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TITLE

THE THESEUS AUTONOMOUS UNDERWATER VEHICLE

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The Theseus Autonomous Underwater Vehicle

A Canadian Success Story

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***Abstract*- Over the past five years, International Submarine Engineering Research and the Esquimalt Defence Research Detachment of the Defence Research Establishment Atlantic have worked together to develop a large autonomous underwater vehicle, named Theseus, for laying optical fiber cables in ice-covered waters. In trials and missions conducted in 1996, this vehicle showed impressive capabilities. It was able to lay a fiber-optic cable in a completely autonomous mode for a distance of 200 km under Arctic sea-ice and then return to the launch station for recovery. It demonstrated a navigational error of less than 0.5% of the distance traveled, and cross-track error was reducible to 0.05%. It operates in either depth-keeping mode or bottom-following mode, was designed to operate at a maximum depth of 1000 m, and has operated at a depth of 425 m.**

The vehicle is equipped with an inertial navigation unit and Doppler sonar speed sensor for autonomous navigation, a forward-looking obstacle avoidance sonar, an acoustic homing system, and acoustic transponders for use with surface tracking stations. An acoustic telemetry system enables communication with Theseus from surface stations, and an optical telemetry system is used for system monitoring while Theseus is laying optical fiber cable. All sub-systems are controlled by an M68030 based sensor integration and control computer.

Although the vehicle is currently configured for cable laying, other missions could be accommodated with minor changes to the payload section of the vehicle. Theseus' qualities of covertness, long endurance and precise navigation make possible such tasks as long base-line oceanographic data collection, remote route surveys, remote mine hunting, the rapid deployment of acoustic and non-acoustic surveillance systems, and even the towing of mobile sensor arrays. Longer missions could be accommodated by replacing the current silver-zinc batteries with fuel cells or other AIP (Air Independent Propulsion) power plants.

The paper describes the vehicle and presents the results of the evaluation trials and its first cable laying mission.

I. INTRODUCTION

Over the past five years, International Submarine Engineering Research and the Esquimalt Defence Research Detachment of Defence Research Establishment Atlantic have worked together to develop a large autonomous underwater vehicle for laying fiber-optic cables in ice-covered waters [1]. The vehicle, named Theseus, was designed to lay up to 220 km of fiber-optic cable from a site near the shore of Ellesmere Island in the Canadian Arctic Islands to a scientific acoustic array in the Arctic Ocean about 200 km from shore. The water depth along the cable route varied from 50 m at the launch site to about 600 m at the array site.

The paper discusses the design objectives of the vehicle, describes the vehicle and presents results of trials in the south and in the Arctic. The suitability of Theseus for other missions is also discussed.

II. VEHICLE DESIGN OBJECTIVES

Both the environment and the complexity of the mission imposed severe constraints on the vehicle design. In the operating area the ocean is completely ice covered, mostly by multi-year ice, 3.5 to 10 m thick, with ice keels that can extend to depths of 30 m within 10 km from the launch site, and 50 m further out; water currents vary from 0 to 25 cm/sec near the launch site and 0 to 10 cm/sec at the array site; air temperatures vary from -40 to -20° C; and water temperatures vary from -1° C in the shallow waters near the launch site to 4° C near the bottom at a depth of 600 m.

An endurance of 450 km was required to lay the cable, return to the launch site and allow a reasonable margin for contingencies. A navigational accuracy of 1% of distance traveled combined with an acoustic terminal homing system was needed to bring the vehicle through a 200 m wide cable recovery loop at the cable delivery site. To minimize the amount of cable in the water column, the AUV was required to follow the bottom at an altitude of 20 to 50 m. To facilitate air transport to the launch site, a modular construction was required, with each section weighing under 1400 kg. Since no currently available AUV could meet these specifications, International Submarine Engineering Research Ltd. of Port Coquitlam B.C. was awarded a contract in November 1992 to design and construct an AUV to meet the requirements.

