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THE USE OF ROBOTS IN HYDROGRAPHY

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ABSTRACT

Robots are increasingly being applied to tasks which are hazardous or which they can carry out more effectively or safely than people. The use of remotely-controlled submersibles for conducting precise undersea surveys has been proposed recently in conjunction with oil industry activities. In Canada robot vehicles are currently under development for offshore surveys of areas under permanent ice cover. This paper describes two requirements, the different technology that is involved in each system, and the progress to date on the developments which, in the case of one system, have now advanced to successful field trials.

1. INTRODUCTION

At the XIIth International Hydrographic Conference, in Monaco in 1982, HASKINS [1] advocated the use of remotely-controlled submersibles to permit hydrographers to carry out the very precise surveys that are now required by the oil industry. The use of remotely-controlled vehicles, or robots, is no longer confined to assembly plants or military operations. For the past decade robots have been used to assist, and in many cases to replace, divers in sub-sea operations. Robots in these operations reduce the possibility of loss of life, allow deeper work and are often more economical than divers. In Canada, the Hydrographic Service is now examining the use of remotely-controlled vehicles to carry out tasks where the work is either arduous or potentially dangerous. In addition it is expected that the use of robot vessels will reduce the overall cost of survey operations.

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One of these tasks is the surveying of the large tracts of offshore continental margin that extend off the Canadian coast. The work can be made more cost effective using small craft in conjunction with a mother ship than when surveys are carried out by a ship alone. However, the crew of such small craft are subject to arduous conditions and production is often weather limited. It is therefore sensible to consider the use of unmanned vehicles for sounding. A second task using robots is for surveys in the Arctic where permanent ice cover exists. In this case the Hydrographic Service has been seeking ways to measure depth profiles beneath the ice, and the use of remotely-controlled submersibles appears to be one possible solution.

Two remotely-controlled submersibles are now being developed by International Submarine Engineering Ltd. under a contract with the Bedford Institute of Oceanography. This paper discusses the requirements and describes the progress of each submersible to date.

2. THE REQUIREMENT FOR REMOTE-CONTROLLED OFFSHORE VEHICLES

The development of the technique of "parallel sounding", using a fleet of survey launches, must be credited to the Scandinavians [2] who have refined the method and associated instrumentation over many years. Coastal hydrographic surveys are usually carried out using a fleet of survey launches. In many countries the launches work from a mother ship, but operate independently from that ship with respect to survey patterns. In the "parallel" technique the launches keep station abeam on each side of the parent vessel, travelling in formation at an identical speed and maintaining station precisely abeam on each side at varying distances off. The result is a precisely-controlled array of parallel sounding tracks. Cost is minimized in that the crews of the launches can be reduced to one or two persons, their navigational equipment can be simple, and the boats themselves can be kept small as they are constantly in close contact with the mother ship. In Sweden special positioning equipment and data-handling systems have been developed [3] and special mother ships have been constructed to facilitate parallel sounding operations.

In Canada attempts have been made to follow the Scandinavian example, but it has been found difficult to develop the reliability of equipment which is necessary for the technique, and on Canada's east coast the sea conditions are considerably more severe than in the Baltic and the eastern North Sea. The problem of equipment reliability can surely be overcome, but the problem of sea state, particularly in the offshore areas, requires a new approach. In 1966 it was decided that a remotely-controlled launch might be the answer, as much of the sea state problem concerned the human crews and not the launches themselves [4]. A 4.4.-metre launch deep-V hull was built and equipped with instruments. Control was provided by an RF link which proved to be less than reliable because of interference by other communications. Furthermore the new micro-computer technology had not then arrived, and it was difficult to build in some of the fail-safe technology that can be employed today. However, the main design fault

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Editor's Note

The following was received from the authors in December 1984 as an update to the status of the developments described.

Since the original paper was written, DOLPHIN has been fitted with an echo sounder and a Loran-C positioning system. Data from these instruments are telemetered to the parent vessel. In the case of the echo sounder an analogue signal is transmitted and the signal is then recorded on a graphic recorder. Although this method was used initially, there is no reason why the echo soundings cannot be digitized and relayed as digital information. The Loran-C system is used in a differential mode with the mothership. Since the control vessel is equipped with an integrated navigation system, employing satellite signals, Loran-C and other navigational data, the Loran-C signal received on the remote vessel provides an offset to the mothership's position.

