TORPEDO TECHNOLOGY IN THE 1980'S

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ABSTRACT

New technology provides the opportunity for significant advances in undersea vehicles. Advances in artificial intelligence will permit vehicles to "learn" from measuring their environment and be able to distinguish desired targets from fish, rocks, boundaries, etc. Very high speed integrated circuitry (VHSIC) will package this capability compactly. Lithium type batteries and high speed motors with new magnetic materials or high energy metallic fuels with turbines or engines combined with computer designed thrust producers in filament wound or composite shells promise high performance systems.

1. INTRODUCTION

The acoustic homing torpedo, designed to attack submarines, is one of the earliest examples of an autonomous undersea vehicle. It has the job of independently searching out a volume of water, discriminating amongst sonar contacts to recognize its intended target, and then selecting an intercept course which not only takes into account the target course and speed, but also anticipates evasion tactics as well as possible countermeasures. Practice rounds used in fleet exercises must do even more. At the last instant they must remember not to actually run into the submarine and to surface after the run is over. They also provide detailed run records that allow detection of performance deficiencies.

Much of the technology that the Navy is developing for torpedoes provides a basis for other applications such as autonomous undersea vehicles. To translate the results of this technology to other applications, however, it must be kept in mind that the torpedo operates within radically different performance envelopes than most other autonomous undersea vehicles. By the nature of its task, the torpedo requires high speed maneuverability and the delivery of a sufficient payload to ensure target destruction. Overall system costs increase dramatically with torpedo weight and volume. Thus, major emphasis has been given to the development of propulsion, guidance, and control techniques that provide

optimum performance in a minimum size. Advances in target technologies demand continuing advances in torpedo technology. In responding to this challenge, the Navy is creating a rich base for the design of other types of autonomous undersea vehicles.

2. PROPULSION

One area where torpedoes press the state-of-the-art is speed. Of necessity, they must travel faster than most other undersea vehicles. What will be discussed here are highlights of some of the areas which have been investigated to achieve maximum sustainable speed and endurance in a minimum volume and weight.

2a. Open Cycle Propulsion

Open cycle propulsion systems are the baseline for the Navy's current torpedoes, and are used in both the Mark 46 surface and air-launched torpedo and the Mark 48 submarine-launched torpedo. These systems utilize an external combustion chamber for hot gas generation. The propellant of choice has been the monopropellant Otto Fuel II followed by a piston engine expander to drive the propulsor shaft. Although this was once considered an "exotic" fuel, it has proved to be safe and reliable in general use.

New Oxidizer

Advanced underwater propulsion systems have made it necessary to investigate higher energy density propellants which will also produce lower wakes than the current Otto Fuel II. Liquid bipropellants offer substantial performance improvement for open cycle propulsion systems.

Research has identified aqueous hydroxylamine perchlorate (HAP) as a potentially attractive oxidizer. Numerous combustion experiments with the HAP oxidizer over the last two years, as well as material characterization of the oxidizer, have validated the selection of HAP as the oxidizer of choice for high energy, underwater bipropellant systems. The oxidizer along with high density

hydrocarbon fuels offers a 57% increase in energy density over Otto Fuel II. Efficient stable combustion has been achieved. No handling or storage problems have been encountered which would preclude the use of this oxidizer in typical open cycle propulsion system hardware to achieve future high-energy-propulsion and low-gaseous-wake requirements. Cost effective methods for the synthesis of HAP oxidizer are under development.

Metallized Fuels

The use of fluidized metals as fuels for a liquid bipropellant energy source for thermal open cycle propulsion is being explored. They consist of a stable suspension of metal powder in a gel made from a liquid hydrocarbon, and are recognized as having the potential to provide a significant performance improvement over Otto Fuel II. An experimental demonstration of high combustion efficiency with aqueous HAP has not yet been made and is considered essential for establishing the feasibility of fluidized metal fuels. The combination of hydroxylamine perchlorate and metallized fuels offers the potential for a 100% increase in energy density over Otto Fuel II.

