The Evolution of AUV Power Systems

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***Abstract* – The heritage of the AUV and associated power system can be traced back to the 19th century clockwork torpedo. Today power systems based on a multitude of concepts from closed-cycle heat engines to solar charged batteries are available. This evolution of AUV power systems has been enhanced by the growing involvement of the non-military underwater science and engineering sectors since the 1960s. However with the present trend of using AUVs mainly in hydrographic survey tasks, especially in the deep oceans, manufacturers are choosing reliable and affordable battery systems in preference to the many potentially high performance exotic power systems which could provide true autonomy to the vehicles. In this paper the authors trace the evolution of AUV power systems and attempt to provide some insights into this evolution.**

I. INTRODUCTION

Underwater vehicle propulsion is achieved through the conversion, transmission and utilization of energy in a sequence of events that includes the development of power in a prime mover, its transmission to the propulsive device, the development of thrust on the working surfaces of the propulsive device and the transmission of thrust to the vehicle's structure in such a way as to move the vessel through the water. In addition for an 'Autonomous' Underwater Vehicle (AUV) propulsion system, other subsystems are required such as an energy source for the prime mover, and sinks which receive the waste products and energy not utilized by the system. Fig. 1 shows the units used in a generic system for the development and transmission of propulsive power in an underwater vehicle.

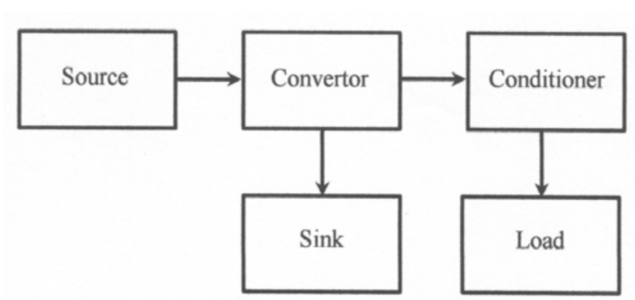

Fig. 1. Power System Components

To carry out its mission the vehicle must also carry sufficient energy and provide sufficient power to operate the various elements of the payload which could include sonar for navigation and mapping, data transmission and reception, cameras, oceanographic sensors and so on. The non-propulsive power needs of the various systems carried by the vehicle are known as the 'hotel load'. The subsystems are normally integrated and packaged within the vehicle structure in a manner such as shown in Fig.2.

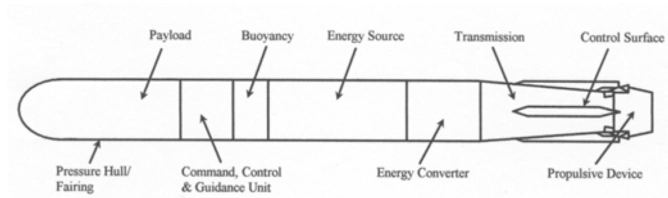

Fig. 2. Typical AUV Sub System Packaging

An AUV, if it is to be true to its description must have the capability of operating without the need for external support in order to carry out its mission. This may seem an obvious statement but as yet there is no precise definition, or at least no universally accepted definition, of exactly what is an AUV. {Similar problems of definition have long existed with submarines and submersibles.} Nevertheless, it would be useful to have a working definition of exactly what is an AUV as this helps define the scope and boundaries of the discussions.

Blidberg, [1] in his paper on the development of AUVs encountered a similar need and used a categorizing scheme where underwater vehicles are classed as either *manned* or *unmanned* and the latter are further categorized into three sub-classes, towed submersibles, tethered Remotely Operated Vehicles (ROV) and Unmanned Untethered Vehicles (UUV). The UUV is considered by Blidberg to be a vehicle which while having its own onboard power is controlled by a remote operator via some form of communications link whereas an AUV controls itself on a pre-defined mission and requires no communication during its mission, Fig. 3.

