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THE UNDER-ICE NAVIGATION OF THE AUV THESEUS

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ABSTRACT

The Canadian Department of National Defence has developed an autonomous underwater vehicle capable of performing long-range missions in ice-covered waters. Autonomous operations in such an extreme environment, often where a priori knowledge of the bathymetry is limited, requires a navigation system that is precise, reliable and repeatable. A hybrid navigation system has been developed which provides precise navigation by combining data from two different types of sensors: inertial and acoustic. This navigation system has been integrated into the large AUV known as Theseus, and for mission lengths of up to 200 km it has demonstrated horizontal navigational accuracies of better than 0.05% of distance travelled. This paper gives details on its navigation sensors and describes the AUV and its successful mission in the High Arctic.

INTRODUCTION

International Submarine Engineering Research (ISER) of Vancouver, B.C. Canada, under contract to the Canadian Department of National Defence, has designed and built an Autonomous Underwater Vehicle (AUV) capable of performing long-range missions in the ice-covered waters of the High Arctic (Butler, 1995), (Butler et al, 1993). Design started in 1992, and construction was complete by 1995. The vehicle was used in the spring of 1996 to lay 180 km of fiber-optic cable from a shore site to a site in the Arctic Ocean, where the cable was spliced to a bottom-mounted experimental system. The vehicle then returned to the shore site where it was recovered. A second cable-laying mission was then cued-up and executed.

The main purpose of this paper is to describe the navigation of the vehicle, but it begins with a more general description of the cable-laying mission and the vehicle.

THE MISSION

Our under-ice cable-laying mission was defined to have the following general operational requirements and constraints:

- Launch the vehicle from an ice camp through ice that is several metres thick.
- Transit up to 200 km over relatively unknown ocean-bottom terrain while dispensing a fiber-optic cable
- Maintain a relatively constant altitude above the seafloor
- Avoid bottom obstacles and surface ice keels
- Deliver the cable to a remote ice camp (in this case by 'flying' through a loop of rope suspended below the ice)
- Return to the launch hole for recovery

THE VEHICLE

The vehicle was named Theseus after a hero in Greek mythology. It was he who braved the labyrinth on the island of Crete in order to slay the Minotaur. As he worked his way to the centre of the maze he laid down a golden thread given to him by the king's daughter Ariadne. After slaying the Minotaur, Theseus followed the thread out of the maze back to safety. The loose parallel between the present-day cable laying mission and a tale from Greek mythology makes the choice of name plausible.

A general arrangement of the vehicle is shown in Figure 1, and the key design parameters are listed in Table 1.

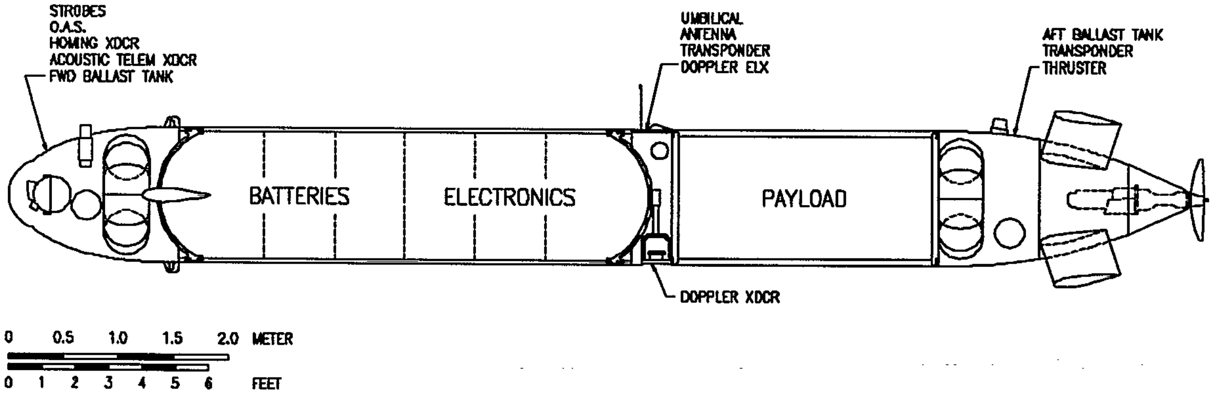

Figure 1 - Theseus general arrangement (side view)

