Development of a Borehole Deployable Remotely Operated Vehicle for Investigation of Sub-Ice Aquatic Environments

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***Abstract*— Investigation of sub-ice aquatic environments on Earth requires highly specialized methods. While ice offers a convenient stable platform for deployment of remotely operated vehicles, tethered vehicles with traditional cuboid form-factors require large diameter holes through the ice that would necessitate impractical logistics for ice-drilling support. Access beneath the front of an ice shelf edge is possible with traditional ship deployed underwater vehicles, however the operational range is generally limited, and exploring the water column towards the grounding zone of larger ice shelves involves distances of hundreds of kilometers, which is beyond the effective range of current autonomous or tethered systems. Many such sub-ice environments are found on and around the continent of Antarctica but only a handful of underwater vehicles have been successfully used in Antarctica to date, which has limited the extent of scientific investigation in these restricted environments. Borehole vehicles have been successfully demonstrated in the past, and we describe here a significant improvement on their past depth and sensorial capability.**

Keywords—ROV; Antarctica; subglacial lake; grounding zone; ice shelf; astrobiology; SCINI; Deep-SCINI; marine robotics;

I. Introduction

Investigation of sub-ice aquatic environments on Earth requires highly specialized methods. While ice offers a convenient stable platform for deployment of remotely operated vehicles (ROVs), tethered vehicles with traditional cuboid form factors require large diameter holes through the ice that would necessitate impractical logistics for ice-drilling support. Access beneath the front of an ice shelf edge is possible with traditional ship deployed underwater vehicles, however the operational range is generally limited, and exploring the water column towards the grounding zone of larger ice shelves involves distances of hundreds of kilometers, which is beyond the effective range of current autonomous or tethered systems. In addition to large ice shelves, over 300 subglacial lakes have been identified on the continent of Antarctica [1], which are also inaccessible by these methods. Small diameter borehole deployable vehicles offer a potential solution to access these areas.

To date, only a handful of underwater vehicles have been successfully used in Antarctica, which has limited the extent of scientific investigation in these restricted environments. Borehole vehicles deployed through sea ice have been successfully demonstrated in the past, e.g. the Submersible Capable of under Ice Navigation and Imaging (SCINI) shown in Figure 1. This 15 cm diameter, 300m depth rated observation ROV contains two cameras and has been used in Antarctica since 2007 [2]. This ROV became the first vehicle to deploy through an ice shelf >250m thick in 2010. During this deployment, the operators discovered an inverted benthic community living on the underside of the ice, dominated by ice burrowing sea anemones [3]. This discovery was made near the front edge of the Ross Ice Shelf (RIS), however ice thickness increases rapidly towards the grounding zone, reaching >750m, making SCINI unusable for exploration in these areas due to its depth limitation.

Ice covered oceans also exist across our solar system, including several icy moons which contain many times the volume of water on Earth. These moons represent intriguing targets for the search for life beyond Earth. For this reason, the National Aeronautics and Space Administration (NASA) Astrobiology Science and Technology for Exploring Planets (ASTEP) program funded the Sub-Ice Marine and PLanetary analog Ecosystems project (SIMPLE), which included development of a small, deeper diving borehole-deployable vehicle to further expand the footprint of investigations into sub-ice environments, while also potentially reducing logistical demands.

The resulting vehicle, named Deep-Submersible Capable of under-Ice Navigation and Imaging (Deep-SCINI), is a highly reconfigurable 2000m depth-capable, <25cm diameter ROV suitable for observation and light intervention through the ice, in the water column, or at the seafloor under any ice shelf in Antarctica and potentially into many subglacial lakes.

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Fig. 1. [Figure 1] Top: CAD model of SCINI [2]. Bottom: Image take under the edge of the Ross Ice Shelf showing many *Edwardsiella andrillae* - an ice-burrowing sea anemone discovered in 2010 [3].

