Icefin: Redesign and 2017 Antarctic Field Deployment

Matthew Meister, Daniel Dichek, Anthony Spears, Ben Hurwitz, Charles Ramey, Justin Lawrence, Kit Philleo, Josh Lutz, Jade Lawrence, Britney E. Schmidt
Earth and Atmospheric Science Department
Georgia Institute of Technology
Atlanta, Georgia

***Abstract*—Icefin is a custom remotely or autonomously operated vehicle (ROV/AUV) designed for sub-ice deployments in Antarctica with a focus on portability for remote field deployments and modularity to accommodate various payloads to characterize the under-ice environment. A prototype iteration of the vehicle was deployed in McMurdo, Antarctica in 2014 and provided data as well as valuable lessons learned. Since then the vehicle has been refined significantly into a more capable and reliable platform that was deployed during the 2017 austral summer Antarctic season (October 2017 - December 2017). Presented here is an overview of the design updates, including mechanical, electrical and software changes that were incorporated in developing the baseline Icefin platform. Also presented are lessons learned and early results from the 2017 deployment of the redesigned vehicle, as well as changes integrated into the vehicle for its 2018 field season.**

Keywords—under-ice; unmanned; autonomous; underwater; ROV; AUV; UUV; Antarctica

I. Introduction

Europa, the innermost ocean world of the Galilean system, has become a key target in the search for life outside of planet Earth. Due to the increased interest in Europa by the scientific community, the past decade has seen the development of deep space robotic platforms to explore this as yet unknown environment. Probing Europa's unique environment poses many challenges, some of which can be satisfied with current satellite technology, such as Europa Clipper, but others will prove to be more demanding. Under Europa's icy outer layer lies a salty ocean environment, and it is extremely challenging to gather scientific data to characterize the environment beneath the ice remotely. Robotic probes capable of penetrating the ice and operating autonomously will be required to characterize the ice shell and ocean and eventually search for life. Fortunately, the Ross Ice Shelf, the largest ice shelf in Antarctica, can be used as a terrestrial test bed to validate these platforms. In this way, such technologies targeted to icy bodies can also further the understanding of our ice shelves here on Earth. Icefin (Figure 1) is a modular, remotely and autonomously operated underwater vehicle (ROV/AUV), and designed with a focus on portability and streamlined operations for remote field deployment, as well as modularity to accommodate various payloads to characterize the under-ice environment as science questions change and evolve.

In 2014 a prototype version [2] of the vehicle was built and tested in McMurdo Station and provided valuable data and lessons learned. The first version of the vehicle was successful in demonstrating the promise of the robotic platform, and provided a foundation for further refinement and development. The 2014 season saw several short test runs under sea ice near McMurdo station, and a single deployment through the McMurdo Ice shelf, amassing approximately 12 hours under the ice. Following operations in 2014, post analysis identified key areas for development and significant design changes for the 2017 season under the NASA-funded Ross Ice Shelf and Europa Underwater Probe program (RISE-UP, PI Schmidt). In addition to high-level engineering changes, new science sensors were integrated into the 2017 science payload. These new sensors further pushed the engineering design to optimize each module for specific missions while keeping portability and reliability of the vehicle in mind.

The vehicle was deployed under the sea ice, Erebus Glacier Tongue, and McMurdo Ice shelf from late October to early December 2017. Weather delays prevented its deployment through the Ross Ice Shelf planned for mid-late

Fig. 1. Exploded assembly view of 2017 Icefin CAD

December 2017, despite all vehicle and science systems being fully operational and ready for the task. Icefin conducted 12 under-ice missions in all over the 2017 season, corresponding to 42 hours under the ice. The maximum operating depth in these missions was 800m at its deepest environment, encountered during its 12th under-ice dive of the season. Both longest horizontal leg distance of 2 km, and longest accumulated distance under ice of approximately 5 km was encountered in its 11th dive. The vehicle was operated in both seafloor (with sensors oriented downward relative to neutral pitch) and ice-ocean interface (with sensors oriented upward) configurations for the first time.