Table 1 - Theseus Key Design Parameters

Design Parameter	Value
Length-Over-All	11 metres (36 feet)
Diameter	1.27 metres (50 inches)
Working Depth	1000 metres (3280 feet)
Displacement	8,845 kg (19,500 lbs)
Range	> 400 km (215 nm)
Speed (nominal)	2.0 m/s (4.0 knots)

The vehicle consists of a segmented aluminum pressure hull with free-flooding fiberglass hull sections fore and aft of the pressure hull. The pressure hull is segmented into six sections, primarily for ease of air transportation. The free-flooding nose contains a forward-looking obstacle avoidance sonar, a variable ballast tank, and transducers for acoustic telemetry and acoustic homing. The pressure hull houses several banks of silver-zinc batteries, electrical power distribution, an onboard computer, an inertial navigation unit, and most of the 'dry' electronics. The free-flooding sensor section immediately aft of the pressure hull houses a Doppler sonar, a medium-frequency tracking transponder and a radio telemetry antenna (used during open water trials). The free-flooding payload section houses the fiber-optic cable packs and buoyancy compensation tanks. The free-flooding tail section houses a second variable ballast tank, a low-frequency emergency transponder, thruster motor and gearbox.

Six independently moveable hydroplanes, two at the bow and four at the stern, are used to provide vehicle stability and control in pitch, roll, yaw and depth. The foreplanes are used collectively to control depth and pitch, and are used differentially to control roll. The aftplanes are used collectively to control depth, pitch and yaw, and differentially to control roll.

For the Arctic mission eleven fiber-optic cable packs were spliced together prior to installation. Each pack contained 20 km of 2-mm-diameter fiber-optic cable, thus providing a single fiber-optic cable 220 km in length. The cable was wound concentrically in the packs and was held intact with a relatively weak glue. As the vehicle moved forward the cable was pulled away from the pack once the tension increased to about 2 lb (4.5 N). For its protection the cable was guided through a tube extending aft past the propeller. Since the fiber is heavier than seawater (i.e., a specific gravity greater than 1.0), the vehicle became more buoyant as cable was dispensed. The onboard computer allowed seawater to fill the buoyancy compensation tanks surrounding each pack as fiber was dispensed.

Part way through the vehicle development program, it became technically feasible for the AUV to utilize the fiber-optic cable it was laying as a telemetry link during the outbound phase of the mission. This was found extremely useful.

Figure 2 is a photograph of Theseus being lowered into its ice hole prior to start of an under-ice mission.

NAVIGATION

Introduction

Navigating underwater in any type of vehicle can be difficult. Theseus's requirements were particularly challenging:

- The vehicle must travel up to 200 km to within ±50 m of a specific position, then return home
- The vehicle must operate in waters with 100% ice coverage
- The vehicle must operate at high latitudes (>80° N)
- The vehicle is to be unmanned (i.e., computer-controlled)

- The vehicle is to be autonomous (i.e., must operate without human assistance)
- The vehicle must have very high reliability.