Another sea trial took place last June and it was found that both the echo sounder and the Loran-C system worked well. The echo sounder provided an excellent depth trace in water up to 250 metres. It is hoped to evaluate the accuracy of the differential Loran-C next month in a further trial in which the Loran-C offsets can be compared directly to offsets measured by Krupp Polarfix. During the summer (1984) trials improvements to the handling system were tested, but calm sea conditions prevailed and this evaluation will be carried out again in November 1984 under rougher conditions.

4.5 Future Activities

Apart from the heavy weather trials being carried out, a program is underway to build a new engineering prototype and two production DOLPHIN vehicles. Characteristics of the existing DOLPHIN are being measured at present in order to develop the characteristics of the new vehicle. It appears, for instance, because the power speed curve is relatively linear, that by using a supercharged engine it will be easy to increase the speed. Other possibilities are the use of a shorter but heavier keel and the use of larger fairing sections on the snorkel mast.

The handling system for a fleet of DOLPHINs remains an unresolved issue. The present method of using the modified ship's davits will not be satisfactory for handling several vehicles in rough sea states and it is clear that some form of special hoist or crane will be required.

The adoption of sidescan sonar to the DOLPHIN remains as one of the program goals. Not only is sidescan sonar seen as a survey tool but also has potential military applications in the mine countermeasures field.

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Since writing the original paper ARCS has progressed to a completed vehicle and initial trials have been carried out in British Columbia. During these trials the vehicle successfully "swam" under water under acoustic control. However, it was found that there was interference between the acoustic telemetry system and the acoustic positioning system and improved receiver filters must be designed. As a result of these problems and other earlier difficulties the ARCS program is behind schedule with acceptance trials planned around December 1984, followed by under-ice trials during the spring of 1985. Arctic trials are now not likely to take place until 1986. In spite of these setbacks ARCS has already demonstrated its potential as one of the most sophisticated remote-controlled vehicles in the field to date.

of the vehicle was that it could not handle waves of any size. In order to keep pace with a mother ship the remote-controlled launch was required to travel at speeds of 12-14 knots, and at these speeds it frequently became airborne between wave crests and consequently lost power. The project was abandoned after several years of development work. In 1982 the idea of a remotely-controlled launch was reviewed, and after some initial studies it was decided that a submersible travelling beneath the surface might succeed where the earlier development had failed.

3. THE REQUIREMENT FOR REMOTELY-CONTROLLED UNDER-ICE VEHICLES

Since 1959 the Canadian Hydrographic Service has been attempting to find improved ways to measure depth in areas of sea that are covered by ice for all or most of the year. This requirement has become even more urgent as a result of the successful oil and gas exploration in the Canadian Arctic in recent years. Plans to construct large icebreaking tankers which will carry oil and gas through areas that are inaccessible by any of today's icebreakers have increased the need to provide accurate charts. Therefore the necessity to develop new technology to sound beneath ice-covered waters is vital.

The earliest developments involved blasting and drilling through the ice, which is typically two and a half metres thick, and then measuring the depth by leadline. An acoustic method of sounding through both ice and water was developed and deployed from both tracked vehicles and landed helicopters [5]. This method has been successful in providing general bathymetric cover, but its shortcoming is that it only provides spot depths, whereas continuous profiling is necessary. In order to provide this type of data it appears sensible to go under the ice, and while a fully-fledged submarine might seem to be the ultimate answer, safety and cost rule it out. It was proposed that a type of remotely-controlled submersible originally developed by the University of Washington [6] in the early 1970's might be the solution, and a version of this vehicle specifically designed for hydrographic, under-ice surveys is now under development.

It is planned to put the vehicle through a hole in the ice and then navigate and control it from that point while it covers a survey pattern over a previously defined area. The conditions existing in areas of interest in the Arctic appear to dictate that this area can be as large as 18 × 18 km.

4. DOLPHIN — AN OFFSHORE SURVEY ROBOT

In 1982 when the concept of remotely-controlled survey vehicles for "parallel" offshore surveys was reconsidered, foremost in the minds of our hydrographers and engineers was the requirement for a vehicle with adequate sea-keeping abilities. The goal was to produce a vehicle which could operate at a speed of

12 knots (the cruising speed of the mother ship) in 3-metre breaking seas and be capable of speeds of 15 knots for manœuvering. Achieving these goals was important, for without them the value of robot vehicles would be impaired.

