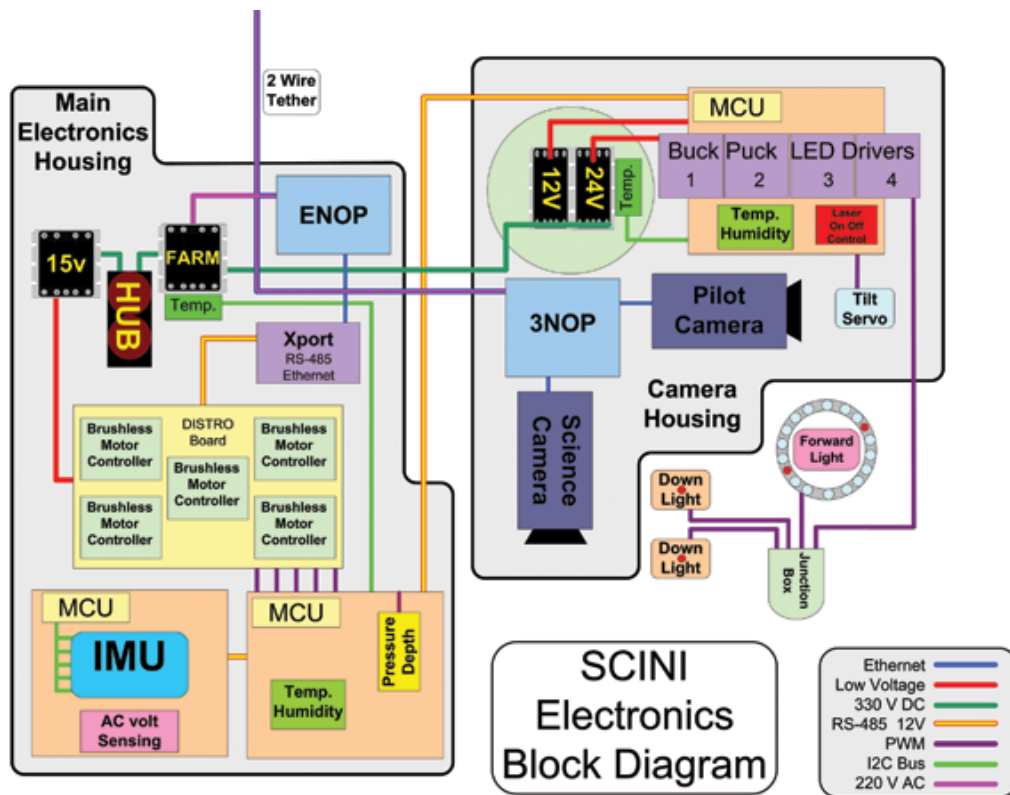


Figure 3: Block diagram of SCINI electronics. Abbreviations used include EtherNet over Power (ENOP), 3-port ENOP (3NOP), Inertial Measurement Unit (IMU), MicroController Unit (MCU), HoldUp capacitor Box (HUB), Filtered Auto-Ranging Rectifier Module (FARM).

measures pitch, roll and acceleration along three axes, as well as by reading a depth sensor, the MCUs communicate the attitude and motion of the ROV. It should be noted that SCINI is not equipped with a heading sensor. Close to the pole, the Earth's magnetic field is nearly vertical, so measuring heading with a compass is very difficult. Finally the MCUs monitor the housing's ambient temperature and humidity, for leak and over-heating detection.

Camera housing

The camera housing utilizes an ENOP to obtain the Ethernet signal from the tether that is looped through the main housing. RS-485 commands and 330 VDC are supplied from the main housing as well.

A three-port version of the ENOP (Model: F5D4075, Belkin) provides the Ethernet ports for the two Elphel cameras. The Elphel camera consists of a main-board linked to an image sensor board. We chose to use the 5 megapixel sensors. This option provides up to 17 frames per second of high resolution video, with each frame being stored on the surface computer in JPEG format. More detail about the cameras and their use on SCINI can be found on the Elphel blog [McPike, 2010].

An MCU provides pulse width modulation signals to the servo that controls the tilt of the forward camera lens and sensor. The MCU also hosts a daughter-board containing four Buckpuck current limited LED light controllers for the dimming of the forward and the downward lights. The MCU also handles control of the two scaling laser pairs, and monitors internal ambient humidity to detect leakage or thermal issues.