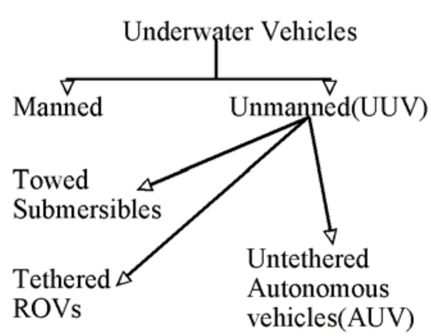

Fig. 3. Underwater Vehicle Classification Scheme

The classification scheme depicted in Fig. 3 is seemingly straightforward but the use of different terminologies and definitions in both the civilian and military communities has given rise to a multitude of acronyms and on occasion inadvertent interchangeability of terms. The US Navy use the term UUV to encompass both ROVs and AUVs [1] whereas many involved in the early commercial and scientific development of unmanned underwater vehicles employed the term AUV. Schubak and Scott [2] define AUVs in terms of comparative size referring to them as *small* UUVs. Perhaps the problem is with the application of the term 'autonomous'?

According to the dictionary the word means 'self-governing' or 'freedom of the will'. If these characteristics were to be strictly applied there would be few underwater vehicles that could be classified as AUVs. Klevebrant and Lindström [3] in grappling with the definition issue suggested the definition "*Autonomous to some extent*." The authoritative publication 'Remotely Operated Vehicles of the World' [4], now in its fifth edition appears to use the Klevebrant and Lindström approach for vehicle classification. The authors have adopted the same stratagem of classification for the scope of this paper with the codicil that the power system of the vehicle is independent of the surface environment during its mission except in the case of the Dolphin/Dorado vehicles manufactured by ISE Research Ltd., of British Columbia, Canada [5]. The development of these particular vehicles has played a pivotal role in AUV technology advances and therefore should not be excluded because of the vagaries of equivocal definitions.

II. EARLY DEVELOPMENTS

The history of mankind's efforts to explore and exploit the underwater environment spans three millennium [6]. Between the 14th and 18th century there are many detailed documents describing conceptual and in some cases, actual, powered underwater craft, the energy source being human muscle. One notable attempt to put underwater technology to naval use was in 1772 when the Chief Engineer of the German Military Academy, J. Chr. Praetorius, was commissioned to build a narrow 'diving boat' [8]. Apparently, Praetorius built a 10 metre vessel which had a fish profile and when submerged it was to be powered by a 'fish-tail' and armed with a falconet – a small type of cannon. This 'diving-boat' was to be part of the Count Schaumburg-Lippe's Lake Steinhuder Fleet. The boat was constructed but it is not known if it actually operated underwater [8]. Although once again this was to be a muscle-powered manned underwater vehicle the idea of using a fish-like profile and a propulsion system mimicking that of a fish was to remerge in AUV research in the U.S.A. and Japan some two centuries later e.g., [9,10] and Fig. 4.

The year 1772 was also noteworthy in underwater vehicle history, in that an Englishman named Day was killed when his submarine boat was crushed by water pressure after he had accepted a wager to take his vessel to the bottom of Plymouth (UK) harbor. He was arguably the first victim of a submarine accident [11].

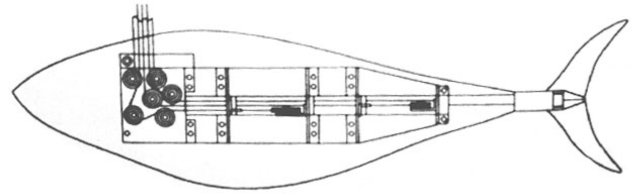

Fig. 4. The MIT Robot Tuna

The most famous early efforts to use underwater craft for naval purposes was during the American War of Independence when Bushnell's human-powered submarine the *Turtle* armed with a clockwork mine was used in an attack in New York harbor on the 50-gun British warship, *HMS Eagle*. The operational failure of *Turtle* lead to a realization that if underwater naval vessels were to be effective they required a suitable weapon [7]. It was in the search for such weapons that modern AUVs and their associated power systems have their origins.

Despite the efforts of Praetorius and Bushnell and others, amongst many of the senior ranking officers of the leading naval powers of the 18th and early 19th centuries the concept of the underwater warship and weapon was rarely greeted with enthusiasm. Underwater vehicle and weapon developments during this period were usually the result of the efforts of private individuals and idiosyncratically these inventors enjoyed more acceptance and success outside of their country of origin.