II. Mechanical

One of the most significant design drivers for the vehicle is the limitation presented by the maximum diameter of access holes drilled through ice shelves by hot water drills. These access holes typically range from 30-40 cm. With this narrow diameter constraint, a low profile torpedo shape design with no protruding control surfaces was chosen for Icefin. The initial Icefin prototype, fully outfitted with minimal science instruments and syntactic foam, was 25 cm in diameter. While the vehicle diameter was sufficient to fit through some hot water drilled holes in thin parts of the ice shelf, it was not small enough to fit through holes drilled in the sea ice and surface lake ice by mechanical techniques, typically by 10 inch (25 cm) drills. In addition, this diameter leaves little tolerance for necking or variability in ice shelf access shafts through thicker ice. With planned deployments of the vehicle now through up to 1km of ice as well as the desire to remain operationally flexible to future deployments, reducing the vehicle diameter was a high priority during the redesign. Along with the reduced diameter, new science instruments were required for integration into a new module to better characterize the chemical environment of the water. Finally, while flexible orientation was an element of the design process for the prototype vehicle, the original design did not permit changing orientations without loss of scientific instruments, thus optimizing for multiple sensor orientations (upward and downward relative to neutral pitch) were required. These changes resulted in two new vehicle modules and new buoyance and syntactic foam design that would better distribute the weight throughout the vehicle and reduce the overall diameter.

Previously, both the science and navigation instruments were placed in the same physical module, which was ideal for reducing the overall length of the vehicle but with the addition of new instruments and constraints on orientation, two new modules were developed to accommodate the upgraded capability. A navigation module was designed that includes the doppler velocity logger, altimeter and depth sensors, and was moved closer to the tail of the vehicle. This navigation module better distributes the weight of the sensors throughout the vehicle but increased the total length of the vehicle by 30 cm. This increase in length allowed for more syntactic foam to be integrated inside the module and reduced the overall diameter to 23.5 cm and total length of 3.5m. A complete list of physical specifications is listed in Table 1.

With the navigation sensors moved to their own module, the original sensor module on Icefin was reconfigured to be solely a science module containing the side scan sonar and high definition imaging equipment (Figure 2). This reconfiguration of sensors allows Icefin to have a dedicated science module that can be configured for different mission types and allows for new sensors to be added to the vehicle, achieving science modularity for the first time. These new sensors include pH/ORP, turbidity, and colored and