The FARM power module in the main housing provides 330 VDC to the camera housing to drive 12 and 24 V Vicor DC to DC modules. The 24 V module provides power exclusively for the LED controllers; the 12 V module supplies power to the Elphel cameras and the RS-485 data bus.

Software

SCINI contains onboard embedded software written in C on each of its three microcontroller PCBs. The embedded software provides robust communication with the surface software, vehicle control, and sensor logging. Data streams from the onboard sensors are read using the RS-485 and I²C communication protocols. Realtime sensor output from the vehicle is converted from RS-485 to Ethernet and then transmitted to the surface software.

The surface piloting software (PCPilot) was written using LabVIEW, a graphical programming language from National Instruments. This development platform was chosen for its ability to provide rapid GUI design, easy hardware interfacing, and general ease of use that allows non-technical users to make software changes while in the field. The PCPilot software allows the pilot to easily control the vehicle and view the appropriate sensor output necessary for piloting. Figure 4 shows the PCPilot software interface.

The surface camera display software (Image Annotation Tool, IAT) was specially developed using Microsoft C# .NET. This software displays and saves the motion JPEG (M-JPEG) streams from both the forward and downward looking Elphel cameras. Motion JPEG is a class of video formats where each individual video frame is separately compressed as a

JPEG image. The streaming forward and downward looking camera images are split into two distinct panels, and are displayed on separate monitors for the pilot and scientist to view. The pilot display is optimized for the fastest frame rate to allow for quick piloting response, while the science display is set for high resolution and image quality. Relevant piloting information (pitch and depth) is

selection of the underwater acoustic navigation system was driven by specific performance requirements. The system had to be compact and rugged. Yet it also needed to offer high accuracy of 1 m or better in order to support tasks such as image transects and repeat visits to specific sites on the sea floor. The project also required some advanced or specialized capabilities such as automated digital image

annotation with position and observation data. Finally, the system needed to support operation by a field science crew as a dedicated navigator or surveyor was not always available.



Figure 4: PCPilot software interface. This interface allows the pilot to monitor vehicle attitude and depth, housing temperature and humidity, and to control the lights, laser, and thruster gains.

displayed as transparent overlays on the piloting video screen. These data are piped between PCPilot and IAT using the Windows Datasocket protocol. The scientist can easily take a high resolution snapshot image, change the camera parameters such as decimation and exposure, and add written annotations to an image. Realtime sensor metadata from the SCINI vehicle such as depth and position is stored in each image in the JPEG Expandable Image File Format (EXIF) header. This provides a way for the scientist to view mission parameters and data directly from the stored image without having to consult a log file.

Navigation System

As with other components of SCINI, the

developed by Desert Star Systems. PILOT consists of a surface control box to which three small (5 cm diameter) sonar transducers are wired via 30 m cables. A small cylindrical transponder (4 cm D x 13.5 cm L), powered by a 9 V battery, was mounted on SCINI.

Short baseline system accuracy is restricted by the cable-limited maximum available size of the surface station baseline. As the ROV moves to greater depths or distances, the baseline separation becomes small compared to the ROV distance. While accuracy as expressed in distance and angular resolution stays the same, a given angular resolution translates to a larger spatial uncertainty at greater distance.

Therefore, in the 2009 season, we used the Southstar long baseline (LBL) acoustic positioning system (Figure 5), also developed by Desert Star Systems. The system was optimized to meet SCINI's principal mission requirements:

- Reliable operation in complex underwater environments, including the presence of ice structures and terrain that can shield the acoustic line-of-sight and cause extensive multipath propagation or reverberations.
- Accuracy of better than 1 m to support photo-transects and return to specific sites, such as a sea-floor organism.
- Small and rugged package, suitable for helicopter, tracked vehicle and sled based deployments.