The development of the vehicle, named Theseus, was carried out in several phases. It was recognized at an early stage that the software control system required to autonomously pilot the vehicle during its mission would be the most difficult aspect of the development. To speed up the process, an existing vehicle named ARCS was used to evaluate many of the software components while the new vehicle's mechanical and electrical design were carried out. ARCS, the Autonomous Remotely Controlled Submersible, had been built by ISER for the Canadian Department of Fisheries and Oceans in 1984.

In addition, it was determined that an obstacle-avoidance sonar (OAS) system would be required to ensure that the vehicle would not crash into uncharted bottom features or into ice keels, which in the mission can extend to a depth of 50 m. Acoustic telemetry was also considered essential for occasional enroute communication with the vehicle. To achieve a navigation accuracy of 1% of distance traveled, a ring laser gyro Inertial Navigation Unit (INU) was selected for heading reference, and a bottom-tracking Doppler sonar for ground speed. Terminal guidance was provided by an ultrashort-base-line acoustic homing system. A provision was included to allow the vehicle to update its position at acoustic beacons located along the route and also at the cable delivery site. Details on the resulting vehicle are provided in the next section.

III. THESEUS DESCRIPTION

A. General

A photograph of Theseus in its Arctic launch tent is shown in Fig. 1 and a cross-section drawing of the Theseus AUV is shown in Fig. 2. The principal characteristics of the vehicle are listed in Table I. A detailed description of the obstacle avoidance sonar, computer control system, and cable dispensing systems is given in the next sections.

B. Obstacle Avoidance Sonar

The vehicle is fitted with a Sonatech Model STA-013-1 forward-looking obstacle avoidance sonar system. This sonar operates at 200 and 230 kHz and projects 20 beams in a 4 by 5 array which cover the region ±9° vertical and ±25° horizontal out to a range of 180 m. A control system was developed to allow the vehicle to autonomously steer over, under or around obstacles, but testing was not completed in time for the Arctic mission [2], [3]. The sonar was monitored on it's own display console in the shore control center during the cable deployment portions of the mission when telemetry to the vehicle was provided over the optical cable. This provided the facility to take manual control action if the sonar had shown need for it.

C. Computer Control System

Overall vehicle operation is managed by an MC68030 computer running Proteus, a real time executive kernel that was developed by ISE Research for AUV control [4], [5], [6]. Proteus is implemented in C++ in an object-oriented fashion with a layered architecture and subsumption, cooperation and supervision hierarchy are included.

One of the fundamental characteristics of Proteus is the ability to reconfigure the control system without modifying the source code. The concept of "scripts" was introduced which are collections of tasks (sequencing components) organized into one or more "steps". Each step in a script may contain any number of "threads" of tasks. Scripts are English-like statements which can be organized by non-programmers to reconfigure the system for a desired sequence of events.

Scripts can be developed to run in parallel at different priority levels, and have many useful operators (verbs). The highest level script is the Mission Plan, a series of mission steps which instruct the vehicle to go from one waypoint to the next, specifying enroute conditions such as depth/altitude, speed, and fault response.

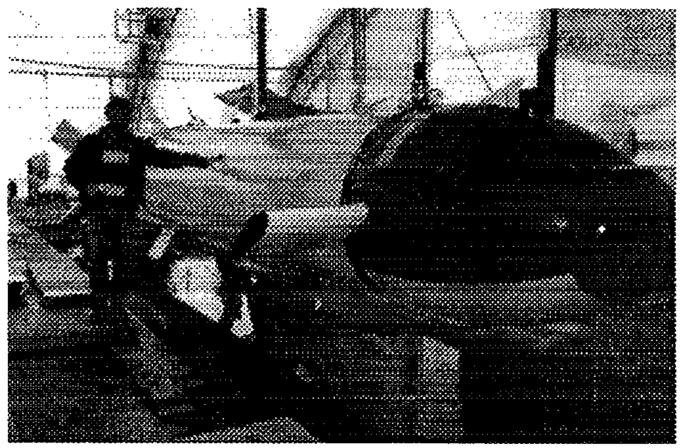

Fig. 1. Theseus ready for launching over Arctic ice hole.