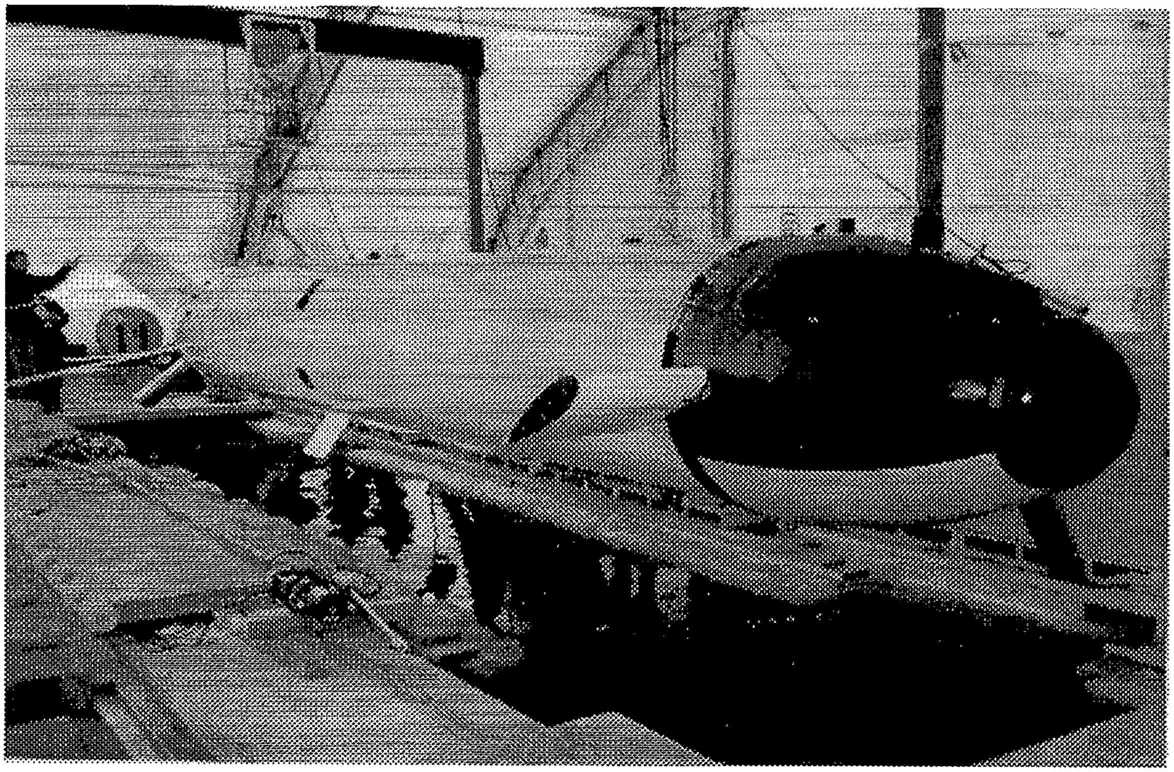

Figure 2 - Theseus being launched through an ice hole

Performing long-range, multi-day missions requires an accurate navigation system. Operating under a permanent ice cover imposes additional constraints. All navigation sensors must be located under the ice cover, but not necessarily onboard the vehicle. Our approach to the problem was as follows.

- A medium-accuracy, velocity-aided inertial navigator which provides dead-reckoned position estimation for en route navigation, and

- An acoustic homing system was used to provide position updates (fixes) at specific points along the mission route. It was also used to guide Theseus through the 'catchment' loop of rope at the remote ice camp.

This paper will deal primarily with the two dimensional (horizontal) navigation problem. The location of the vehicle in the vertical is measured two ways: a pressure transducer measures vehicle depth below sea level, and a sonar measures height above the seafloor (altitude).

The navigation sensors selected for Theseus are summarized in Table 2.

Table 2 - Theseus Navigation Sensors

Sensor	Outputs	Accuracy
Honeywell MAPS INU	Heading	0.1°
	Position	0.8 nm/hr (Note 1)
	Velocity	2.5 ft/s (Note 2)
	Attitude	0.05°
EDO 3050 Doppler Sonar	Ground speed	0.2% (Note 3)
	Water speed	0.5%
	Altitude	0.3 m
Datasonics ACU-206 Acoustic Homing System	Range	1-2 m (Note 4)
	Bearing	±5°

Notes:

1) Circular Error Probable (CEP), for flights less than or equal to 1.0 hr
2) For flights up to 2 hrs
3) Percentage of forward speed
4) Not including errors due to acoustic ray bending

Inertial Navigator

The Honeywell MAPS INU is a medium-accuracy strapdown inertial navigation unit (Air Force Systems Command, 1991) that provides a full set of navigation sensor data to the onboard computer via a MIL-STD-1553 bus. In theory, the INU alone could be used to provide the complete navigation solution for an under-ice AUV mission, since it requires no external sensors. In a practical application however, additional sensors are required due to certain inherent weaknesses of the INU.