The early adventures and often disasters with underwater vehicles although gradually improving the state of knowledge about the design requirements of such vessels and demonstrating the promise of the efficacy of underwater warfare did not lead to any significant developments in underwater power systems. Then, as now, advances in power systems technology were largely left to other fields and usually when such systems showed some engineering maturity attempts were made to modify them for use in underwater vehicles.

By the 19th century reciprocating steam and hot-air engines had already been developed and the foundations of internal combustion engine development had been established by the work of Otto, Benz and Daimler. The German designer, William Bauer, in 1858 proposed a submarine of over 400 tonnes displacement using an IC engine of about 170 kW output when submerged to give the vehicle a speed of 4.12-4.62 m/s {8-9 knots}[8]. Bauer also suggested using a combustion mixture of kerosene and oxygen. The latter was to be obtained underwater from the decomposition of manganese dioxide. Bauer was the first researcher, on record at least, to realize that oxidant selection underwater was to be a challenging issue, a situation that still exists [e.g., 12]

However, without doubt, the major technical breakthrough not only in AUV design but also AUV power systems was the development of the Whitehead's torpedo [13], Fig. 5. Robert Whitehead, an Englishman who found fame and fortune as a marine engineer in continental Europe, was introduced to the concept of what is now called a torpedo by an Austrian naval officer, Commander Giovanni de Luppis who had been trying to develop around 1860 the *Der Küstenbrander* (literally – the coastal fireship) without a great deal of success [13]. One of the major problems was the method of propulsion and the power source. Although the device had progressed from the direct human-muscle system it was still in a way human powered since it used a mechanical clockwork mechanism. Whitehead not only improved the overall Luppis design so that the 'torpedo' could operate fully submerged but used radial engines powered by compressed air. This form of propulsion and energy source was to become the standard system for many years.

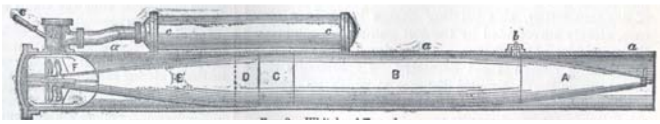

Fig. 5. Early Whitehead Torpedo

Some torpedo designers eventually replaced the radial engines with turbines but all were, by and large, *cold* engines with a compressed gas such as air, carbonic acid gas being expanded via a radial or turbine engine. By the start of the 20th century hydrogen peroxide turbines has also been developed which proved to be the forerunners of the British torpedoes of the mid 20th century and the modern day Swedish torpedoes.

Although in the developments from the time of Whitehead to the Great War of 1914-1918, the Whitehead torpedo power and propulsion systems were not bettered many innovative concepts were tested with some success especially the Howell torpedoes which used the stored energy of a spun flywheel as the energy source. One of Howell's designs achieved speeds up to a maximum of 15.4 m/s {30 knots} and were the standard torpedo of the U.S. Navy between 1890 and 1900 [13, 14]. During the period from 1870 to the Russian-Japanese War, steam and rocket propulsion was experimented with both in the USA and Britain. In the former case a container would be charged with superheated water, under pressure, which generated steam as the valve leading to the engine was opened [14]. The famous Swedish–American engineer Ericsson experimented with electric propulsion whereby a motor would be energized by lead-acid accumulators. The noted entrepreneur of the same period Nordenfelt also developed electric torpedoes as well as a number of different submarines [15].

By luck as much as judgment it was found that if the compressed gas for the expansion engines was warmed by the surrounding seawater significant power system performance resulted. To some extent this was a fortuitous observation since during the gas expansion frosting of the engine, radial or turbine, was a common operational problem. Heating systems such as the 'Elswick' heaters were developed to pre-warm the compressed gases [13] but it was the introduction of the 'combustion' pot by the Bliss Leavitt company in 1904 – with further improvements in 1910 – which greatly improved the performance of the Whiteheads system [14]. This pot was located between the compressed gas reservoir and the engine and a hydrocarbon or alcohol fuel – usually kerosene – was combusted. This system was so successful that it was used in torpedoes of the Second World War, Fig. 6.