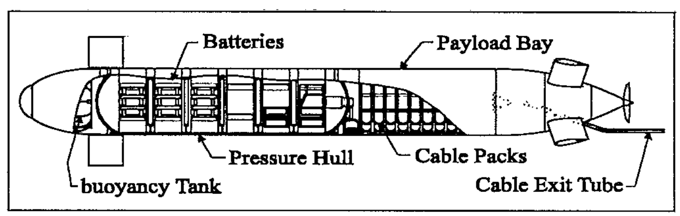

Fig. 2. Theseus schematic (foreplanes, exit tube in plan view, remainder in elevation view)

D. Fault Manager

In order to increase the tolerance to system faults, the control system manages fault responses using a pre-defined fault table. This table allows the user to divide a mission into any number of phases, where a phase consists of one or more manoeuvres between waypoints. Each phase of a mission script has its own series of responses to each of the vehicle faults: a response is either stop up under the ice, stop down to the sea bed, change to another mission step, or ignore the fault. Therefore, a change of phase occurs when the desired response to some fault changes, such as when approaching a manned camp. At this point a new series of entries in the

TABLE I

THESEUS VEHICLE CHARACTERISTICS

Length	10.7 m (35 feet)
Diameter	127 cm (50 inches)
Displacement	8600 kg (19,000 lbs)
Speed	2 m/s (4 knots)
Range	700 km (380 nm)
Maximum Operating Depth	425 m verified, 1000-m (3280-foot) design depth
Cable Capacity	220 km
Navigational Accuracy	achieved ~0.5% of distance traveled
Propulsion	6 hp brushless dc motor and gearbox / single 61 cm diameter propeller
Power	360kWh Silver Zinc battery pack consisting of 280 individual cells manufactured by Yardney. 450 km mission plus an additional 24 hours of hotel load with a safety factor of two.
Variable Ballast	±95 kg (250 lbs) in each of 2 toroidal tanks, located fore and aft
Controller	Proprietary real-time kernel running on MC68030 microprocessor
Transit Navigation System	Honeywell H-726 MAPS Inertial navigation unit EDO 3050 Doppler sonar (bottom tracking)
Terminal Homing	Datasonics ACU-206 acoustic homing system. Used with ORE 6701 transponder beacons (8 to 14 kHz). Ranges up to 10 km in 500 m water depth.
Acoustic Telemetry	Datasonics Model ATM-851 using Multiple Frequency Shift Keying (MFSK) plus error encoding operating in the 15 to 20 kHz band.
Fiber Optic Telemetry	Used on outbound leg of mission for vehicle status. Allows operator to assume control
Surface Tracking	ORE 4336B Transponder mounted on Theseus' top-side. ORE LXT ultra-short base line tracking system operating at 19/22 kHz from ice-surface stations.
Emergency Beacon	ORE 6702 acoustic transponder located in the tail section. Interrogated with ORE LXT Ultra-short base line acoustic tracking system operating at 11kHz.
Obstacle Avoidance	Sonatech STA-013-1 forward-looking sonar, 5 by 4 beams, operating at 200/230 kHz.
Pressure Hull	2-inch-thick Aluminum (7075), 4.5 m by 127 cm in 5 sections plus end domes. Design depth 1000 m.
Payload Bay	Free-flooding fiberglass shell with syntactic foam lining, top half removable. Inner dia. 114 cm, length 228 cm. Payload up to 1960 kg dry, 320 kg in water.
Current Payload	11 packs of 20 km cable, each weighing 60 kg in water. 11 toroidal compensation tanks fill as cable paid out. Tank inner dia. 76 cm (30 in).
Transportability	Modular construction in sections under 1400 kg each.

fault table takes effect. Eighteen phases were used to adjust to the changing circumstances during the 1996 Arctic mission.