The inertial velocities reported by the INU are subject to Schuler oscillations, a characteristic of Schuler-tuned inertial platforms (Bowditch, 1984; Siouris, 1993). When disturbed by short-term errors such as accelerometer bias or scale factor, the INU's inertial velocity measurements will oscillate like a Schuler pendulum. Figure 3 shows the free-inertial velocity V_X of an aligned Honeywell MAPS INU over the period of several days. Following a two-hour gyrocompass alignment, the Schuler oscillations, with a period of approximately 84 minutes, dominate the display. Since these unbounded oscillations are a significant percentage of the AUV's normal operating speed of 2 m/s, they will seriously degrade any position estimations.

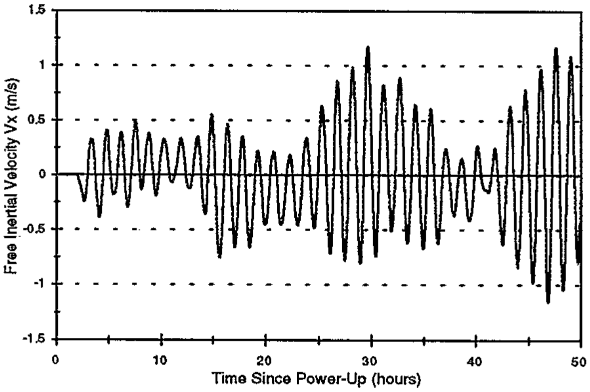

Figure 3. Schuler Oscillations of an aligned Honeywell MAPS INU (82° 30'N 62° 12'W, April 17-19, 1993)

To mitigate the growth of the Schuler oscillations and to bound the position estimation error, the INU is operated in velocity-aided mode. In this mode, the INU uses velocity measurements reported by other sensors which have better long-term, bounded error characteristics – in particular, the Doppler sonar. Although the INU was not used to determine velocities, it was the primary attitude sensor; it performed the calculations of position, and it served as an accurate compass.

A very accurate initial heading was required to ensure accurate navigation for the cable-laying mission. It was hoped that the self-alignment capability, or gyrocompassing, of the Honeywell INU would be sufficient to provide an initial heading error of 0.1° or better.

During gyrocompassing, the INU determines its initial heading by measuring the horizontal component of the earth rate. As this component is quite small above 60-65° latitude, most INU's have difficulty in gyrocompassing at high latitudes. Although the INU was qualified for navigation at any latitude, its gyrocompass alignment performance above 65° latitude was known only theoretically. Since the launch site for the cable-laying mission was above 82° N latitude, it was decided that field experiments were necessary to quantify the INU's alignment performance.

More than 100 separate INU alignments were made at CFS Alert (82° 30' N) in 1992 and 1993 (ISE Research, Ltd., 1992-1995), varying a number of key parameters: length of gyrocompass alignment time, the initial heading, and yaw motion during alignment. The following alignment procedure was repeatedly found to provide an initial heading error of less than 0.1°:

Orient the INU at a non-cardinal heading (a heading other than 0°, 45°, 90°, 135°, ...)
  Power up the INU and download initial position
  Switch INU to gyrocompass alignment mode
  Leave INU undisturbed for 30 minutes
  Rotate the INU clockwise 90° over a 15 second period
  Leave INU undisturbed for 90 minutes
  Switch to air-align mode (navigation mode)

Doppler Sonar

The EDO 3050 Doppler sonar provides forward and lateral ground-referenced velocities when the Doppler is within acoustic range of the seafloor (typically 150-200 m at a frequency of 287.5 kHz). The velocity measurements are very accurate, stable and are bounded in the long-term. They are obtained by a phased-array transducer which generates four downward-looking acoustic beams that are perpendicular in azimuth (fore, aft, port, starboard) and oriented 60° down from the horizontal plane. This particular configuration minimizes the effects of transducer pitch and roll. The Doppler shifts from returns off the seafloor are averaged to provide highly accurate forward and lateral speed measurements. In addition, the measurement of the two-way travel times of each beam provides an average measurement of the vertical distance to the seafloor (altitude).