Unlike common LBL systems that employ transponders, Southstar uses a small pinger with a high-precision clock on SCINI. The pinger's clock is synchronized to the GPS timing signal prior to deployment. The pinger's

signals are received by baseline stations placed around the periphery of the survey site. Each baseline station includes a small underwater acoustic transceiver that can receive SCINI's ping, cabled through the ice to a topside unit that includes a GPS timing receiver and a radio modem to transmit ping descriptors and other information to the control station. As the small pinger on SCINI pings at the top of each GPS second, the signal is received by each baseline station after a delay corresponding to its distance from the vehicle. The method results in a position fix nominally once per second, the default transmit rate of the pinger. Ping reception at any three of the four baseline stations is sufficient to obtain a position, with the built-in redundancy yielding vehicle positions even if a baseline station is shielded by terrain. The use of pingers instead of transponder technology means that positioning accuracy is not degraded by vehicle speed. The short, 4 ms pings provide a position reference for that moment in time, as compared to transponder systems where signals are bounced

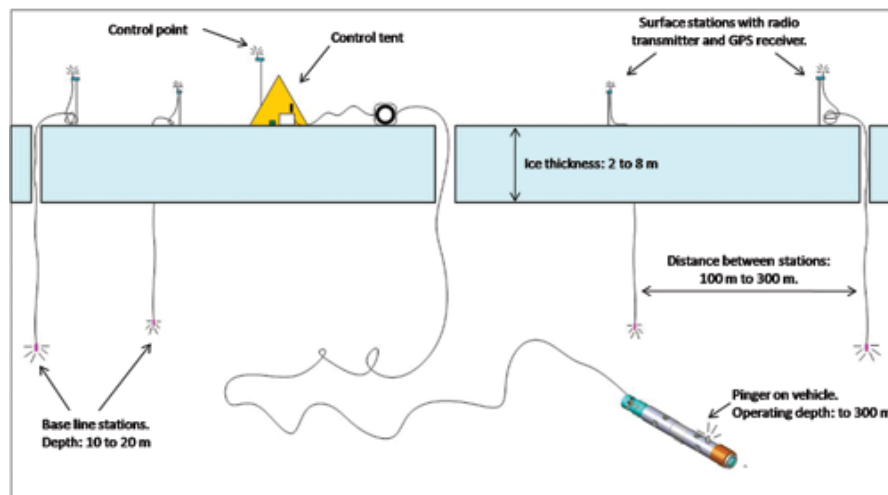


Figure 5: Southstar navigation system configuration. The signals of a small pinger mounted on SCINI are received by the acoustic transceiver of each baseline station. Both the pinger and the baseline stations are synchronized to the GPS timing signal, so that ping time-of-arrival at a baseline stations relative to the GPS timing signal corresponds directly to SCINI's distance from that station. The baseline stations relay the ping information via an integrated radio modem to the control tent, where the vehicle position is computed and displayed.

back and forth and vehicle motion over the length of the transponder cycle can result in a speed dependent position error. Finally, Southstar includes an acoustic self-survey capability that quickly measures relative baseline station positions in lieu of a more time consuming differential GPS survey.

Southstar's ranging precision is approximately 0.015 m. Various factors come into play to obtain the actual positioning error. These include the baseline survey error, sound speed estimation accuracy, depth sensing accuracy, baseline geometry, etc. While discussion of these factors is beyond the scope of this article, computations predict a total horizontal positioning accuracy of around 0.37 m within a 300 m radius operating area (after synchronization of the pinger's clock and assuming the transducers are fixed).

DEPLOYMENT IN ANTARCTICA

Deployment and Survey Methods

SCINI can easily be transported to remote places and deployed rapidly. For survey sites within 30 km of McMurdo station, tracked vehicles (Pisten Bully or Mattrack) were used. All required personnel and equipment can fit in one vehicle with a trailer. The cabin of the vehicle was used as a control room (Figure 6). Short surveys can be done in one day using this method. For survey sites that were inaccessible by surface travel, helicopters were used. All equipment and a team of four people could fit in one Bell 212 helicopter. A small tent was used as a control room (Figure 7). For short surveys or reconnaissance missions, one day deployments with a helicopter are possible when conditions are favourable (easy to drill ice, smooth terrain, etc.), but for more

extensive surveys or more difficult conditions, several days may be necessary. One solution is to set up a field camp, directly on the sea ice or on land nearby. Equipment can be person-hauled using two sledges from the field camp (Figure 12). During a two-week field camp on the sea ice at Bay of Sails, we carried out an extensive survey of the sea floor right at our camp and at several other sites up to 5 km away (detail in **Examples of Surveys**).