2b. Closed Cycle Propulsion

In tight maneuvers the torpedo's sonar can ensonify its own wake creating false targets for the guidance logic. Open cycle propulsion with its concomitant evolution of gas bubbles into the torpedo wake exacerbates this problem. Also, the significant back pressure encountered at necessary search depths can reduce engine performance and make search speed depth dependent. To avoid these limitations various closed cycle systems have been developed including thermal sources with sealed reaction chambers as well as electric motors operating from primary battery cells.

Closed Cycle Thermal Systems

Over the years, a number of high energy, bi-propellant torpedo propulsion systems have been investigated by in-house Navy laboratories and industry. Currently, only one bipropellant program is active to the point where it could be considered for torpedo applications. That program is SCEPS, Stored Chemical Energy Propulsion System. SCEPS is a closed cycle (Rankine) steam loop heated by the highly energetic reaction of molten lithium (Li) and sulfur hexafluoride (SF₆). The equation for the reaction is:

An important aspect of this is the high heat of reaction. On a reactant volume basis, this is comparable to that of a liquid oxygen/liquid hydrocarbon combination.

The basic elements of the system are a boiler-reactor, turbine/gearbox, feedwater pump, and skin condenser. It also contains an oxidant system, speed control system, start system, and

limit and check system. The Li-SF₆ reaction heats water in the boiler to make high pressure, superheated steam, which is then expanded through the turbine. The low pressure turbine exhaust steam flows to the condenser, where it is cooled and condensed to liquid water, rejecting heat to an external sink. The liquid water condensate is pumped to a high pressure by the feedwater pump and returned to the boiler to complete the cycle. The reaction products are entirely solid and more dense than the reactants so that the heat-producing reaction occurs in a sealed reactor chamber entirely independent of ambient depth. Consequently, no gaseous wake is produced.

2c. Electric Systems (Batteries)

Electric propulsion is a very important concept for torpedoes with its potential for low noise and negligible wake, which would thus enhance performance of the acoustic guidance system. Historically these attributes have been enhanced by the simplicity of electric systems, which are thus inherently reliable. Battery-electric systems have been used in past lightweight torpedoes, and substantial exploratory and advanced development is underway on improved electric components.

Aluminum-Silver Oxide Battery

The aluminum-silver oxide (NUSCAL) battery invented at the Naval Underwater Systems Center (NUSC), Newport, R.I., has been pursued as a candidate propulsion system for lightweight torpedoes because of its projected high energy density. Original estimates placed it at twice that of a magnesium-silver chloride seawater battery, and subsequent developments indicate that this system will be only slightly less dense than anticipated.

Recent developments in aluminum-silver oxide battery studies indicate that substantial gains in power density can be realized by operating at increased current densities and temperatures. A lithium-silver oxide battery is currently being investigated for even greater power densities.

Lithium Thionyl Chloride Battery

Another energetic system now under development is based on lithium and thionyl chloride (Li-SOCl₂). On a weight basis lithium is the most energetic element in the electromotive series. The lithium metal is considered not suitable for use in aqueous systems because of its chemical reactivity with water. Thus, it is generally used in non-aqueous electrolyte systems, which have been the subject of concentrated research since the early 1960's as the avenue to develop a reliable high energy lithium battery.

The theoretical gravimetric energy density of LiSOCl₂ is very high at 1470 W-hr/kg. In practice very large Li-SOCl₂ cells operating at low discharge rates have achieved energy densities of

nearly 600 W-hr/kg. Intermittent high discharge rates (300 mA/cm²) have been demonstrated in sizes of a few centimeters.

The largest prism-shaped cells built to date are low rate cells designed to deliver in excess of 12000 A-hr. The largest disc-shaped cells constructed to date are those built under a program directed by NOSC. These 0.43 m (17 in.) diameter 1500 A-hr cells are designed to deliver between 2 and 3 mA/cm² for 100 hours. However, higher rates can be achieved for shorter periods of time. Eleven-in.-diameter cells in 10-cell bipolar stacks have recently been discharged at power densities suitable for high-rate torpedo applications. Current densities on the order of 80 mA/cm² have been demonstrated.

Rechargeable Lithium Batteries

An ambient temperature rechargeable lithium battery is the most recent development in high energy density electrochemical systems.