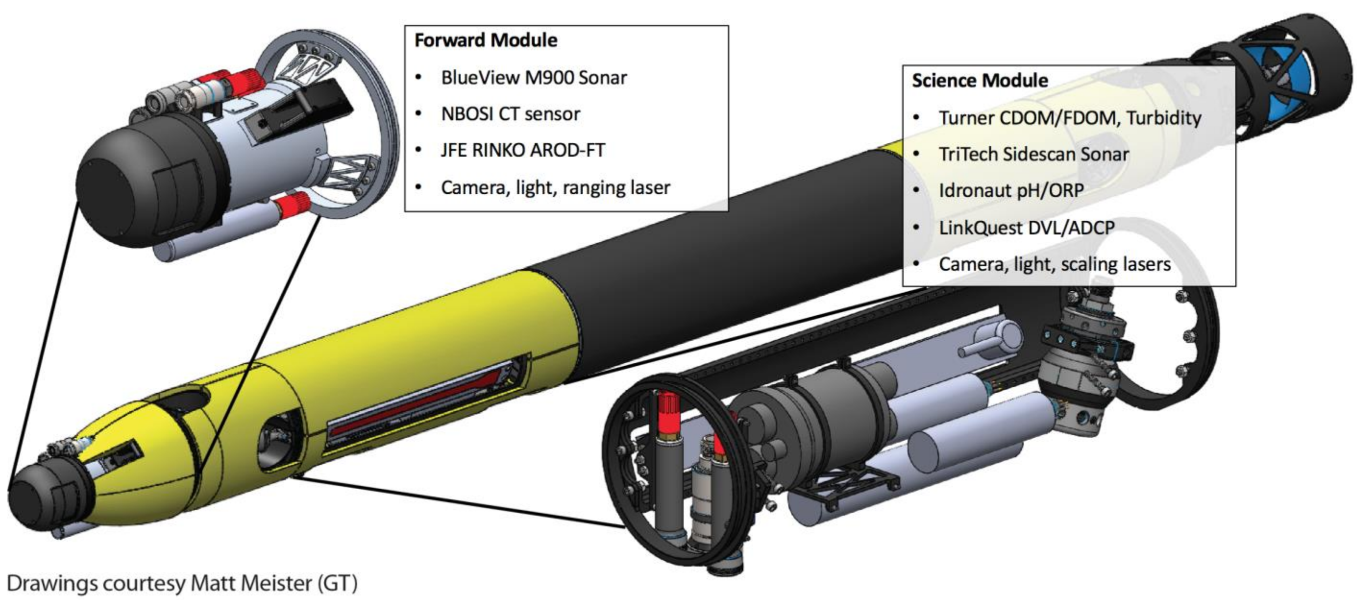

Fig. 2. Exploded assembly view of 2017 Icefin CAD

TABLE I. ICEFIN VEHICLE SPECIFICATIONS

Depth	1000 m
Weight	130 kg
Diameter	23.5 cm
Length	3.5 m
Range	3.5 km
Control	5 DOF

fluorescent dissolved organic matter (CDOM/FDOM)sensors to characterize the chemical characteristics of the under-ice environment. The new sensors are mounted to a bracket that can be easily added or removed from the science module depending on the vehicle mission plan. Like the original design of the sensor module, the new science module can be rotated to point the sensors down towards the ocean floor or up towards the ice interface. A list of sensors that Icefin is capable of carrying are listed in Table 2.

TABLE II. ICEFIN ELECTRONIC COMPONENTS AND SENSORS

System Component	Manufacturer	Part
Forward Looking Sonar	Blueview	M900
Sidescan Sonar	Tritech	SeaKing ROV
Inertial Measurement Unit	KVH	1750 IMU
DVL/ADCP	Link Quest	NavQuest 600
CT Sensor	Neil Brown	G-CT
Dissolved Oxygen	JFE Advantech	RINKO FT Deep
Turbidity	Turner	Cyclops-6K
CDOM/FDOM	Turner	Cyclops-6K
pH/ORP	Idronaut	Ocean Seven 306
Depth	Valeport	miniIPS
Downward Camera	Deepsea Power and Light	HD Multi SeaCam
Forward Camera	Deepsea Power and Light	Nano SeaCam
Onboard Computer	RTD	IDAN Intel-i7
Power/Battery Management	OceanServer	XP-08SR
DC Voltage Regulation	Vicor	DCM
Batteries	Inspired Energy	Ni3020HD25
Tether	Linden Photonics	SPE-7055
Optical Multiplexer	Focal MOOG	907E Mux, HD-SDI

III. INTERNAL ELECTRONICS

The original prototype pressurized electronics housing, carrying vehicle power, controls and communications, was built to withstand depths of up to 2000 m. During the 2014 season numerous issues were encountered with poor thermal management, extreme temperature gradients and inconsistent communications. Solutions to these issues were incorporated into the new architecture to make it more compact, reliable and efficient. A new pressure housing was designed with a reduced operating depth of 1000 m to reduce the total weight of the module with the ability to be configured in a 1500 m variant if necessary. By reducing the operational depth of the housing the internal diameter of the module was increased from 16.5 cm to 20.3 cm which allowed for a new chassis to be built to address the thermal challenges encountered in the prototype. The new chassis is machined from 6061-T6 aluminum and mounted to the face of the forward end cap with increased surface area to improve thermal conductivity between the chassis and pressure housing seen in Figure 3.