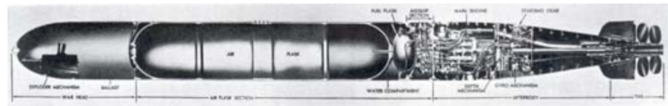

Fig. 6. US Navy WWII Torpedo [14]

By the start of the 1914-1918 War, the birthright of many of the propulsion and power systems still being developed today, including:

- Dynamic Heat Converters
- Battery-Electric
- Expanded Gas (Cold and Heated)
- Rocket-Jets

had been established. Moreover, not only had the selection of the 'fish'-like profile provided good hydrodynamic characteristics but individuals such as Whitehead and Froude full appreciated the need for such profiling and the need for feedback controls to improve vehicle performance and thus make efficient use of the onboard energy supply [13]. As Corell [16] stated in 1987 when reviewing the state-of-the-art papers presented at the 5th International Symposium on Unmanned Untethered Submersible Technology (which attracted 330 attendees, a 20-fold increase over 1980), Whitehead, as early as the mid-1800s had been using control function monitoring. The point being that although significant advances in control and autonomy were manifest in the many research papers presented the advent of many of the principles described had occurred well over a century ago.

III. THE EXCLUSIVELY MILITARY ERA 1914 –1965

Exactly which year the military era of AUV development started and the 'exclusively' ended is a matter of opinion. However, especially for the sake of discussion the period 1914-1965 seems to be reasonably distinctive. There is no doubt that as soon as the naval powers began to fully appreciate the awesome power of the submarine during the build-up to the 1914–1918 War, that underwater vehicular technology developments and the subsea environment became, with few exceptions, the sole jurisdiction of the military. The only true form of the UUV/AUV during this era was the torpedo which in some cases were also were manned either for clandestine [17] or 'kamikaze' type operations.

The development of underwater power systems continued during the 1914-1918 War and throughout the inter-war years. For manned operational naval submarines a two-unit power system configuration became the universal standard until the mid-1950s. The units were separate and different, one being used for surface propulsion and the other for underwater propulsion. On the surface the diesel engine was the heat engine of choice although attempts were made at using steam propulsion [18]. Underwater the battery-electric motor arrangement using the ubiquitous lead-acid system reigned supreme. The essential features of the two-system diesel-electric approach the remained the same throughout this era [19,20] and survive up to the present day. The diesel-electric powered or *conventional* submarine is still the most populous. Obviously since 1913/14 there have been many performance and operational improvements both to the diesel engine and the battery-electric motor systems.

The dominant performance parameter for underwater vehicles until the 1940s was surface speed. By the end of the first decade of the 20th century navies had started to appreciate the offensive capabilities of the submarine and expanded its role in their order-of-battle beyond the coastal defense applications hitherto envisaged. Initially, the submarine was intended to operate as part of a battle-fleet but this *modus operandi* was quickly abandoned in favour of independent action. In either case the submarine was required to be faster when on the surface in order to keep up with the rest of the fleet or to outrun a hostile surface warship or convoy escort. Indeed the smooth fish-like profiles used by the great early designers such as J.P.Holland soon disappeared in a clutter of hull and deck appendages including increasingly larger guns.

As naval tactics changed and as submarine detection began to rapidly improve the need for greater submerged endurance and speed became necessary. Hull forms returned to the cleaner lines of earlier years and the snorkel was adopted to enable air to be drawn into the vessel whilst submerged to allow the diesel engine to be operated for battery charging purposes.

Nevertheless, improvements in vehicle hydrodynamics and battery technology alone could not enable submarines to operate at high speeds (then 7.7-9.3 m/s {15-18 knots}) for more than a few tens of minutes. Efforts were made to improve this limitation especially by the German Navy in the 1930s and early 1940s. The focus of the developments were closed-cycle heat engines, both reciprocating and rotary. The latter involved the hydrogen peroxide Walter turbine system. In both cases the application was for manned underwater vehicles. These developments achieved some notable technical successes but the vehicles never entered operational service [8]. Patents on such systems were lodged as early as 1906 [19] and the German Navy developed a working system before the 1914-18 War only to cancel it when on the point of success due to a fatal accident involving a non-diesel fuelled version.