Survey sites were chosen depending on the scientific goal, water depth (SCINI can be deployed to a maximum of 300 m) and ice thickness (8 m maximum for Jiffy drills). Once a site had been selected, holes were drilled for deploying SCINI and its navigation system. Using a Jiffy drill (gas power drill, for two operators), drilling one 20 cm hole for SCINI and one to four 15 cm holes for the navigation system took 30 minutes to two hours, depending on ice thickness, ice hardness and distance between the holes. Sea ice is generally no more than a few metres thick. Ice shelves are generally much thicker, but cracks that form thin-bottomed ice canyons or "barrancas" can sometimes be used for deploying. Setting up the control room took approximately 15 minutes when using a vehicle, and 30 minutes when using a tent. The most time consuming task was to setup the navigation system, especially for deep dives, when holes are far apart (up to 300 m). In optimal conditions, the entire system can be set up in less than two hours. In difficult conditions (thick, hard ice, rough terrain, wind, long distance between holes) it can take half a day. SCINI can be deployed by as few as three people, but having five or more speeds up the set up process.

During the 2009 field season, SCINI was



Figure 6: Deployment from McMurdo station. Up to six people and all equipment were transported in a tracked vehicle to sites within driving distance from the station. The cabin of the vehicle was used as the control room. Thanks to SCINI's small size and light weight, one person can easily launch the vehicle.



Figure 7: Deployment from a field camp. The entire SCINI ROV setup weighs less than 350 kg and was person-hauled by three or more people, in two sledges. A small tent was used for the control room.

deployed 37 times in two months. Dives lasted three hours on average and up to five hours. The length of the dives was limited by several factors: hole refreezing, personnel fatigue, and battery life of the navigation system. SCINI runs on a small 1 kW generator that only uses about one litre of gasoline per hour, so fuel is

a minimal issue. Early in the spring, ice holes had to be cleared with the drill every two hours; later in the season, when air temperatures are higher, the holes did not need to be cleared.

Immediately after launch, SCINI was lowered down to the seafloor. Surveys were of three types: search missions, transects, or grid patterns. For search missions, SCINI was flown at up to 2 m above the seafloor and at speeds up to 1 m/s, thereby covering very large areas in little time. For transect and grid patterns, SCINI was generally flown closer to the seafloor (0.5 m to 1 m) and slower (0.1 to 0.5 m/s) to allow the scientist to identify small species and to get enough overlap between each image taken by the downward looking camera to allow mosaicing of sequential images.

Examples of such surveys

are given in **Examples of Surveys**.

Vehicle Behaviour and Results of Field Testing

Unlike most ROVs, SCINI is shaped like a torpedo, which at first seems less than ideal for an ROV. Four seasons of successful testing have shown that this shape can be advantageous

in many situations. In addition to the fact that it allows deployment through a small hole in the ice, it makes for a very efficient vehicle for doing video transects of the sea floor, or for searching large areas. SCINI can travel at 2 m/s (4 knots) in the forward direction, keeping a very straight-line course because of its shape and because the tether is attached in the back. Achieving this with a typical box-shaped ROV is much more difficult. Being able to control the pitch also presents several advantages. First it allows SCINI to look at objects from almost any angle. It also allows SCINI to fly to depth very quickly, which saves a lot of time for deep dives. Several videos of SCINI filmed by a scuba diver during the 2009 field season show SCINI's speed and manoeuvrability; see www.youtube.com.

However, SCINI is relatively unstable on the pitch axis, so hovering and station keeping are more difficult. This problem could be solved by using a more sensitive IMU and appropriate control software. A sudden acceleration of the main propeller causes SCINI to roll, which can result in image blur. This could be solved by using counter-rotating propellers and improved motor control. Pilot training also makes a big difference. The controls on SCINI are very intuitive and a novice pilot could fly SCINI for a survey with only a few hours (even minutes) of training. Tether management is another challenge. SCINI is very light, so it is sensitive to tether pull. Also, with the tether attachment point being far away from the vehicle's centre of mass, tether pull can cause SCINI to change direction.