Acoustic Homing

As mentioned before, the dead-reckoned navigation was updated from time to time with the aid of an acoustic homing system.

The Datasonics ACU-206 Homing System measures range and relative bearing to an acoustic transponder. This system consists of an electronics box located inside the pressure hull and an acoustic transducer located in the (flooded) nose of the AUV. For the under-ice mission, acoustic transponders were deployed at key locations by lowering them on ropes through holes drilled into the ice. Each transponder had specific interrogate and reply frequencies, which, of course, were different from each other. Several different frequencies in the 8-12 kHz range were used during the cable-laying mission.

At pre-planned points in a typical mission, the onboard computer powered up the homing system, which sent out acoustic pulses at the interrogating frequency of the expected transponder. Once a response was obtained, the range was computed from the combined travel time of the transmit and reply signals and the assumed speed of sound through the water. The bearing to the transponder, relative to the vehicle's heading, was obtained from the transponder's reply signal, the necessary phase information being measured by an array of receive elements in the transducer. The measured bearing provided enough information for the guidance subsystem to steer the AUV towards the transponder. Also, the combination of range, bearing and the known geographic position of the transponder allowed the AUV to update its own position.

The Arctic Ocean has several unique characteristics that affect acoustic propagation: extremely low water temperatures (-1.5° C), a permanent ice cover and relatively unknown bottom terrain (bathymetry). Because of the uncertain propagation, a substantial amount of experimentation was performed in order to ensure that the acoustic homing system used in Theseus would operate as required.

Various frequencies, power levels, water depths and horizontal ranges were tried (ISE Research, Ltd., 1992-1995). Slant ranges of over 5 km were attainable in deeper water, with somewhat shorter ranges in shallower waters. Data collected from these trials assisted in developing the overall mission plan, particularly as it pertained to the locations and depths of the acoustic transponders.

Autonomous Guidance Capabilities

Three different guidance controllers are available for autonomous navigation: targeting, line following and homing. Each of these 2-D controllers generates heading setpoints to the vehicle's autopilot, and are described briefly below.

Targeting. The targeting controller steers the vehicle directly towards a waypoint, which is a geographic position. Each time the INU reports a new position (typically once per second), the targeting controller computes the heading from the current vehicle position to the waypoint. Since this controller is fairly simple, the vehicle may make its 'final' approach to the waypoint from an unpredictable heading when it is used in the presence of cross-currents. Because of this possible behaviour, this controller is used only under specific conditions.

Line Following. When it is necessary for the vehicle to follow a straight-line trajectory between two waypoints, the line following controller is used. Each time the INU reports a new position, the controller adjusts the vehicle's heading so as to decrease the cross-track error. This is done using a simple proportional-integral-differential (PID) controller. Extensive sea trials have demonstrated that Theseus can consistently stay within two or three metres of a line.

Homing. Homing is an acoustic version of targeting. Each time the homing system measures a range and relative bearing to the transponder being interrogated, the homing controller adjusts the vehicle's heading so as to keep the relative bearing at 0° (directly ahead). A contingency mode of homing is provided for the unlikely situation where the INU has failed, and the heading autopilot is unable to operate. In this situation, the homing controller directly controls the vehicle's aftplanes to yaw the vehicle towards the transponder.

Homing was used during terminal navigation to deliver the fiber-optic cable to the remote ice camp, as shown in Figure 4. Two transponders were deployed from the surface 1.2 km apart in such a way that they lined up with the center of the cable recovery loop. When the AUV arrived in the vicinity, it began to interrogate the first transponder. When it replied, the AUV steered towards it. Once homing to the first transponder was completed, the vehicle began homing to the second transponder. The effect of this double homing was to force the vehicle to fly through the cable-recovery loop along a path perpendicular to the loop.