E. Navigation System

Designing a navigation system to allow an AUV to navigate autonomously under-ice for more than 400 km is a challenge. The presence of a permanent ice cover requires that all sensors used to determine position must be located below the ice cover but not necessarily on board the vehicle. The chosen solution for navigation was to use an onboard, medium-accuracy positioning system for outbound/inbound transits, and an external, but subsurface, terminal-guidance acoustic positioning system for cable delivery and vehicle recovery.

Theseus monitors its position by dead reckoning. It uses a Honeywell 726 ring-laser INU and an Edo 3050 Doppler sonar. The INU provides heading and attitude data, while the Doppler sonar measures forward and lateral ground speeds, as well as altitude above the sea floor. This combination was selected to provide positions with an accuracy of approximately 1% of the distance traveled.

F. Cable Dispensing System

The cable is stored on a series of spools which are stacked longitudinally along the vehicle axis. The ends of each spool are spliced to adjacent spool ends prior to launch. The cable winds off the spools from the inside-out, and exits through a tube in the stern. A deployment peel tension of two to four pounds is maintained through the use of a special adhesive which is applied to the cable jacket during the spool winding process. To keep the system simple and reliable, no active tensioning or dispensing devices are used.

As the cable leaves the vehicle, weight is lost. To prevent this from affecting vehicle trim, the loss in cable weight is counteracted by an automatic buoyancy compensation system. Surrounding each cable spool is a toroidal hard ballast tank which is filled with water as the cable is dispensed from its companion spool. This keeps the net buoyancy of each spool/tank assembly near neutral. Metallic tabs at the end of each cable spool signal the vehicle control computer as each pack is emptied.

IV. Shakedown Trials

A. First Arctic Trials

The first Arctic trials of Theseus were carried out in April 1995 in shallow ice-covered waters near Ellesmere Island. The objectives of the trials were to verify launch and recovery procedures, test all vehicle systems in an under-ice environment, and refine techniques for delivering the fiber-optic cable and bringing it up onto the ice.

Four under-ice dives were carried out. The longest individual dive covered a total distance of 5 km, and the cumulative distance for all dives was 13 km. The acoustic telemetry initially performed rather poorly, but an investigation revealed that the propulsion motor controller was interfering strongly. When the interference was reduced, the telemetry range increased to 3 km, which is considered reasonable for the shallow water situation.

The cable deployment system worked well, just as it had done during trials in the south, and the on-ice cable recovery system was successfully tested. A 9 km length of fiber optic cable was left on the ocean bottom until April 96 to provide some information on long-term survivability.

Following this first Arctic trial, the vehicle controller software was completed between June 1995 and January 1996. The Obstacle Avoidance Control System algorithms were not fully tested during this time; hence, it was decided to carry out the subsequent Arctic missions without this function.

The Ag-Zn battery banks were commissioned and tested in November 1995.

B. First Mission-length Trial

The next extensive trials were carried out at the Canadian Forces Martime Experimental Test Range in Georgia Strait during January, 1996. Here, a full mission-length trial was carried out in order to verify the endurance of the vehicle, to test the projected power budget and to test the navigational accuracy.

The Tracking Range is 20 km long, and the endurance trial consisted of eight round trips plus transit to and from the Range from the launch point at Winchelsea Island. Theseus ran a total distance of 360 km in a time of 51 hours without stopping. An extra 18 km on previous trials brought the total distance that was traveled on the battery to 378 km which used a total of 145 kWh. Since approximately 360 kWh was available from one charge, the energy safety margin was more than adequate.