Other design parameters were loosely defined in the interests of promoting creativity in the design. For example, although low weight and small size were preferred, size and weight would be satisfactory if the resulting vessel could be handled adequately from our existing survey ships which normally carry 6-tonne, 9.5-m launches; while an endurance of 8-16 hours was preferred, lesser endurance would be acceptable if a quick refuelling scheme were devised, and so on.

Explicit hydrographic specifications were not stated, on the basis that echo-sounding and positioning systems could be readily added to the vehicle after it had proved capable of operating satisfactorily in 3-metre seas.

4.1. Engineering Prototype

There was sufficient confidence in the DOLPHIN concept that a design and construction contract was awarded to International Submarine Engineering Ltd. of British Columbia, and work on the project commenced in early 1982. Deep-V mono-hulls, submerged twin-hulls and submerged mono-hulls were considered for DOLPHIN. An analysis concluded that the latter would meet, and could probably exceed, our sea-keeping requirement.

An initial decision was made that diesel propulsion would be used because of the amount of power required at 15 knots, the endurance, and the comparative safety of the fuel over gasoline. Through an iterative process which examined resistance and the power available from a range of commercial diesel engines that would fit the various hull sizes considered, a hull measuring 1 m diameter by 5.5 m long was chosen (Fig. 1). The vehicle displaces 2.3 tonnes and is powered by a 6-cylinder, naturally-aspirated engine rated at 115 HP.

Combustion (and secondary cooling) air for the engine is drawn in through a 10 cm snorkel tube equipped with a special float/impact valve at the top and a water separator at the bottom. The snorkel doubles as a mounting site for a radio telemetry antenna, a strobe light, and a radar transponder (Fig. 2).

A segmented fairing on the snorkel mast reduces cross-track "lift" on the mast during high speed turns. the rolling moment is thus reduced, and vehicle stability is improved. A substantial keel with faired lead ballast (0.5 tonne) also contributes to passive roll stability and righting moment.

4.2. Dynamic Control System

DOLPHIN uses dynamic controls in all three axes to minimize pitch, roll, and yaw motions and to maintain the vehicle at the desired attitude and depth. These control systems comprise active planes, hydraulic actuators, electro-hydraulic servo valves, microprocessor hardware and software and motion sensors (gyro, inclinometers, accelerometers, angular rate sensors).

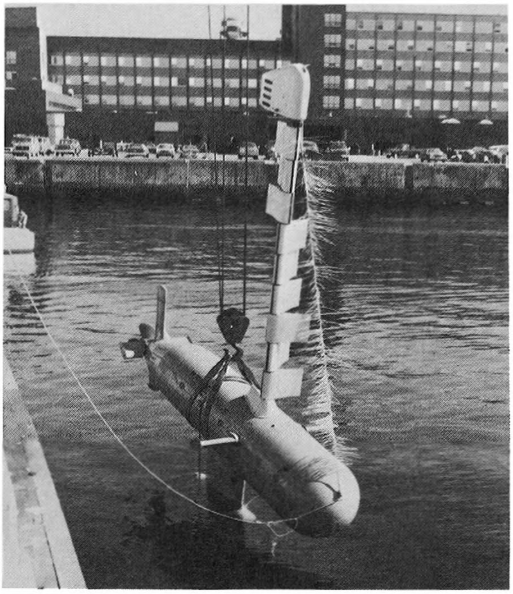

FIG. 1. — DOLPHIN ready for deployment and test at Bedford Institute of Oceanography. (Photo by H. Wiele).