Depending on its intended science payload and available in-field support, the new vehicle can be as little as 120cm long and light (<20kg), or up to several meters long and heavy (>100kg) to meet the needs of various missions.

The development cycle for this vehicle provided a synergy with the National Science Foundation (NSF) funded Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project, which was planning to drill an access hole near the grounding line of the Ross Ice Shelf (RIS). A clean hot water drill system was used to penetrate over 740m of ice, in order to investigate water column properties at a distance of over 800km from the front of the ice shelf edge. Deep-SCINI was successfully deployed at this location, providing scientists with a detailed inspection of an ice shelf grounding zone, including high resolution images of the sediment-laden borehole wall for geologists and glaciologists, as well as the first glimpse of a new biological community.

This paper serves to describe the science motivation and logistical framework behind the design of the Deep-SCINI vehicle as well as some results from its first in-field deployments.

II. Background

A. *SIMPLE Project Background & Requirements*

The Sub-Ice Marine and PLanetary analog Ecosystems (SIMPLE) project is an interdisciplinary science effort aimed at exploring previously inaccessible regions below permanent ice cover (e.g., ice shelves and ice sheets) in Antarctica. For many reasons, these areas represent the best Earth-based analog for extra-terrestrial ice-covered oceans on moons in our solar system such as Enceladus and Europa. The project seeks to better understand the connection between the ice-ocean interface and its influences on habitability, climate change, sea level rise and the evolution of ice sheets. Data gathered will provide increased spatial resolution for modeling of ice-sheet dynamics and a ground truth for an ice-penetrating radar system which has recently been selected for a Europa flyby mission. In addition, the project is expanding the technological foundation for future Europa lander missions.

The SIMPLE project provided research and development funding for Deep-SCINI. As proposed, the vehicle is required to:

- Deploy through a small (~30cm) bore hole
- Deploy without the use of a crane (manageable by two people for low logistics field deployments).
- Be depth qualified to 1000msw (minimum)
- Implement a light weight gripper/manipulator to conduct simple tasks
- Be easily expandable for future instrumentation and/or sensor packages
- Cost under $37,500 (excludes tether/winch and acoustic navigation, as well as instrument packages)

Other design goals include increasing the available system power for manipulation and light intervention, and increasing sampling capacities beyond imaging. In addition, an effort was made to improve vehicle simplicity, reliability, and field serviceability, all of which are of paramount importance when operating in remote regions of Antarctica.

B. *WISSARD Project Background & Requirements*

The Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project is an, integrated, interdisciplinary effort brought about by the merger of three separate, but interrelated subprojects that were proposed to the Antarctic Integrated System Science (AISS) program in the Polar Programs Division, Geosciences Directorate of the U.S. National Science Foundation. The three subprojects were (1) Lake and Ice Stream Subglacial Access Research Drilling (LISSARD), which focused on how active subglacial lakes control temporal variability of ice stream dynamics and mass balance; (2) Robotic Access to Grounding-zones for Exploration and Science (RAGES), which focused on ice stream grounding zones; and, (3) Geomicrobiology of Antarctic Subglacial Environments (GBASE), which focused on microbial metabolic and phylogenetic diversity and associated biogeochemical processes linking subglacial lakes and grounding zone environments [4,5]. The WISSARD project sought to conduct an integrated assessment of how water beneath an Antarctic ice stream interacting with the ocean beneath the Ross Ice Shelf influences complex glaciological, geological, microbiological, geochemical, hydrological, and oceanographic systems.

Geophysical surveys were conducted to identify potential drilling sites at subglacial lake Whillans (SLW) [6] and the grounding zone [7,8]. The WISSARD project scientists wanted to use a combination of geophysical, chemical, geological and biogeochemical/genomic measurements to address questions about ice stream dynamics and mass balance, marine ice shelf stability, metabolic and phylogenetic biodiversity, and the biogeochemical transformation of major nutrients within subglacial environments [5].