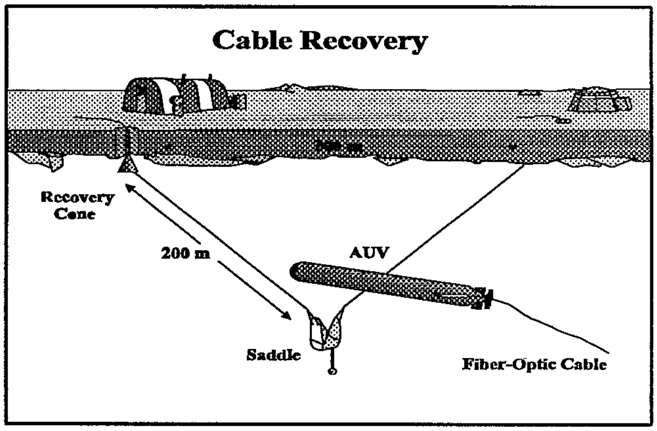

Figure 4. Under-ice fiber-optic cable delivery

TRIALS

Arctic Shakedown Trials

The first Arctic trials were held in April 1995 in Jolliffe Bay, a small bay just 6 km west of Canadian Forces Station (CFS) Alert, in the Northwest Territories (82° 30' N, 62° 42' W). This site was the same as that of the full cable-laying mission the following year. The reason for these shakedown trials was partly one of logistics and field technique. We wished to test the procedure for assembling the vehicle at a remote location and refine our techniques for launching and recovering the vehicle through the solid cover of pack ice. The main reason for the trials, however, was to test the vehicle and all its systems in the under-ice environment.

Four under-ice runs were carried out, the longest of which was 5 km. Since the acoustic telemetry was not yet trusted to give good communications with the vehicle, control was exercised through the fiber-optic cable that was dispensed during the dive.

This was wise, for the acoustic telemetry at first behaved very poorly. However, it was found that the propulsion motor controller was operating at a frequency very close to that of the telemetry and was seriously interfering with it acoustically. When the interference was reduced (by wrapping the motor with bubble pack) the acoustic telemetry's operable range increased to 3 km, which was a reasonable distance for the shallow waters adjacent to Jolliffe Bay. Following these trials, the motor controller frequency was permanently changed to eliminate this interference problem.

The homing system was tested successfully out to ranges in excess of 7 km when both source and receiver were fixed and out to 3 km when the source was moving.

The vehicle's cable dispensing system worked well, as did the techniques for launching and recovering the vehicle through the two-metre-thick ice.

Navigation Trials at Nanoose Range

The first extensive navigation trial was held at the Canadian Forces Maritime Experimental and Test Range (CFMETR) at the Nanoose Range (Vancouver Island, British Columbia) during January 1996. The trial, which was the length of a full Arctic mission, was held to confirm vehicle endurance and reliability as well as to test the navigational accuracy.

Theseus ran eight circuits around a 20-km-long range plus the distance to and from the range for a total of 360 km. The elapsed time was 50.6 hrs. Theseus performed very well, using less than half of its battery power (145 kW-hours out of 360).

The navigational accuracy was determined by comparing Theseus's true position, as determined acoustically by fixed bottom installations on the Range, with its own internally-calculated dead-reckoned position. On the first traverse of the range the vehicle's cross-track error was 0.45% of the distance traveled, and its along-track error was about 0.5%. This cross-track error corresponds to a heading error of approximately 0.26°. On the assumption that this error was due solely to yaw misalignment between the INU and the Doppler transducer, an INU yaw correction was sent to the vehicle via acoustic telemetry. After this correction was applied, the navigational accuracy on subsequent legs was of the order 0.05% of the distance traveled, a heading error of 0.03°. This exceptional accuracy was much better than had been expected.

The vehicle's ability to home to a transponder was found to work very well out to a range of 5 km, the maximum range attempted during the trial. When Theseus reached the appropriate distance from the transponder, it updated its position without any measurable error.