We found that operating SCINI in current was difficult, and impossible in current speeds over 25 cm/s, especially for deep sites when tether

drag in the water column is significant. Adding a clump weight to the tether made operation at depth or in current much easier. For example, in the case of a dive to 250 m depth, a 10 kg lead weight was attached to the tether, 50 m away from the vehicle. The clump weight was lowered to slightly above the seafloor, giving SCINI a 50 m radius to work within. With this configuration, the survey area is reduced but SCINI's operation is only hindered by water drag on 50 m of tether, instead of 300 m. Fortunately, most of the sites we surveyed had very little to no current.

Field Operations with the Navigation System

For ROVs designed primarily for visual survey and mapping, high navigational accuracy is required. In polar regions a compass or magnetic heading sensor is of little use, particularly in the Ross Sea, which is so close to the magnetic South Pole that the inclination of the magnetic field lines exceeds 80°. Moreover, attempts to use SCINI's IMU as a relative heading sensor proved unsuccessful because of its low resolution. Unable to rely on an instantaneous heading sensor to judge turns and orientation, the SCINI pilot uses the developing navigation trace to follow through turns or keep a straight heading. This demands both a high precision and frequent availability of the position fixes.

Figure 8 shows the navigation display for a typical dive. The developing coverage trace grows darker as SCINI slows down or remains in position. Coverage traces from previous dives can be overlaid, so that a site can be gradually explored over multiple dives. Beyond the current position and the coverage trace, the display also provides position

quality and status indicators. For example, the 'Current Error' displayed at the bottom of Figure 8 indicates how well the range circles of the four baseline stations converge in one spot (SCINI's assumed position). Averaged for one analyzed dive at Bay of Sails (Table 1), this residual position error was 0.27 m, a value close to predicted performance. With quality filters set to a 1 m precision cut-off, the effective position update rate for the analyzed dive averaged at one fix every 1.53 seconds, compared to the theoretical best case of one fix per second. Both the positioning precision and update rate were sufficient to guide SCINI through its tasks as evidenced for example by the transect line plots in Figure 11.

The long baseline navigation system yielded accurate and robust positions. The built-in redundancy of four baseline stations provides a position-quality metric and functions effectively in most shielding situations. The need for only a single ping per position fix yields a high position update rate in the presence of extensive reverberations.

During our 2010 deployment to Antarctica we tested and effectively utilized a Tritech

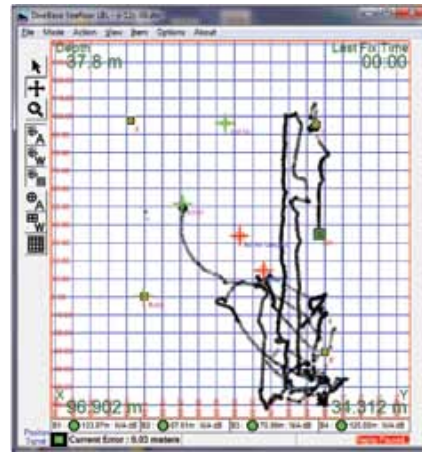


Figure 8: Southstar navigation plot (grid 10 m x 10 m). As SCINI (green square) progresses, it 'paints' a coverage trace that is useful to guide exploration. The baseline stations (yellow squares) are spaced far apart, yielding optimum accuracy throughout the operations area. The Current Error at the bottom of the screen provides an estimate of precision based on an evaluation of the convergence of the multiple acoustic range measurements.

Miconav ultrashort baseline (USBL) navigation system. USBL typically relies on a compass in the dunking transducer head to establish its relationship to the dive site. Since compasses are ineffective in these high latitudes we had to deploy the dunking transducer on a 7-metre collapsible pole that would hold the transducer rigidly on a fixed heading, determined at the surface using GPS. The second limitation was due to the angular error inherent in USBL. The operational

Parameter	Performance
Average position precision (residual error)	0.27 m
Average distance from dive hole (slant range)	102 m (143 m max.)
Depth Range	5-39 m
Dive Duration	2 h 49 min
Number of position fixes with < 1 m precision	6616 fixes (average one fix every 1.53 sec)

Table 1: Summary of Southstar navigation performance on a mission at Bay of Sails.

navigation range was shorter than with the LBL system; however, the combined ease of setup, intuitive user interface, power system reliability, and suitable data output made this the preferred system within our operating parameters.