In the austral summer of 2012-2013, the WISSSARD project drilled into SLW. Access was achieved using a, clean-access hot water drill specially designed for the project [9,10,11]. A number of scientific instruments were deployed including a CTD, Niskin water samplers, an in situ filtration unit, sediment corers, a geothermal probe, and a geophysical sensor string. Data from these instruments verified existence of the subglacial cavity and provided an important ground truth for ice-penetrating radar and seismic data. Additionally, CTD casts and sediment samples have provided valuable information for glacial modeling [12], and water samples led to the discovery and characterization of a unique subglacial microbial community [13,14]. Science results from this mission are being actively published.

Deep-SCINI ROV development began after the successful access of SLW. The vehicle was added to the project for the subsequent access to the RIS grounding zone in the austral summer of 2014-2015. The WISSARD project science objectives required that the Deep-SCINI vehicle:

- Provide visual inspection of the borehole walls, bottom side of the ice-shelf, and the ocean floor
- Perform conductivity, temperature and depth measurements
- Withstand hydrogen peroxide spray for microbial decontamination

In addition, due to project timeline and budget constraints, the vehicle was required to integrate with an existing heavy armored tether and winch system for deployment (provided by Northern Illinois University, designed by DOER Marine™ for the WISSARD project). This provided subsea data and power to an active clump weight via single mode fiber optic line and high voltage copper pair. Deep-SCINI connects to this subsea equipment using a light weight neutral buoyancy maneuvering tether containing a single copper pair to transmit power and data.

III. Deep-SCINI System Design

Deep-SCINI is designed to be highly modular and reconfigurable, as such there is no single form factor. For convenience we will focus on the configuration, as successfully deployed at the Ross Ice Shelf grounding zone in January 2015, which was two meters long, 35kg (in air), and contained three HD camera systems with LED lighting, as well as a one degree of freedom grabbing manipulator, a variable trim system, 2x 100ml samplers, a suctioning filter sampler, and conductivity, temperature and depth sensors. Figure 2 shows a diagram of the vehicle, and Table 1 contains some relevant Deep-SCINI specifications.

Fig. 2. A CAD model of Deep-SCINI

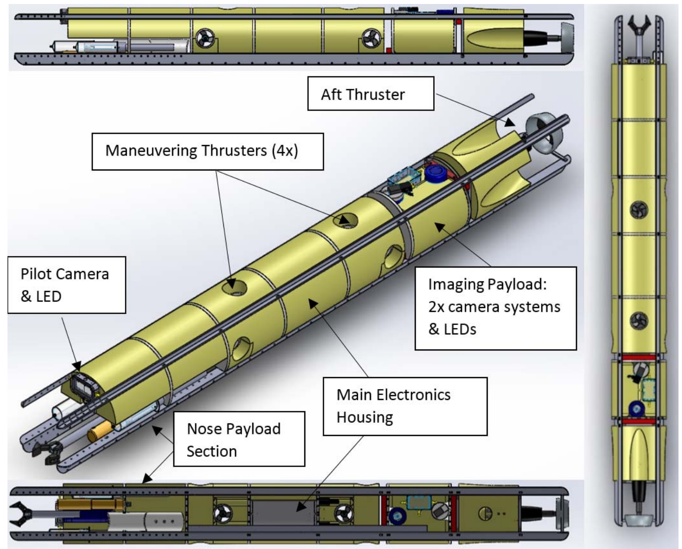


TABLE I. Specifications of Deep-SCINI

Deep-SCINI Specifications		
Performance	Depth rating	2000m
	Range	400m radius from borehole (2km+ via planned fiber-optic tether system)
	Aux Payload	5kg+ (depending on configuration)
Physical	Dimensions	23cm Diameter, 2m length (depending on configuration)
	Weight	35kg (in air, depending on configuration)
	Variable Trim	30 degrees of pitch adjustment
Navigation	Acoustic	Desert Star Systems - South Star LBL, 1km range
Imaging	Optical	3x Elphel NC353L-369, Full HD video (1080p@25fps), 5Mpix stills @14fps
Sampling	Slurp	2cm diameter suction sampler with 300ml tank
	Liquid	2x 100ml syringe-style water samplers
	Grip	force feed back 1 degree of freedom gripper, 7.5cm wide jaw
Sensing	Chemical	Valeport™ Mini CT
	Physical	Keller™ 20d Depth Sensor
Power	Wattage	660W (expandable in 330W increments)