The Acoustic Telemetry system performed very well for most of the mission; maximum ranges were typically greater than 2 km. However, 40 hours into the run, acoustic communication with the vehicle was unexpectedly lost for the remainder of the trial. The problem occurred when a momentary loss of communications (due to either noise interference or multipath problems) occurred while a command was being sent to the vehicle. This resulted in an unrecoverable synchronization error in the onboard communications software. Even with the absence of telemetry, the mission was completed autonomously as per the mission plan.

Navigation During Cable Deployment In The Arctic

Two cable-laying missions were carried out in April 1996. The first one, as shown in Figure 5, was to an ice camp called Knossos, a one-way distance of 180 km. The second one was to an ice camp called Minotaur, which was about 33 km from Knossos, and, from the navigation point of view, was a repeat of the first mission.

The cable-laying mission to Knossos consisted of navigating from Jolliffe Bay to Knossos via six sites where transponders had been deployed. Figure 5 shows four of these sites: First Base, Second Base, Shortstop and Third Base. Sliding Home, which was quite close to Jolliffe Bay is shown in Figure 6. The sixth site, called Catcher, was right at Knossos and just beyond the cable catchment loop. The mission plan called for Theseus to home on each of the transponders in turn to update its position. First Base and Second Base were manned in order to make contact via acoustic telemetry in case the vehicle encountered problems. The transponder at Sliding Home was to aid Theseus in entering a fairly narrow channel on its return trip.

Theseus was launched from Jolliffe Bay at 0022 on 17 April. It passed First Base at 0220 and Second Base at 1112 with successful homing and position updating. At both locations acoustic telemetry was used to contact the vehicle. This was done as a learning experience and as reassurance – not because it was strictly necessary. At Shortstop the homing was not successful because, as was learned subsequently, the transponder was not functioning. Theseus continued on to Third Base, as programmed, where it ascended from a depth of 420 metres to 30 metres and did a successful homing at 0118, 18 April. It then headed toward Catcher, about 1.6 km away. Although the homing to Catcher was good at first, it deteriorated as Theseus approached the catchment loop. Control was taken by the operators back at the control room in Alert, who were still in communication with the vehicle via the fiber-optic cable. They piloted Theseus through the loop using position information obtained from a surface-based acoustic tracking system at Knossos and relayed to Alert via radio. Theseus successfully flew through the loop and parked up under the ice some 600 m beyond.

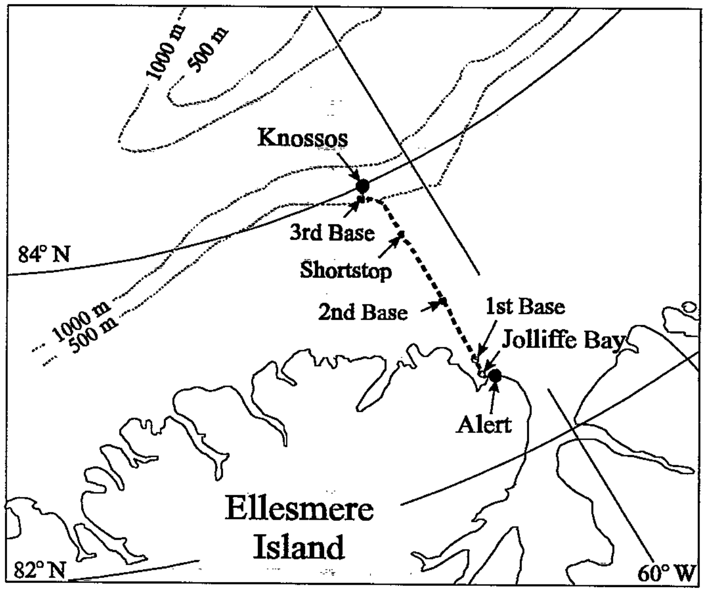

Figure 5: Theseus's route in laying the fiber-optic cable from Alert to the ice camp Knossos. The transponder sites are shown.

After the cable was retrieved from the catchment loop, commands were sent over the fiber-optic cable to adjust Theseus's ballast for the return trip. Once this was complete and after a 1-km excess of cable had been pulled up onto the ice, Theseus was commanded to return to the launch site, and the fiber-optic cable was cut. The return voyage was truly autonomous.