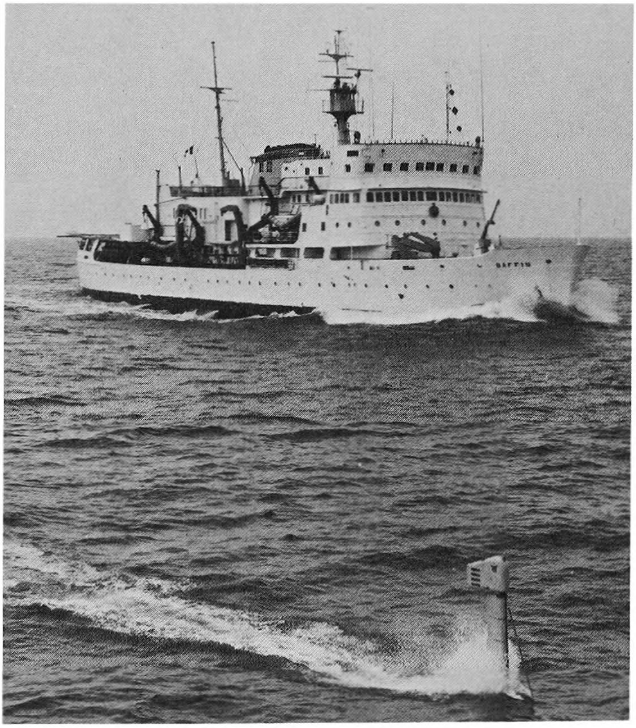

FIG. 2. — DOLPHIN underway at normal operating speed of 12 kt with CSS *Baffin* during sea trials. (Photo by R. Belanger).

The DOLPHIN vehicle (Fig. 1) uses a pair of forward lateral planes located near the center of mass (and center of pressure), and operated in unison to control depth without significantly changing pitch. The same planes, when operated differentially, control the roll of the vehicle. A pair of aft lateral planes, operated in unison, controls pitch; a rudder controls yaw and, of course, heading.

Active depth control is implemented using a pressure sensor and a vertical accelerometer whose integrated output (heave rate) is also used to ensure stability. Operational experience has shown that the direct accelerometer signal is not required, and that the vertical movement of the vessel is well controlled at all times. Some contouring of long waves takes place, particularly in a following sea.

To assist in evaluating DOLPHIN the various control loops can be adjusted by remote control.

4.3. Operational Aspects of DOLPHIN

By the use of simultaneous two-way (full duplex) digital telemetry in the UHF radio-frequency band, all operational functions of DOLPHIN can be remotely controlled, and the status of all vehicle parameters can be observed at the control console on the mother ship.

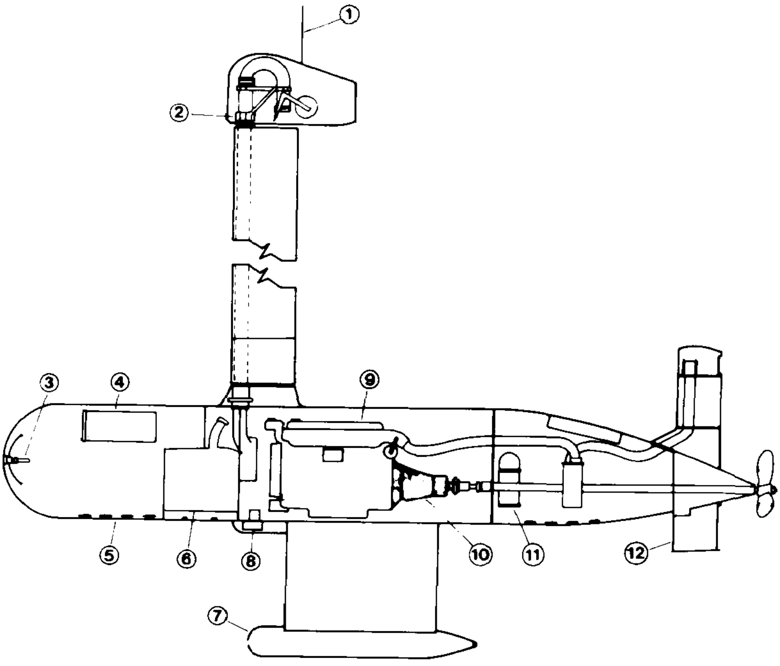

FIG. 3. — General arrangement of DOLPHIN. 1. Radio antenna. 2. Snorkel head. 3. Pressure sensor. 4. Electronics modules. 5. Future electronics. 6. Fuel bag. 7. Ballast. 8. Bilge pump. 9. Engine. 10. Transmission. 11. Air tanks. 12. Rudder.

DOLPHIN's operating depth is normally set for 3 m (at the center of the main hull) giving a keel draft of 4.5 m and a snorkel height of 2 m with reference to mean water level. Forward and aft floodable ballast tanks enable a buoyancy change of 0.6 tonnes to be effected via telemetry. The vehicle has a reserve buoyancy of some 70 kg (adjustable by trimming the lead ballast). Through the use of a bladder-type fuel tank, buoyancy change resulting from fuel consumption is minimized. Sufficient buoyancy exists when the ballast tanks are "blown" to keep the vehicle afloat even if the engine compartment were to be flooded. The tanks may be vented or blown on command, and they will blow automatically if any of a number of fault conditions exist, e.g. vehicle depth greater than 10 m, total loss of telemetry, etc. Certain fault conditions also cause a valve at the bottom of the air induction mast to close (thus isolating the engine compartment) and force the control planes to go to the climb position so that DOLPHIN surfaces quickly.