A. *Mechanical Design*

The physical design of Deep-SCINI includes an open bay at the nose of the vehicle to provide space for instrumentation (nose payload section, shown labeled in Figure 2). The lower portion of the vehicle contains a 14cm wide by 5cm deep enclosed area which runs the length of the vehicle, providing a convenient cable storage and routing area. This area also houses a 1.4kg trim weight, capable of adjusting pitch angle by up to 30 degrees, useful for piloting and for quickly trimming when changing between payloads of different weights.

In addition, larger instruments can be added inline by extending the length of the vehicle and adding syntactic foam floatation blocks of a standardized geometry. Deep-SCINI uses four pieces of standard 6061 aluminum angle which run along the major axis and are drilled with a simple slotted-hole pattern to allow flexible mounting configurations. The total material cost is under $50US and machining can be done on a manual end mill or drill press, hence longer (or shorter) configurations can be created at minimal expense, and even in the field. The metal structure extends past the forward camera and instrumentation to protect against impact, specifically, ice layers which can rapidly build up at the air-water interface near the top of a borehole [12]. Impact with this ice layer is partially responsible for the failure of a smaller ROV, which attempted deployment at SLW in the 2012/2013 Antarctic Summer season [15]. The aft section of Deep-SCINI's metal frame also protects the aft propeller and Kort nozzle, important during vehicle retrieval as the vehicle is pulled back into the borehole around sharp ice and debris.

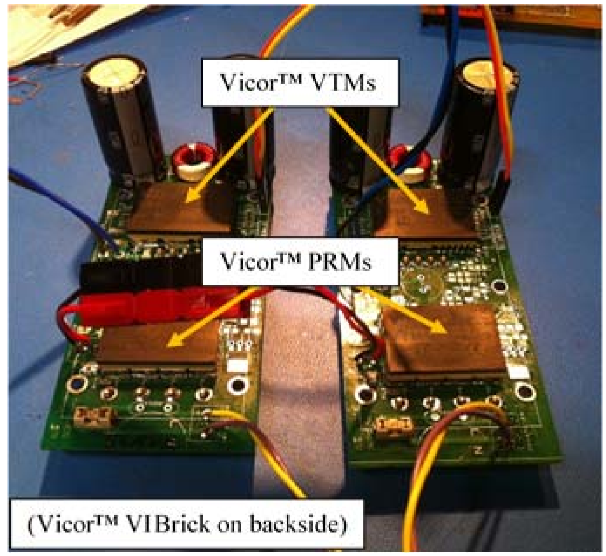
The metal frame is joined using stainless steel fasteners threaded into polymer discs of 1 cm thickness acetal-resin, used for its durability in cold temperatures, high degree of machinability, and because it does not contribute to galvanic corrosion. This feature becomes important during subglacial access, where current clean entry methods require spraying the vehicle with hydrogen peroxide (a strong oxidizer) for microbial decontamination purposes [16]. These polymer discs are located between each vehicle section and provide a convenient mounting surface for most components.

B. *Electrical Design*

Deep-SCINI contains a newly developed high density parallel stacking power supply based on a series of power converting modules produced by Vicor™ on a custom printed circuit board. Each stackable board contains a VIBrick Front End Module which accepts 85-260VAC (continuous) input (supplied from the maneuvering tether) and supplies 48 VDC output, at 330W each. The output of each VIBrick is fed to a VIChip PRM Module located on the same board, which regulates the 48V output and enables current sharing between paralleled outputs of multiple PRMs, at up to 97% efficiency [17]. This is used to power the vehicle's higher current systems such as thrusters and lighting. Each board also contains a secondary landing for a VIChip VTM Current Multiplier, in order to supply various instrumentation voltages 0.65-55VDC. These output voltages, can also be paralleled with managed current sharing between modules.