One of the first changes made to the new electronics was the addition of a high voltage power bus that increases power distribution efficiency and incorporates commercial-off-the-shelf isolated DC-DC converters to prevent conducted electromagnetic interference in vehicle diagnostic and science data. Multiple custom circuit boards were developed for this system to leverage the powerful power-converter chips and add precise sensing of the power system, a new and necessary ability for better power management of the vehicle to increase mission time. These boards were also designed to withstand the large number of thermal cycles that are encountered with fieldwork in Antarctica where temperatures inside the vehicle can range from -10C before deployment to 85C during a mission. While the new DC-DC converters are more efficient than the previous converters used on the vehicle, most of the new components require large heat sinks to keep the chips from overheating during maximum loads. Since the volume of the pressure housing is largely consumed by batteries and other electronic components, the new chassis was designed to incorporate large surface areas for directly mounting the custom boards (Figure 3). With the chassis mounted to the face of the end cap the components could be cooled using the conduction between the -2C water outside the vehicle and the chassis rather than a small amount of convection provided by the original heat sinks.

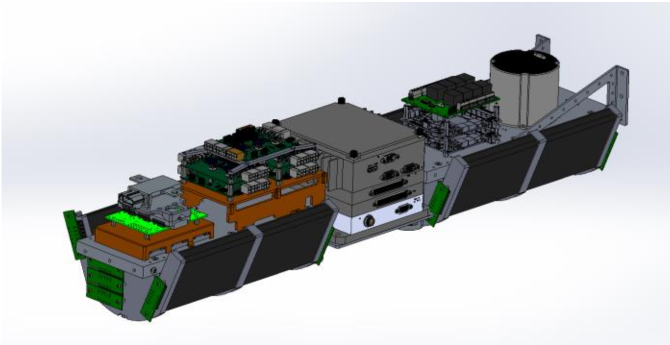

Fig. 3. Detailed CAD view of redesigned internal electronics

The main computer on the vehicle was upgraded from a small single-board computer to a ruggedized Intel-I7-core computer. Critical power system controls were moved to a custom embedded system. The separation of power controls improves vehicle safety by implementing a robust state machine, which eliminates uncertainties encountered in the high-level operating system. To further improve the power efficiency of the vehicle, relays were introduced to power off non-critical devices depending on the vehicle state during a mission. With the addition of new analog sensors in the science module, digitization of the analog signals was improved over the prototype version. Isolated differential amplifiers, anti-aliasing filters and shielded, braided twisted pair wires minimize electrical noise in the collected science data.

IV. Software

For field deployments, topside controls from a portable base station communicate with the onboard computer in the vehicle over a 3.5km fiber optic tether, passing serial data, video feeds, and Ethernet packets between the vehicle and operators. Communications occur using the Lightweight Communications and Marshalling (LCM) [3] protocol, and multicast LCM messages are used both locally on the vehicle as well as across the fiber optic tether.

The replacement of the prototype 2014 vehicle's main computer system both required and enabled changes to the command and control of the vehicle and interaction with onboard instruments. In 2017, the software team implemented changes to interfacing between the current operating platform, Greensea Systems' Balefire, the science sensors and the topside operations to achieve greater visibility into the vehicle state as well as better integration of the science data into vehicle operations. Monitoring high-level tasks, including battery management, was achieved via Python modules that receive and parse RS-232 or RS-422 serial messages, encode them as LCM messages, and broadcast for other software modules to utilize. Interfaces for low-level components were written in C++ to optimize for embedded real-time processing These modules accept data through an I/O or serial interface, encode the data into an LCM message, and then broadcasts the messages over UDP multicast. These changes increase the quality of the scientific return through more streamlined instrument control, as well as interacting with instrument data during missions to enable mission optimization.