Theseus' navigation was checked by comparing its true position, as determined by the Range, with its own calculated position. On the first leg the vehicle's cross-track error was 0.45% of the distance traveled (bearing error of 0.26 degrees), and its along-track error was about 0.5%. This is much better than had been expected. At the start of the next leg, a heading error correction was sent to the vehicle over the acoustic telemetry link. This correction had the effect of rotating (in software) the heading of the Doppler sonar relative to the INU. After this correction was applied, the navigational accuracy was exceptional; the average cross-track error was of the order 0.05% of the distance traveled (bearing error of 0.03 degrees).

The vehicle's ability to home to a beacon and do an automatic position update were tested on the final five round-trips. The homing system worked very well out to a range of 5 km, the maximum range attempted during the trial, and the position update procedure worked flawlessly.

V. Arctic Cable-Laying

A. Introduction

On 17 April, 1996, a fiber-optic cable was laid from Jolliffe Bay, just west of CFS Alert, to Ice Camp Knossos, a one way distance of 175 km (as shown in Fig. 3). A more detailed map of locations in the Alert area is shown in Fig. 4. At this time of year, the Arctic Ocean is completely ice-covered. Theseus was deployed through ice that was 1.7 m thick, and the fiber-optic cable was delivered to an ice camp where the ice was 2.7 m thick. The launch and recovery procedures and the technique of catching the fiber-optic cable at the ice camp are sufficiently new and different that they are discussed separately.

B. Launch and Recovery Procedures

Theseus was launched through a large (2.0 m x 13 m) ice hole made by cutting 0.9 m x 1.5 m x 1.7-m-thick ice blocks with a hot water slot cutter. The ice hole was located at Jolliffe Bay (Fig. 4) in a large (11 m x 20 m) heated tent which housed the vehicle and served as a maintenance shop. Two traveling gantries with 5450 kg-rated hoists were erected inside the tent to handle Theseus (8600 kg) and to hoist the ice blocks (2000 kg) out of the water.

When Theseus returned after a mission it parked itself either on the bottom or up under the ice within tethered vehicle range of the large hole. A Phantom DHD2+2 remotely operated vehicle (ROV) was used to attach a recovery line to Theseus which was then pulled back to the launch/recovery hole.

C. Trunk Cable Recovery at Array Site

When Theseus arrived at Knossos it delivered the fiber-optic cable by flying through a loop suspended from the ice surface. This loop was in the shape of an equilateral triangle, 200 m on the side, and it consisted basically of two ropes and a saddle-shaped weight.

After the vehicle passed through the triangle, the cable sank slowly into the saddle at the bottom of the triangle. (The saddle kept the fiber-optic cable from kinking over the small-diameter rope.) The saddle was then pulled to the surface, and the cable was recovered. However, before the cable could be cut and spliced to the array cable, it was necessary to