4.4. Performance Trials

DOLPHIN has been tested in enclosed waters and on the continental shelf off Nova Scotia. Including the manufacturer's own trials, the vehicle has been deployed on more than forty occasions, and total running time up to December, 1983 is estimated to be 300 hours which includes approximately ten 8-hour runs. Most recently, DOLPHIN was tested in 2.5-m seas on the continental shelf using the CSS *Baffin* as the mother ship. Performance in seas of approximately the design specification was excellent. The values of the gain and damping constants in the dynamic control system had been selected during previous trials in calm waters and the settings proved close to optimum in rougher water. Vehicle stability was surprisingly insensitive to changes in gain or damping. Visual observation clearly indicated DOLPHIN to have dramatically superior stability compared to that of a 9.5-m hydrographic launch. The vehicle followed the surface contour of long waves, but the heave error was clearly much less than that for the launch.

The maximum vehicle speed during the sea trials was 13 knots, just below the goal of 15 knots, and several factors may be responsible and are now being investigated :

(a) The optimum propeller has not been obtained.
(b) Several hoisting appendages, not faired for low drag, were fitted after delivery of the vehicle.
(c) The available shaft power of the diesel engine may be less than the maximum rated because of the pressure drop through the induction mast and the back pressure at the submerged exhaust.

4.5. Future Activities

DOLPHIN has entered the second phase of testing to determine its suitability as a platform for hydrographic instrumentation. Plans are underway to incorporate an echo sounder and a positioning system for operational evaluation during May-July 1984 in conjunction with CSS *Baffin*, our major survey vessel. Because of the intended use of DOLPHIN for offshore surveys, Loran-C is being considered for positioning, particularly as the position deduced from the mother ship's integrated navigation hardware can be used in a differential way to improve the DOLPHIN's Loran-C fix. Frequency-shifted retransmission of Loran-C or other (private) radio positioning signals from DOLPHIN to the mother ship is also being examined so as to minimize the cost per vehicle.

Also under review is the form and capability of "production" vehicles, in contrast to the engineering prototype. These plans and reviews, together with work on handling systems, will take place during the next 12-18 months. Following this, work must take place to develop the concepts and the engineering for handling an entire fleet of DOLPHINS.

5. ARCS — AN UNDER-ICE SURVEY ROBOT

In contrast to DOLPHIN, the development of ARCS (Autonomous Remotely-Controlled Submersible) was, at the outset, much more concerned with vehicle control and position than with the selection of an explicit vehicle suitable for the task. Because of the need to minimize propulsion power requirements (from batteries), a low-drag "torpedo" shape was quickly identified as a viable, economical hull form (Fig. 4.). It was clear that positioning and communications with the vehicle could only be via acoustics; however, the limited available data indicated there could be propagation problems under ice in shallow water. Consequently, an Arctic experiment was necessary before proceeding with the vehicle development. Confidence in the project would be lost if the results of the acoustic tests were poor.

The experiments were carried out near Resolute, NWT, in April/May 1982 and showed that accurate ranges (standard deviation, < 1 m; absolute range

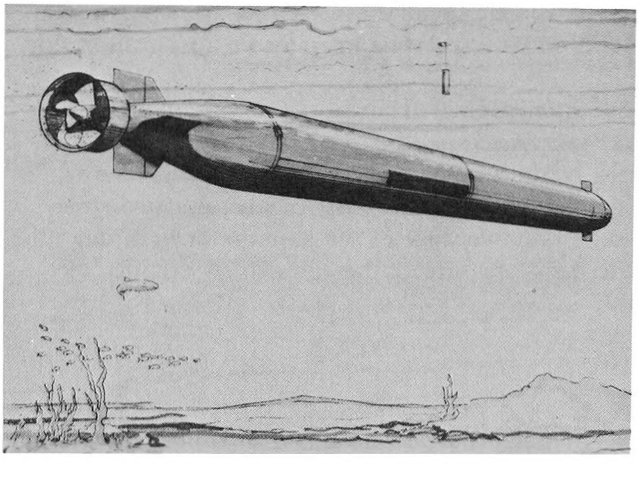

FIG. 4. — Artist's impression of ARCS operating under ice. The rectangular area on the vehicle's side represents a side-scan sonar transducer; the first ARCS vehicle will not be so fitted. (Illustration by Miles Fenton).