Although a variety of underwater vehicles, such as midget submarines, two-man underwater chariots and even underwater canoes were developed for 'special forces' in the wars of the first part of the 20th century the only unmanned untethered vehicles were still the torpedoes. The Japanese Navy made extensive use of heat engines in their technologically advanced torpedoes whilst the German Navy developed similarly advanced electric torpedoes.

After the end of the 1939-45 War using in many cases captured technology the British, Soviet [21] and especially the US Navies [20] embarked on the intensive development of submarines that were to be much faster underwater than on the surface. The advent of the first fully functional nuclear-powered submarine the USS *Nautilus* [22] severely curtailed for almost thirty years any further international attempts to develop non-nuclear underwater power systems for naval submarines. Ironically, the Nautilus was slower than some of the advanced but largely experimental non-nuclear submarines of the time but she had the ability to maintain high underwater speeds several orders of magnitude longer than her rivals.

There were some developments with torpedo power systems in the search for higher speeds. First in the UK and then in Sweden the hydrogen peroxide turbine systems became operational and a number of closed cycle heat engine systems paralleling the pre-1955 submarine power systems developments were investigated. A new player on the scene was the Stirling Engine [23], originally patented in 1815, but redeveloped by the Dutch Company NV Philips of Eindhoven in the 1930s. For many years, after early interest from the Ford Motor company, the giant US company, General Motors, in conjunction with NV Philips developed a Stirling engine powered underwater power system for a heavyweight torpedo.

By the start of the 1960s an extensive array of underwater power systems had been either quite thoroughly investigated or developed for naval applications. However, most were further developments of ideas whose heritage was almost fifty and in some cases over a hundred years old. The underwater Stirling Engine and specialized liquid monopropellant and metallic fuels were the only new developments which attracted more than cursory attention. The naval torpedo remained the only AUV in use but the discovery of offshore liquid and gaseous hydrocarbon deposits was soon to bring about the start of a revolution in underwater vehicle engineering [24].

IV. WEALTH FROM THE OCEANS

Until the 1960s the subsea environment or *"inner space"* was almost exclusively used by the military, with the naval submarine and the torpedo proving their combat effectiveness in two world wars. Even today the submarine is probably the greatest maritime asset and threat a nation can possess. However, over the last forty years the commercial and scientific communities have also started to explore and exploit the deep oceans. In the commercial field, with many non-renewable land-based resources, not just hydrocarbons, becoming depleted, the search for alternative sources of raw materials is intensifying. This situation lead by the start of the penultimate decade of the 20th century to the involvement of a number of countries, especially those of the European Community, in the heavily funded *"Wealth from the Oceans"* projects. In the scientific community, attention began to focus on developing a greater understanding of the ocean's fragile ecosystems [25], whilst all users of the oceans were seeking to obtain better hydrographic and mapping data .

With the advent of the offshore hydrocarbon industry there was a growing realization that the safety hazards and the financial costs associated with using human intervention systems in the often hostile, and always challenging underwater environment, were daunting. Moreover, as the need or desire to operate in ever deeper waters and under the ice-caps increased, alternatives to manned underwater vehicles were also sought. Thus, in the 1970s and 1980s with the growing number of identified potential military, commercial and scientific missions the development of many varieties of unmanned underwater vehicles were instigated [26,27].

At first the type of vehicle preferred especially in the oil and gas fields of the European North Sea was the remotely controlled or Remotely Operated Vehicle (ROV). These vehicles were supplied with power and control functions via an umbilical cable or tether attached to a surface vessel or installation. By the end of the 1980s a great deal of operating experience had been gained and reported on ROV operations and technology. The single most restrictive item in terms of both improving operational effectiveness and reducing costs of ROVs was found to be the inherent need for the use of an umbilical cable or tether [28]. The ideal solution was considered to be the Autonomous ROV and to achieve this seven technology development areas were identified in the technical literature as requiring attention [e.g., 28]:

- Energy/Power Source
- Propulsion Systems
- Command, Control Telemetry
- Navigation/Obstacle Avoidance
- Tooling/Manipulators
- Communications
- Data logging/visual recognition

Several other similar lists were suggested some including such areas as hull shapes and materials, launch and recovery systems and so on. In all the lists power and energy systems were identified but it was invariably decided that developments in these areas would come largely from outside the oceanic and underwater research and development communities.