The configuration of the vehicle as deployed with the WISSARD project, contained two of these boards, supplying 660W of power, (as shown in Figure 3) doubling that of the legacy SCINI system. Up to five boards can be easily stacked in parallel to supply 1650W and by populating a few components, the master board can current balance an unlimited number of slave boards [17], paralleled for extremely high current output for heavier intervention tooling.

Fig. 3. Two paralleled power supply boards supplying 660W total.

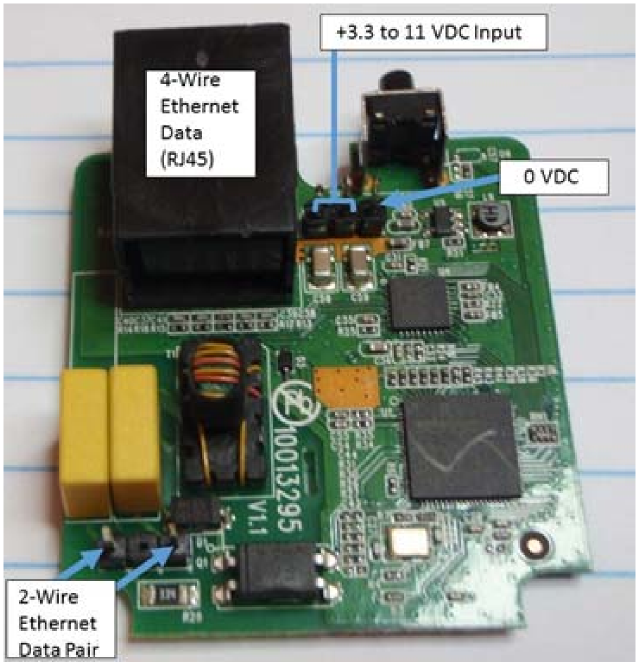


C. *Network Architecture*

The network architecture heavily utilizes distributed Ethernet nodes, using two-wire Ethernet bus technology adapted from off-the-shelf Broadband over PowerLine (BPL) devices (Medialink™ MHP-EA200). This device provides a 5cm square board which transmits ~50Mbps over a point-to-multipoint two-wire Ethernet data bus, reducing the number of pins required in wet mate connectors to transmit Ethernet data, and obviating the need for a bulky subsea Ethernet switch inside of a one atmosphere housing. For safety purposes these devices are modified for transmission over low voltage lines, similar to those used for the tether system of the OpenROV platform, as shown in Figure 4. [18]. The average tested throughput of this network (isolated node to node) is 53 Mbps at 5ms latency over 400 meters of 18ga twisted pair.

Surface-side Ethernet packets are sent from a control computer, across a single mode fiber optic line in the armored WISSARD umbilical, to a subsea pressure housing below the borehole. In this housing, data is converted to transmit over a single copper pair, via a BPL device, up to 400m through the maneuvering tether. This bus is connected to a BPL board in each camera module. The camera systems themselves, function as Ethernet to USB, I2C, RS232, or RS485 data converters (depending on the addressed port and IP address), in order to communicate with various distributed microcontrollers in a call/response manner. Lower bandwidth instrumentation such as the vehicle water samplers or conductivity and temperature sensors are primarily implemented using individually addressed serial nodes communicating over several RS485 buses. Serial syntax is primarily handled using VideoRay™ PRO4 (version 1.05) which provides a robust addressing header and packet checksums for communicating on a busy serial bus.

Fig. 4. A low voltage modified BTP device [18].