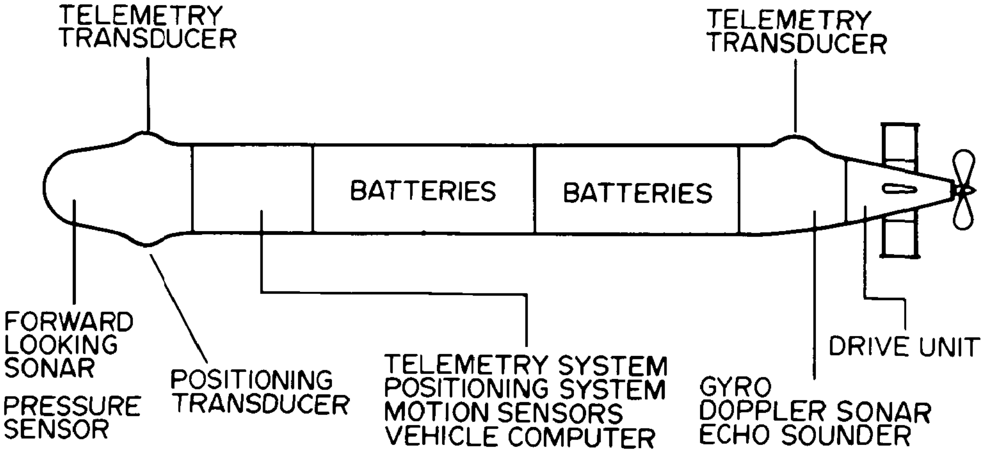

FIG. 5. — General arrangement of ARCS.

compared to surface range measured by laser, < 5 m error) could be measured to 6 km in water ~ 50 m deep, and to 10 km in water ~ 150 m deep. The results also indicated that the typical multipath-induced fading, which severely limits acoustic telemetry, could be significantly overcome by a suitable choice of modulation, viz., frequency diversity. Telemetry ranges of 6-9 km could be expected using moderate amounts of power (10-100 watts) and frequencies below 20 kHz. The experiment also determined that an area 18 km square could be surveyed with only *one* set-up of an ice camp at the center, making the ARCS approach worth pursuing.

A contract was awarded to International Submarine Engineering in mid-1982 to develop a suitable vehicle. A number of design goals were established at the outset based on the hydrographic requirements. These goals included a minimum endurance of 20 hours at 5 knots, a maximum weight of 1.1 tonnes, a maximum size of 54 cm diameter by 4.8 m long. In addition, the vehicle was to be capable of collecting bathymetry and position data while following a pre-programmed survey pattern and avoiding collision with ice keels or driving into a shoaling bottom.

During the early part of the design phase it became clear that the goals could not all be achieved unless advanced composite materials were used for the hull. Because of the uncertain low-temperature performance and the increased cost of a composite hull, a compromise in displacement was reached coupled with an increase in weight. Using aluminium for the hull a weight of approximately 1.5 tonnes was achieved. However, the concept of using only one of two battery modules was incorporated allowing the user to trade off weight against endurance.

During the design process it became clear that a certain amount of redundancy would be needed to achieve adequate assurance that the vehicle would not be lost because of a subsystem failure. While the "space program" approach of multiple systems and majority voting was considered to be excessively costly, the ARCS design has nevertheless incorporated several important redundancy features :

1. Dual navigation systems : (a) long baseline acoustic positioning from which "line following" information is computed, and (b) dead reckoning using a directional gyro and two-axis doppler sonar. The dead reckoning

system also provides position smoothing and improves vehicle guidance between acoustic fixes.

2. Back-up computer : The operating computer is supervised by a triply-redundant fault monitor which determines if the vehicle control software is being executed on a pre-established timing schedule and, if not, takes steps to restore the first computer; if unsuccessful, the second computer can be brought into operation.
3. Propulsion : Dual propulsion motors are used to drive the one propeller.

ARCS uses dynamic stabilization in only the pitch and the yaw axes. Roll stabilization is unnecessary because there is no cyclic wave action under ice, and propeller reaction torque is small enough to be easily countered by the righting moment. Vehicle depth and pitch are controlled by a single pair of elevators driven by an interactive feedback system. Yaw and heading are controlled by a dual rudder and a gyro.