Examples of Surveys

During the 2009 field season, we worked out of McMurdo Station, Antarctica, to test and refine the scientific research capabilities of SCINI. SCINI was deployed at six sites, and performed extensive surveys at three of them. The depth range was from 30 to 300 m, across seafloor topography that ranged from smooth gentle slopes to irregular boulder-strewn bottoms with relief changes of 1 m depth over 1 m distance. The ability of SCINI to perform detailed observations and assessments of marine habitats and ecosystems well beyond the scuba diving limit of 40 m depth was thoroughly proven.

Knob Point is an area of volcanic cinder cones 7 kilometres from McMurdo Station (Figure 9). The ice cover is fast ice that in November 2009 was 3 to 4 m thick, and had been in place since 2000. Because of the proximity to the station and a maintained ice road, we were able to drive to the site in a tracked vehicle. In six one-day missions, we completed a survey of the area that encompassed water depths from 30 to 280 m. Transects 100 m long were done, at a height of 1 m above bottom, at 10 m depth intervals from 30 to 150 m, and at 50 m intervals from 150 to 300 m, for a total of 16 transects (Figure 10).

At the Bay of Sails, a field site 100 kilometres from McMurdo (Figure 9), the wind and bathymetry contribute to a local buildup of icebergs, which drag across the seafloor leaving swaths of disturbance in their wake. We set up a field camp on the sea ice for six people using helicopter support, and completed

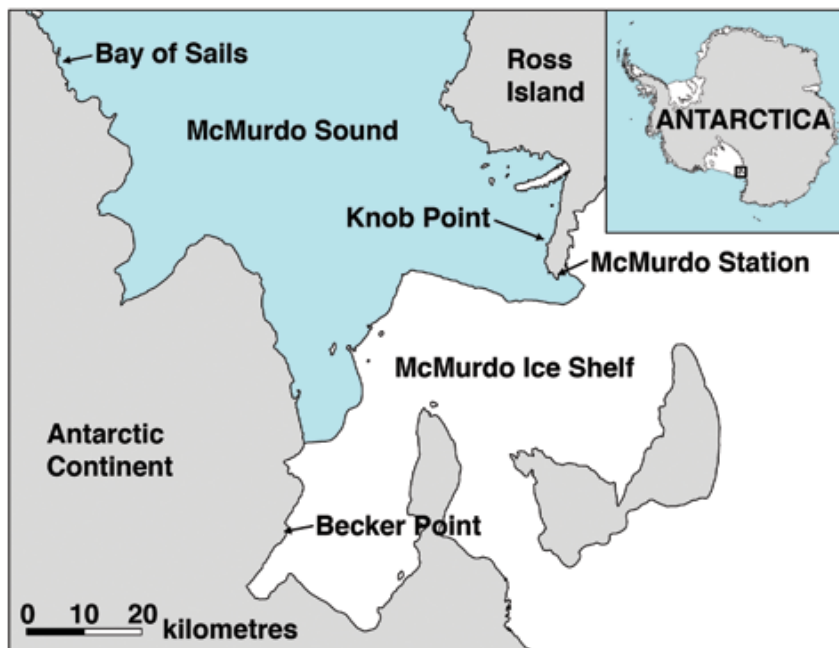


Figure 9: Map of the McMurdo Sound region, Antarctica, showing place names mentioned in the text.

10 ROV missions in 14 days, with two days confined to tents due to weather conditions. Ice thickness ranged from 2 to 3 m, and water depth from 30 to 85 m. We surveyed near four icebergs, at distances up to 4.2 km from the camp, which we reached by person-hauling the entire ROV set up across the relatively smooth ice. The most intensively sampled area was covered by twelve 100 m long transects at approximately 10 m spacing, flown at a height of 1 m above bottom, with water depths varying from 30 to 38 m (Figure 11). We could clearly distinguish areas that had been recently scoured by the iceberg.