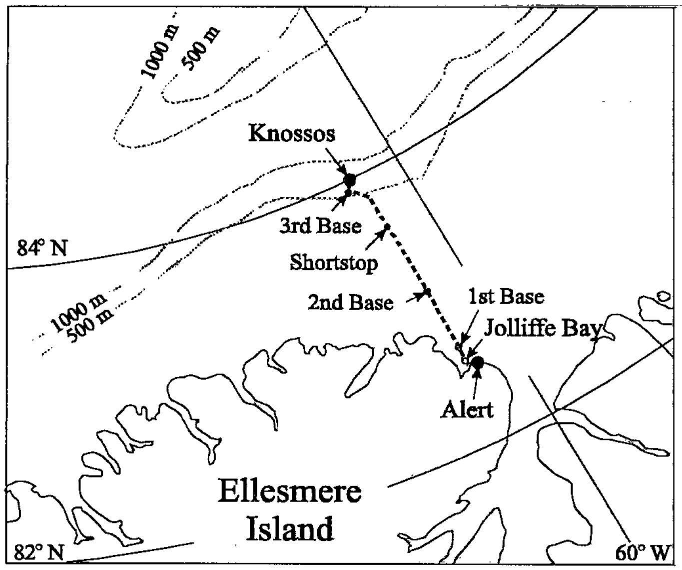

Fig. 3. Map showing cable route and homing

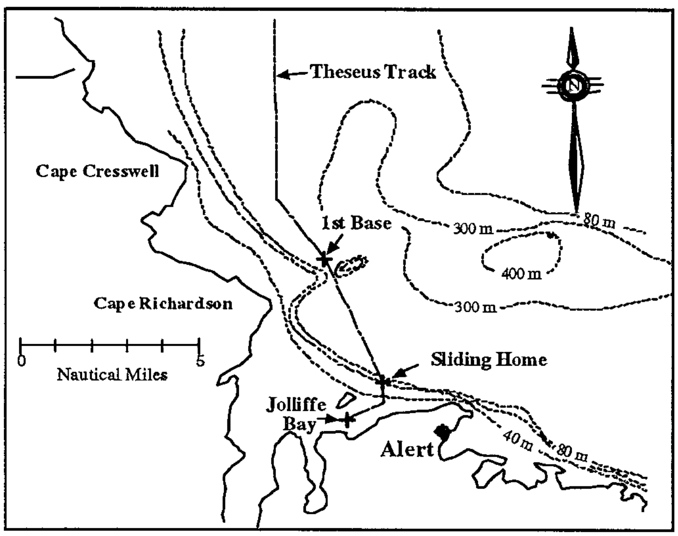

Fig. 4. Near-shore locations

allow for possible ice motion during the splicing period which was estimated to be 2 hours. To compensate for cable that might be pulled away by ice motion, one extra kilometer of slack was pulled up onto the ice.

D. Narrative of Cable-Laying Run

The Knossos mission consisted of navigating from Jolliffe Bay to the array site via 35 waypoints. Acoustic beacons were located at six locations as shown in Figures 3 and 4: Sliding Home, First Base, Second Base, Shortstop, Third Base and Knossos. First Base and Second Base were manned in order to make acoustic telemetry contact in case the vehicle encountered problems. Figure 5 shows the depth profile along this track. The solid line is the bottom profile, and the dotted line is Theseus' depth.

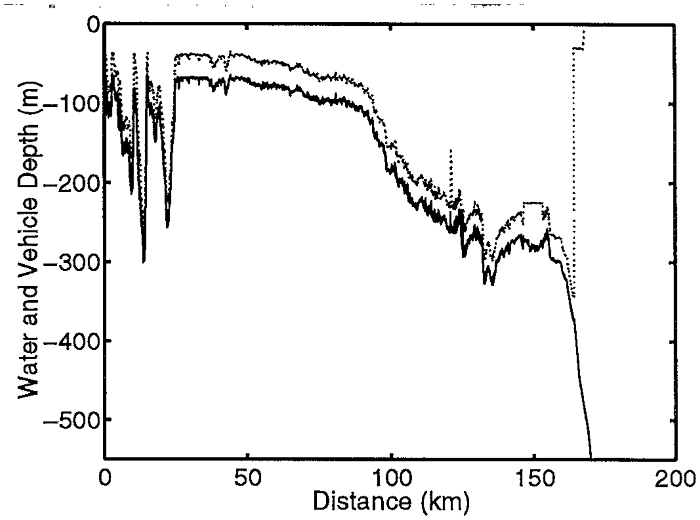

Fig. 5. Depth profile along cable route: solid line is bottom depth ; dashed line is Theseus depth.

The mission began at 00:22 on 17 April. Theseus passed First Base at 02:20 and Second Base at 11:12 with successful homing and acoustic telemetry contact at both. Shortstop was passed at 19:00 without successful homing but continued on to Third Base as programmed. (Later investigation revealed that the Shortstop beacon was not functioning). At 01:18, 18 April, Theseus arrived at Third Base, homed to the transponder there and continued on to Catcher, located about 1.6 km away. Homing was good at first, but deteriorated as Theseus approached the catchment loop. As a result, the decision was made to fly Theseus through the loop under shore-based pilot control through the cable telemetry system. A surface-based tracking system at Knossos provided position information via voice radio to the pilot who was located in the Theseus Control Room at Alert. Under human pilotage, Theseus successfully flew through the loop and parked under the ice some 600 m away. The cable settled down into the saddle at the bottom of the catchment loop and was recovered.