New modules to interface with increased onboard sensing, including temperature and humidity sensors, updated imaging and sonar acquisition, and new custom science instruments are integrated into the 2018 software environment. Testing of autonomous operations enabled by the upgraded Balefire-Icefin interfaces commenced during operational testing in 2018 prior to Antarctic deployment. Updated communication between custom developed Python navigation modules and Balefire will enable autonomous missions in 2018. Future work includes developing bridges between LCM and the ROS and MOOS controls architectures to move toward fully autonomous vehicle controls. More complete details of the software redesign can be found in Ramey et al 2018 (OCEANS) and Spears et al 2018 (AUVSI).

V. Field Deployment

Icefin was deployed in the sea ice off McMurdo Station (Figure 4) funded by the current NASA PSTAR Ross Ice Shelf and Europa Underwater Probe (RISEUP) program. The primary objective of the program is to study the glaciology and oceanography of Antarctica's largest ice shelf, the Ross Ice Shelf, to gain a better understanding of ice-water interaction here on Earth and use those insights to further our understanding of the ice shell of Jupiter's moon Europa. The program also collaborates with the New Zealand Antarctic Program's Ross Ice Shelf Program (RISP) which provides hot water drill (HWD) access under the Ross Ice Shelf as well as field camp logistics in the 2017 and 2019 field seasons.

Initial dives were completed at a field site located close to the ice shelf edge, between Black Island and McMurdo Station. This field site was chosen for the initial vehicle dives because of its proximity to the edge of the McMurdo Ice Shelf, which was approximately 800 meters away from the basecamp. After initial vehicle checkout dives, three final dives were completed using a new launch and recovery system (LARS) that is designed to lift Icefin vertically over a mechanically drilled hole and lowered through the sea ice near the Erebus Glacier Tongue and just north of Scott Base.

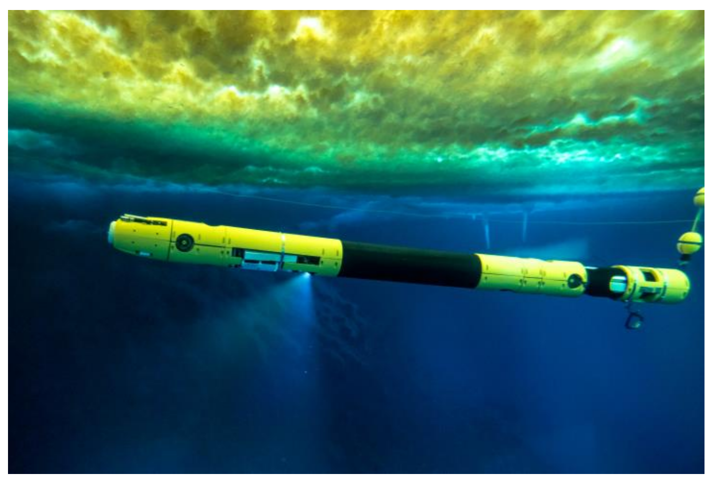

Fig. 4. Icefin under sea ice off McMurdo Station

VI. Conclusion and Future Work

Icefin completed 12 successful dives over the 2017 season, amassing over 41 hours under the ice, reaching a maximum depth of 800 meters in its final dive and completed a 2km track under the McMurdo Ice Shelf. All of the dives during the 2017 season provided valuable datasets for both the science and engineering teams to further optimize the vehicle design and improve mission planning. Many lessons were learned during the 2017 field season and are being carried into the update of the vehicle for the upcoming 2018 field season. Two new sensors will be integrated into Icefin for 2018 including a new forward imaging system with the ability to record 4K video and capture high resolution stills as well as a new upward facing altimeter to characterize the ice thickness as Icefin begins to map ice shelf grounding line conditions.

ACKNOWLEDGMENT

The authors would like to thank the School of Earth and Atmospheric Sciences for the resources provided to conduct this work, including funds for the development of the 2014 prototype and recent updates. Deployment was funded under the RISEUP project, NASA PSTAR grant NNX16AL07G, with principal investigator B.E. Schmidt. RISEUP deployed under the National Science Foundation (NSF) and the United States Antarctic Program (USAP) Event B-041M.

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