The limited life cycle of rechargeable lithium cells is attributed to irreversible changes in the positive electrode and to the unfavorable morphology of the electrodeposited lithium. The failure mode of the positive plate is associated with the rupture of chemical bonds, and results in the reduction of lithium acceptance. The unfavorable morphology refers to the formation of dendrites or mossy growths during recharging. They may detach from the bulk material because of mechanical forces and/or an uneven distribution of the transfer current density.

Although extremely promising, a substantial research effort is required before these systems can be given serious consideration for Naval applications. Primary units may prove more cost-effective for torpedo applications, even though torpedoes are exercised periodically.

2d. Drag Reduction

Over the years, increases in target speed have necessitated corresponding increases in torpedo speed and endurance. Thus far, the latter increases have been achieved by improvements in propulsion rather than drag reduction. Although this trend seems likely to continue through the 80's, serious investigations of various methods of drag reduction will also be continued. Principal techniques include changes in body shape, polymer ejection, boundary layer heating, and boundary layer suction.

The cylindrical shape of current torpedoes has proven advantageous to transducer installation, internal design, water entry, the design of delivery systems, and fleet logistics. These advantages tend to outweigh the drag advantages that can be achieved by significant changes in shape, even though the latter are substantial. The transition from cylindrical shapes would be complex and costly. Consequently, this method of drag reduction is likely to receive serious con-

sideration only if speed and endurance requirements cannot be achieved within reasonable cylindrical envelopes.

Polymer ejection produces substantial drag reduction and can be implemented through careful engineering. Thus far, it has been more cost-effective to simply increase horsepower. The underlying trade-offs may favor polymer ejection for future undersea vehicles that must run for longer periods of time. FY82 research efforts will be focusing on methods of ejection that may prove more efficient.

In theory, dramatic decreases in drag can be achieved via heating and suction. The problems of implementation appear formidable at the present time, particularly for mass-produced weapons.

2e. Computer Designed Thrusters

Torpedo hydrodynamics has been a field of long range supporting research in a variety of areas including those drag reduction techniques indicated above. One of the most fruitful areas of research where transition to application has been made is in propeller design. Detailed analytical techniques have been confirmed by extensive water tunnel tests resulting in a computer-aided propeller design code which produces the numerically controlled milling machine tapes to fabricate high efficiency, cavitation resistant, quiet propeller sets. Techniques have been demonstrated for low-cost investment casting in aluminum and plastic molding for these complex, three-dimensional skewed designs.

3. GUIDANCE AND CONTROL (G&C)

A key element of the G&C for torpedoes is, of course, the sonar sensor and its associated signal processing. This will not be covered here, but rather some areas in G&C have been selected for their inherent applicability to autonomous undersea vehicles in general.

3a. Fiber Optic Data Links

In the past, the vast majority of unmanned submersibles operated at the end of a tow cable which provided mobility directly or supplied power for mobility. Mimicking the torpedo's self-propelled autonomous state, the unmanned submersibles now in design favor on-board power but retain a tether for the data link. Torpedo technology efforts are pioneering this field through the development of single cable, low loss optical fiber communication links which operate in a duplex mode. No metal strength member or electrical conductor is used. Very compact, tightly wound assemblies are obtained by computer controlled winding, and pretwisting assemblies the lightweight fibers into spools. A 5 km spool has been accomplished. High speed pull-out testing up to 35 meters per second has been performed, and

further high speed tests are scheduled. In addition, much greater lengths will be sought. The lightweight, almost neutrally buoyant optical tether imposes little weight penalty on the vehicle and reduces the changing center of gravity associated with copper wire tethers. The very large bandwidth capability of the fiber optic system offers tremendous growth potential. A family of optical sources, detectors and components such as pressure feed-throughs and pressure tolerant packaging are being concurrently developed for a complete data link capability.

3b. Information Processing

Historically, decision logic and signal processing have been hard-wired in torpedoes. Advances in digital technology now allow most of these functions to be effected via software and implemented in inexpensive, densely packaged hardware such as that which will result from the DoD Very High Speed Integrated Circuit (VHSIC) programs.