Theseus was given a final position update through the cable, and, after the ballast was adjusted, the cable was cut, and Theseus was sent home. Theseus returned to Jolliffe via homing beacons at Shortstop (a new beacon was now in place), Second Base, First Base and Sliding Home. At First Base, the homing step failed to complete, possibly due to poor acoustic conditions. In this situation, the Fault Manager had been programmed to have Theseus stop and park under the ice to await further instructions. Acoustic telemetry and surface tracking were established, and the vehicle's health was checked. The vehicle's ballast was adjusted, and it was sent on its way. At 11:40 (19 April) Theseus came to a stop under the ice at the launch hole. Lines were attached, and it was recovered safely.

E. Navigation Accuracy

As Theseus passed by the accurately-positioned acoustic beacons at Second Base and Third Base, it made corrections to its own position. From these corrections it is possible to determine Theseus' navigational accuracy. When Theseus arrived at Third Base its overall cross-track error was 0.5% of the distance traveled, and its along-track error was 0.4%.

A new heading-error correction was calculated for the return trip in order to reduce the cross-track error. Nothing was done for the along-track error since it was not deemed to be as important.

With the new heading-error correction, the cross-track error on the return was 0.04% of the distance traveled, a substantial improvement. The along-track error measurements were contaminated, but over a short range of good data (from Short Stop to Second Base) the along-track error was 0.6%, essentially the same as before.

F. Energy Consumption

The energy used on this mission was 149 kWh, less than half of the estimated battery capacity.

VI. OTHER POTENTIAL USES

The vehicle is currently configured solely for cable laying; however, its modularity and design features make it suitable for other missions. The fiberglass payload bay can be modified or even replaced economically to accommodate other payloads. These factors combined with Theseus' qualities of covertness, endurance and navigational precision make possible such tasks as remote route surveys, remote mine hunting, the rapid deployment of surveillance systems (acoustic and non-acoustic), and even the towing of mobile sensor arrays. Longer missions could be accommodated by replacing the current silver-zinc batteries with fuel cells or other AIP (Air Independent Propulsion) power plants. ISER is currently carrying out trials of an Aluminum/Oxygen semi-fuel cell which was developed by Fuel Cell Engineering Inc. (FECI) of Kingston, Ontario. This unit has been mounted in a spare hull section of ARCS and trials of ARCS powered by this system have been carried out in 1994 and 1997[7].

VII. SUMMARY

The Theseus Autonomous Underwater Vehicle, developed jointly by EDRD and ISER over the last five years, recently completed an impressive cable-laying mission under the permanent polar ice cap. The vehicle successfully deployed 175 km of fiber-optic cable and returned to the launch site for an overall mission length of 350 km. The characteristics of Theseus that made this feat possible are summarized below:

- modular design for ease of transport,
- fault-tolerant control software,
- navigation accuracy better than 0.5% of distance traveled (cross track error reducible to less than 0.05% of distance traveled),
- acoustic and fiber optic telemetry systems,
- terminal acoustic homing,
- variable ballast tanks fore and aft,
- payload section capable of carrying 220 km of fiber optic cable plus associated ballast tanks,
- round-trip endurance of 450 km with a safety factor of 2,
- operating depth to at least 425 m (designed for 1000 m), and
- obstacle avoidance sonar

Theseus' modular design and flexible payload section make it easily adaptable to other missions such as remote mine hunting, route surveys, the rapid deployment of underwater surveillance systems and the towing of mobile underwater sensor arrays.

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