Theseus returned via Shortstop (where a new transponder had been installed), Second Base, First Base and Sliding Home. The homing step failed to complete at First Base. This was considered to be a major problem by Theseus' navigation fault table since it might mean that there had been a major navigation error. Consequently, Theseus was programmed to stop and park up under the ice where it was to await further instructions via acoustic telemetry. Acoustic contact was established with a unit at First Base, so it was not truly lost. By means of acoustic telemetry it was sent on its way, and at 1140, 19 April, it parked itself under the ice at the launch hole in Jolliffe Bay.

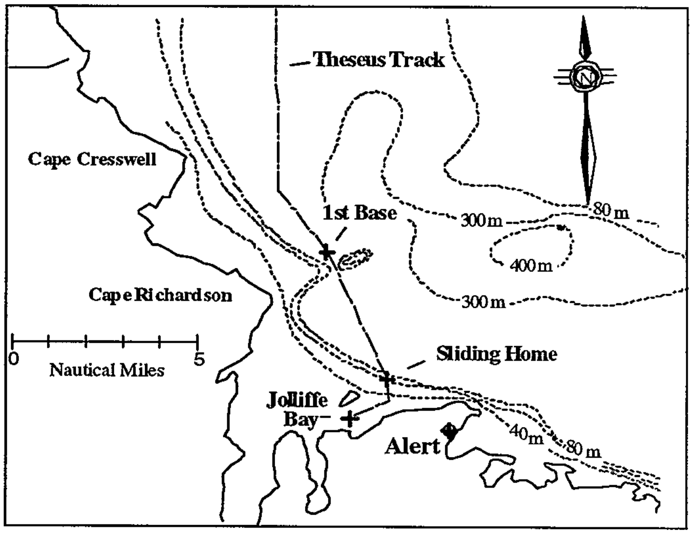

Figure 6: The southern portion of the fiber-optic route showing the launching area and the transponder site at 'Sliding Home'

NAVIGATION ACCURACY

It is possible to determine Theseus's navigational error at each transponder where it did a positional update. The record of these updates gives the positional accuracy. One must, of course, assume that the position of the transponders was accurate in order to blame the error on Theseus's navigation. There is no doubt of this, however, since the transponders were located with P-code GPS.

When Theseus arrived at Third Base on the outward-bound trip, its cross-track error (as accumulated from Jolliffe) was 0.5% of the distance traveled, and its along-track error was 0.4%.

For the return trip an INU yaw correction was calculated and downloaded to Theseus. Nothing was done for the along-track error since it was not as important. The heading was important so that Theseus would pass close to each transponder (where it was given a corrected position), but an along-track error would not prevent it from passing close to the transponder. With the corrected heading, the cross-track error on the return was 0.04% of the distance traveled, a significant improvement. The along-track error between Short Stop and Second Base was 0.6%, much the same as before. Elsewhere, the along-track records were contaminated and not useable.

Another, more tangible indication of the precise navigation occurred during the second cable laying mission. Due to a failure in one of the vehicle's subsystems near the end of the return transit, it was necessary to deploy an ROV to inspect Theseus on the seafloor. During this inspection, the fiber-optic cable laid during the outbound transit was observed in the immediate vicinity of the vehicle. Since the outbound and inbound transits used the same waypoints, it was apparent that the vehicle's return transit was nearly identical to its outbound transit, after having traveled over 250 kilometres.

CONCLUSIONS

A hybrid inertial/acoustic navigation system was developed for the AUV known as Theseus. It enabled Theseus to lay cable with great precision at high latitudes (84° N) and under heavy Arctic pack ice. The navigator has demonstrated an accuracy of approximately 0.05% of the distance travelled and a position drift rate of 4 metres per hour during missions of about 200 km in length and 28 hours in duration. With the acoustic transponder assist to the navigation, Theseus showed itself capable of flying autonomously through a rope triangle (200 metres on a side, suspended from the ice) after having travelled 180 km.

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