A crack through the permanent ice of the McMurdo Ice Shelf reaches the Antarctic continent near Becker Point, 65 km from McMurdo Station (Figure 9). The ice in the crack was less than 8 m thick in places, compared to more than 30 m thick in the surrounding ice shelf, affording ROV access to the seafloor. We again set up a field camp of six people using helicopter support. Late enough in the season for the crack to be thin enough that we could drill through it, the surface ice conditions were also very wet, so the field camp was on dirt. We person-hauled one sledge (275 kg) with two-three people and one sledge (70 kg) with one to two people up to 5 km from the camp across some fairly rough ice to reach the study sites (Figure 12). Surveys of areas from 30 to 130 m water depth were completed in seven missions in 10 days. Three replicate 100 m long transects were conducted at 1 m above



Figure 10: Camera views during the Knob Point transects. The downward looking science camera shows a *Rossella nuda* sponge crowned with *Promachocrinus kerguelensis* feather stars. The red laser dots are 10 cm apart. Inset shows the forward looking pilot camera view with a swimming crinoid in front of the sponge and the perched crinoids that are seen in the downward view a few seconds later.

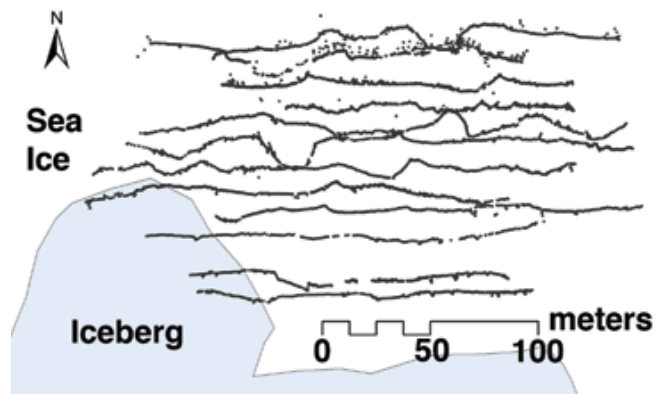


Figure 11: The ROV navigation tracklines from transects surveying the seafloor disturbance near one iceberg in Bay of Sails. Dots off the transect lines indicate bad navigation returns, demonstrating the importance of frequent returns to successfully maintain heading. Iceberg outline at sea ice level was obtained with a handheld GPS unit. The depth of the transects was between 30 m and 38 m.

bottom, at depth intervals of 10 m, for a total of 33 transects.

During the 2011 field season, SCINI was used in collaboration with the ANDRILL drilling project [Andrill, 2011A; 2011B] on the Ross

Ice Shelf. We deployed the ROV into the Ross Sea through a 250 m hole in the ice shelf, and conducted visual inspections of the drill hole and surrounding underside of the Ross Ice

vehicle, or one helicopter, which allows easy and quick access to remote locations that were previously inaccessible to ROVs and unavailable for marine research.



Figure 12: Walking to the survey site from the Becker point field camp. The entire SCINI ROV setup weights less than 350 kg and can be person-hauled by three or more people, on two sledges.

We envision SCINI as one component of a suite of tools now becoming available for polar use. Autonomous underwater vehicles (AUVs) such as AutoSub and Endurance have proven successful in polar missions [Stone et al., 2009; Nicholls et al., 2008]. Gliders have been used off the Peninsula region and in the Ross Sea [Montes-Hugo et al., 2009]. A larger ROV (sub ice ROV) has also been developed for use under the ice shelf [Vogel et al., 2008]. Gliders and AUVs are well suited for surveying large areas.

ROVs like SCINI provide visual data and immediate responsiveness to unexpected conditions or discoveries.

Shelf. A winch and powered cable reel (Model: Contained Cable Reel, Shark Marine Technologies, Inc.) were used to facilitate deployment and recovery operations with a 365 m tether. An active clump weight was used to provide tether stability and increased data throughput.

CONCLUSION, FUTURE DEVELOPMENT AND USES

The ROV SCINI fills a need for an initial reconnaissance and research vehicle in ice-covered seas. The vehicle offers a robust, inexpensive tool (approximately \$45,000 USD) to advance polar marine science. The entire system (ROV, tether, computer, tools) and personnel can fit in one tracked or wheeled

In 2011/12, multibeam sonar will be added to SCINI. A parallel project to expand a deep operating SCINI, depth capable to 1000 m, is proceeding with corresponding development of a powered winch deployment and recovery system and improvement of the wireless LBL navigation system prototyped in 2010. Successful hot water drilling technologies will allow SCINI to be deployed through hundreds of metres of ice [Bentley et al., 2009], giving access to previously unexplored environments.

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