5.1. Operational Scenario

ARCS will be deployed through an ice hole cut inside a heated shelter at the center of the 18 × 18-km working area (Fig. 6). Using four transponders and an acoustic telemetry unit, one quarter of the area can be surveyed at a time. The pre-programmed computer on ARCS will guide the vehicle over the desired survey pattern. Forward-looking sonar will detect objects on the flight path, and the computer will take the vehicle through a series of predetermined avoidance

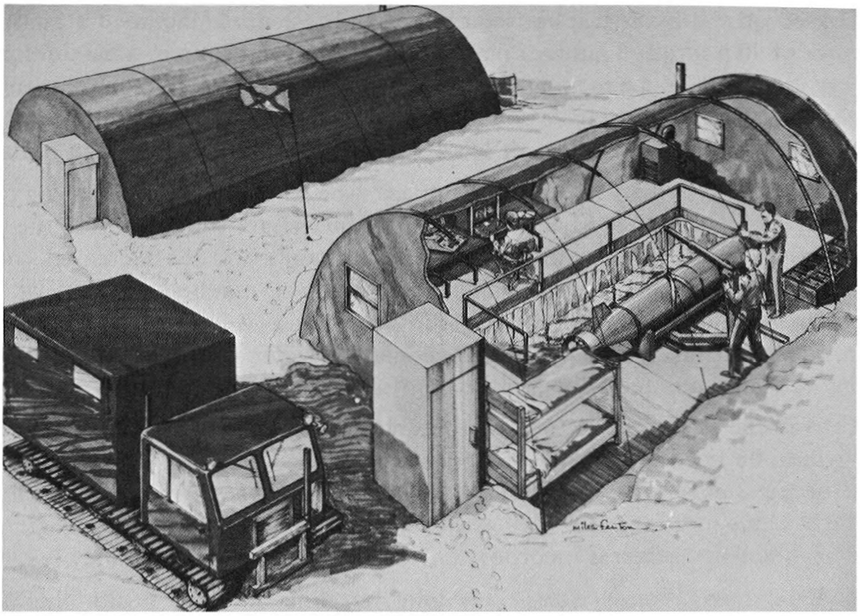

FIG. 6. — Artist's impression of ARCS being deployed through the ice. (Illustration by Miles Fenton).

manoeuvers and then attempt to get it back on line; if unsuccessful, an adjacent line will be surveyed. In the limit the vehicle will retrace its path back to the ice hole. Vehicle status and data quality indicators are telemetered to the control center at the ice camp, where an operator can choose to modify the vehicle's programmed survey path. Bathymetric data and position are recorded in the vehicle and are available upon recovery.

Many aspects of vehicle handling and recovery and other logistical problems are now being examined in preparation for an evaluation of ARCS in the Arctic during April 1985. In the more immediate future, ARCS will be evaluated in the waters around Halifax, Nova Scotia, after delivery in May 1984.

6. THE FUTURE OF ROBOTIC VEHICLES FOR HYDROGRAPHY

HASKINS has already noted robots' use in carrying out precise surveys to eliminate the errors caused by measuring from the surface of the water to the seafloor, particularly in deep oceans. Several authors have commented upon the need to more thoroughly map the continental margins, and various sidescanning and swathe-sounding sonars are being developed for this purpose. However, the parallel sounding technique eliminates the need to measure obliquely through the water column with its inherent errors of refraction, and results in a systematic, well-controlled set of depth profiles. To accommodate the parallel technique in rough, open waters it appears that remotely-controlled vehicles have a definite place. At this stage DOLPHIN has shown that the vehicle itself is feasible; it remains now to develop it into a production survey instrument. This will include the development of concepts needed to equip, deploy, and control a fleet of DOLPHINS.

Surveys beneath the ice have been an object of technological development for nearly a quarter century in Canada, but we have to date been unable to measure continuous profiles and operate as freely as we can in open water. Here again, robots may have a place, and it is to this end that the ARCS development is being directed.

There have been some thoughts that remote-controlled vehicles could replace survey launches for general coastal surveying, but this must be examined on the basis of cost effectiveness. At this time, we are enthusiastic about the progress of DOLPHIN, but we realize much is still to be done before we can employ such new survey systems in a routine way.

ACKNOWLEDGEMENTS

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Services, and Ship Division for their help in the evaluation of DOLPHIN. Special thanks are extended also to Mr. John BROOKE for his contribution as Technical Project Manager on the ARCS development contract.

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