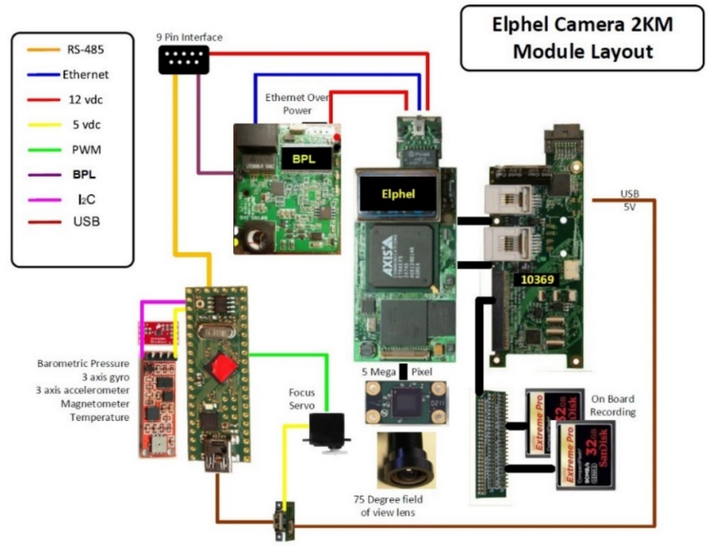
The RS485 and Ethernet data bus technology, when combined with stacking hermaphroditic wet mate connectors (courtesy of VideoRay™), provides rapid instrument reconfiguration without the need to access a junction box or one atmosphere housing.

D. Imaging System

A custom camera system was designed to meet the space requirements and provide desired network flexibly. Figure 5 shows a power and data diagram for this system, which is based around the Elphel™ NC353L-369, an entirely open source hardware and software camera platform. This camera hosts a local Linux based web server to send video and images over Ethernet, thus a low voltage modified BPL device is added to the board stack to allow this module to communicate with the Ethernet bus. The camera produces full HD 1080p (1920x1088) video at 25.2 frames per second (fps), and can also take 5MPix images at 14fps. Bandwidth usage of the camera is reduced by performing onboard .jpeg compression of images prior to transmission. The total surface side delay experienced from this process is <200ms, which has proven adequate for piloting.

This platform offers an accessory board (part number 10369), which provides local compact flash storage and a hardware driven multi-camera image synchronization pulse. This is useful for creating a 3D piloting experience, photogrammetry measurement applications, and structure-from-motion point cloud generation for 3D modeling of objects. This accessory board also provides, four USB data ports, allowing the camera to serve as an Ethernet-USB media converter for communicating with local sensors. One USB Port is connected to a Crumb™ 644 V1.1 board, measuring only 5cm by 2cm, containing an Atmel™ ATmega644P.

Fig. 5. Power and data diagram for camera module.



This microprocessor provides two UARTS, and the board contains a USB FTDI chip, and an RS485 transceiver chip. This hardware stack enables a communication path for the camera module to act as an Ethernet-to-USB/RS485/RS232/I2C converter for vehicle control and sensing. The Crumb™ board is also used to communicate (via I2C through a 5V to 3V level shifter) with a local Geeetech™ model 610027008158 inertial measurement unit(IMU) containing a 3-axis accelerometer, 3-axis gyro, 3-axis magnetometer, and (internal) pressure and temperature sensors, to provide navigation aids and for diagnostic information.

A focus mechanism was designed for this system using the Hitec™ HS-35HD Ultra Nano servo to drive the mechanism, which provides ample torque (0.8 kg.cm) and measures only 26x20x8mm. The servo is controlled via pulse width modulation (PWM) signals generated by the Crumb™ 644 board.

The nested board stack fits into a 5.5cm diameter by 15cm long internal volume. The Sexton Corporation™, a manufacturer of custom underwater housings, was contracted for design input and manufacturing of the housing and board trays. The tray assembly attaches to the end-cap using radial slots, enabling 360 degree rotation of the image sensor relative to the right angle wet mate connector bulkhead. The pressure vessel itself is made of anodized 6061-T6 Aluminum, with a 3mm thick sapphire window, and a low profile nine pin connector (Impulse™ LPBH9). The end result measures 6.5cm diameter by 20cm long and weighs approximately 0.5kg in water.