Nevertheless some AUV development did take place in the 1960s although there is a dearth of open literature on the subject [1]. Moreover, notwithstanding the outcomes of the many ROV experiences [e.g., 28] the potential of the AUV was explored in the 1970s with a handful of vehicles being developed as test-beds by US and Scottish Universities and Japanese, Soviet and US government agencies [29,30], as illustrated in Table 1.

The advent of advanced microprocessors and accompanying software and hardware architecture provided the AUV community with the opportunity for significant technology leaps in the two decades starting 1980. the ability to provide rudimentary intelligence together with sophisticated control and navigational systems hastened the development of many times of AUVs as the example list in Table 2 demonstrates. The specifications of the US DARPA AUV vehicle, high speed and long endurance, spurred a flurry of activity especially of power systems development [31,32]. By the start of the 21st century a wide range of underwater power systems, Fig 7., were in various stages of development and in some instances commercialization. The problem had become which one to choose and which one was the best [29]?

TABLE 1
EXAMPLES OF AUV c. 1960-1979

YEAR	VEHICLE	COUNTRY/ DEVELOPER	POWER SYSTEM
1963	SPURV1	USA/ University of Washington	Electric (Silver-Zinc Battery)
1972	UARS	USA/ University of Washington	Electric (Silver-Zinc Battery)
1973	SPURV2	USA/ University of Washington	Electric (Silver-Zinc Battery
1975	SKAT	USSR	NK
1977	Unnamed	Japan (JMSTC)	NK
1979	EAVE-111	USA/ University of New Hampshire	Electric (Lead-Acid)

TABLE 2
EXAMPLES OF AUVs DEVELOPED 1988-1997

MODEL	MANUFACTURER	DEPTH (m)	PROPULSION/ ENDURANCE	ENERGY SYSTEM	SIZE (m)	WEIGHT (kg)	YEAR
XP21	Applied Remote Technology Inc. US	610	2 x 1 h.p. 2 x 0.5 h.p. Thrusters	Aluminium Oxygen Fuel cell	Ø 0.525 L 7.45	828	1988
SEA LION MT-88	Russian Institute for Marine Technology Problems	6000	25-35 miles, 6 hours	Silver Zinc Battery	Ø 0.7 L 3.8	1000	1988
R1	Mitsui Engineering and the University of Tokyo	400	20 hours @ 3.6 knots	Closed Cycle Diesel	Ø 1.1 L 8.2	-	1990
MUST	Perry Technologies, US	610	8-24 hours Hotel load: 7.5 kW	Lead Acid Battery	Ø 9.0	8853	1990
DARPA	Charles Stark Draper Laboratory, US	457	24 hrs @ 10kts. DC Brushless Motor	Silver Zinc Battery	Ø 1.1 L 10.8	6810	1992
AUSS	US Naval Command, Control & Ocean Surveillance Centre	6000	10 hrs @ 6 kts	Silver Zinc Battery	Ø 0.75 L 5.1	1226	1992
THESEUS	ISEL, Canada	>1000	>275 Nm @ 4.0 knots	Nickel Cadmium/ Silver Zinc Battery	Ø 1.27 L 10.7	8600	1993
ARUS	Tecnomare, Italy	6000	2500 km/240 hrs	Closed Cycle Diesel	Ø 1.2 L 9.0	-	1993
ODYSSEY II	MIT	50	3 km/6-12 hrs	Silver Zinc Battery	Ø 0.59 L 2.15	160	1994
AUTOSUB 1	Southampton Oceanographic Centre, UK	300	> 5km/6 hours	Lead-Acid	Ø 0.9 L 7.0	1400	1997
AURORA	ISEL, Canada	3000	750 km @ 1.5-2.0 kts Brushless DC Thruster	Lithium Battery	Ø 0.9 L 2.7	430	1997