3c. Artificial Intelligence and Robotics

A robot has been defined as:

robot - A device equipped with sensing instruments for detecting input signals of environmental conditions but with a reacting or guidance mechanism, which can perform sensing, calculations, etc., and with stored programs for resultant actions, i.e., a machine running itself.

Current torpedoes certainly qualify as robots under this definition. Directions for advanced capabilities for the acoustic sensor and guidance and control packages will press that robot's ability to learn and adapt. Volume reverberation must be countered. Returns from the surface must be characterized and recognized. Bottom bounce and multipath conditions must be remembered or observed and accounted for. Background noise and ensonification of fish schools must be characterized and recognized. Hostile countermeasures and deception must be planned for and counter-countermeasure strategies developed. Environmentally adaptive techniques and sensors will be developed which sense the acoustic environment in space and time to predict the optimum sound channel for directed search. Selection of the proper choice between passive/active strategies based on the changing attack profile will be automated. Finally, the modeling of the physics of the environment, the target and torpedo must be done to achieve credible simulation and design synthesis tools.

Thus, we see that the rudimentary robot which is today's torpedo must become a machine which learns from its environment, adapts its sensor and guidance strategy to fit the environment, is capable of sorting out algorithms for "best" approach and corrects itself when it discovers it has been deceived.

Definition:

artificial intelligence -- Research and study in methods for the development of a machine that can improve its own operations. The development or capability of a machine that can process or perform functions that are normally concerned with human intelligence, as learning, adapting, reasoning, self-correction, automatic improvement.

Thus, it appears that the results emerging from artificial intelligence research will be of great benefit to the torpedo community and much more so to the vast majority of other autonomous undersea vehicles where the problem space to be searched allows for considerably more learning time than a brief 12-minute encounter.

4. SUMMARY

The U. S. Navy has sponsored and will continue to sponsor the development of advanced technologies of high potential in civilian/industrial applications for autonomous undersea vehicles. A brief listing of unclassified reports on these efforts is provided below.

BIBLIOGRAPHY

1. Marine Batteries - An Overview, J. F. McCartney and P. L. Howard, NUC, San Diego, Dec 1976.
2. Investigation of Lithium-Thionyl Chloride Batteries for Navy Applications, J. F. McCartney, W. H. Shipman and C. R. Gundersen, NUC, San Diego, Sep 1976.
3. Reactions of Tetrahydrofuran and Lithium Hexafluorarsenate with Lithium, V. R. Koch, EIC Corporation, Feb 1979.
4. Vanadium Oxide Cathode Materials for Secondary Lithium Cells, D. W. Murphy, P. A. Christian, F. J. DiSalvo and J. N. Carides, Bell Telephone Laboratories, Mar 1979.
5. Effect of Suspended Particulates on Intermittence and Boundary Layer Transition of Suction Stabilized Boundary Layer Flow, Ladd, D. M., NOSC TN 834, Mar 1980.
6. Theoretical Comparison of Single and Counterrotating Propellers with Propeller Having Upstream Swirl-Inducing Stator, D. M. Nelson, NOSC TD 327, Feb 1980.
7. Wind Tunnel Tests to Provide Propeller Design Information for WSHS Test Vehicle, D. M. Nelson and J. J. Fogarty, NOSC TN 778, Feb 1980.
8. Free-Swimming Submersible Testbed (EAVE WEST), P. J. Heckman, NOSC TR 622, Sep 1980.
9. Application of Robot Technology to the Marine Tactical Environment, S. Y. Harmon, NOSC Technical Publication, Jun 1980 (in publication).
10. Manned and Remotely Operated Submersible Systems: a Comparison, H. R. Talkington, NUC Technical Publication 511, Jun 1976.
11. Fiber-Optic Communication Links for

Unmanned Inspection Submersibles, S. J. Cowen, M. Kono, and P. J. Heckman, NOSC TR (in publication).

12. The NOSC/MIT Submersible Manipulator: An Experiment in Remote Supervisory Control of a Microprocessor Based Robot, P. Heckman, D. Yoerger, and T. B. Sheridan, Session F10P on Robotics, International Conference on Cybernetics and Society, Cambridge, Massachusetts, Oct 1980.