IV. WISSARD DEPLOYMENT

In the austral summer of 2014-15, the WISSARD project drilled into the Ross Ice Shelf near the suspected grounding zone and outlet water path of Subglacial Lake Whillans, whereby Deep-SCINI succesfully flew an 8 hour dive, without insurmountable problems and completed the deliverables assigned. The vehicle demonstrated it could be assembled and deployed easily in the field with only two trained technicians, and operated in low-logistics field camp scenarios. Figure 6 shows an image of the vehicle being carried by two people at the WISSARD field camp.

Unexpectedly, a variety of macrofauna were observed at the grounding zone, over 800 kilometers from open water. A number of small translucent fish were observed (see Figure 7), as well as other life currently being identified by project biologists in preparation for future publication. Notably, there was no evidence of stationary benthic life (e.g. sponges, anemones, etc.). This is attributed to the constant sediment rain-out observed, caused by melting of the base of the ice shelf. This falling sediment varies in size and could rapidly burry or destroy any creatures without adequate mobility. Deep-SCINI performed its required imaging and sampling tasks, and was succesfully recovered at the end of its dive. Total deck time for setup and teardown was approximately four hours, however this could be reduced with some minor modifications and deployment practice.

Fig. 6. Deep-SCINI is carried by two people at the WISSARD field camp.

Fig. 7. A fish is observed living in 750m of water near the Ross Ice Shelf grounding zone.

V. Conclusion

A borehole deployable vehicle has been developed and successfully demonstrated near the grounding zone of the Ross Ice Shelf in Antarctica. The configuration, as flown, was 2.1 meters long, 35kg in air and 660W powered. On board were three HD camera systems with LED lighting, as well as a one degree of freedom grabbing manipulator, conductivity, temperature, and depth sensors, a variable trim system, 2x 100ml syringe-style water sampler, and a suctioning filter sampler.

The Deep-SCINI vehicle is a highly reconfigurable, 2-km-depth capable, <25cm diameter ROV suitable for observation and light intervention though the ice, in the water column, or at the seafloor under any ice shelf in Antarctica and potentially many subglacial lakes. Depending on its intended science payload and available in-field support, the new vehicle can be as little as 120cm long and light (<20kg), or up to several meters long and heavy (>100kg) to meet the needs of various missions. The vehicle power supply can also be expanded to 1.6 kW or more for heavier intervention tooling.

Deep-SCINI has demonstrated its utility as a borehole deployable science vehicle, and is currently being optimized for future potential missions in Antarctica and Greenland.

Acknowledgments

The development of Deep-SCINI was made possible through the multidisciplinary Sub-Ice Marine and PLanetary analog Ecosystems (SIMPLE) research project funded by the National Aeronautics and Space Administration (NASA), Astrobiology Science and Technology for Exploring Planets (ASTEP) program through grant #NNX12AL65G to the Georgia Institute of Technology and a subaward to the University of Nebraska-Lincoln.

The development of Deep-SCINI was further aided by the Marine Technology Society ROV Scholarship Committee, awarding the prestigious first place prize and contributing to education funding of the first author.

The deployment of Deep-SCINI was made possible through the multidisciplinary Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project, funded by the U.S. National Science Foundation, Directorate for Geosciences, Division of Polar Programs (GEO-PLR), Section for Antarctic Sciences, Antarctic Integrated System Science Program, utilizing funding from the American Recovery and Reinvestment Act (ARRA). Additional thanks go to all the WISSARD team members who worked to make this deployment a reality.

The authors would also like to thank VideoRay™ for providing crucial engineering support and consultation during the development process. The success of Deep-SCINI is a reflection of their engineering excellence.

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