V. RECENT TRENDS AND DEVELOPMENTS

In the most recent edition of the most comprehensive catalogue [4] of ROVs and AUVs, there are some forty-five different (depending upon interpretation) types of AUV commercially available or in the prototype testing phase such a bottom crawling AUV. Of these over 84 per cent have operational or maximum diving depths of 200 metres or more, almost half have diving depths of 500 metres or more and 11 per cent are designed for operational depths down to 6000 metres. The use of dynamic heat convertors below 200 metres becomes problematic because of the need to expel the exhaust gases from the vehicle against the prevailing back-pressures. Although such operations are technically possible the amount of power required to force the gases into the surrounding water becomes excessive. Not surprisingly the power system of choice has remained the secondary battery-electric motor combination especially for the deep diving AUVs.

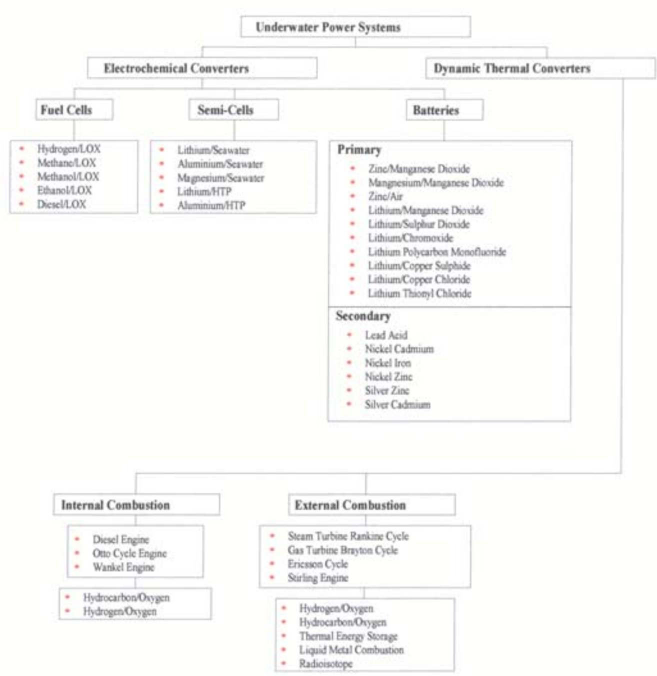

Fig. 7. Underwater Power System Candidates

In the selection of batteries, the lead-acid type remains popular but by no means dominates the market, Fig 8. The nickel-cadmium and the more expensive silver-zinc batteries are frequently used and the lithium primary based batteries are becoming more popular. Fuel cells and semi-cells systems are also being tested with one Canadian company, Fuel Cell Technologies (FCT) Ltd., developing an aluminum-oxygen cells in the range 50 W to 5 kW specifically for underwater applications [33].

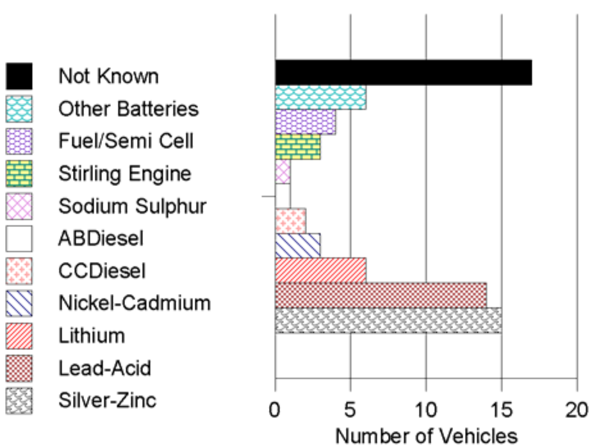

Fig. 8. Survey of Current AUV Power Systems

In terms of applications it appears for the moment that the AUV is becoming a hydrographic tool of choice particularly for deep water survey applications by both the military and non-military communities. The former is also relying increasingly of AUVs for countermine warfare - hunting, detection, identification and neutralization . Indeed if the PAP#5 mine-hunting vehicle , is accepted to be an AUV then it is the most successful AUV with over 450 already produced [4]. In the majority of hydrographic applications then the AUV is a self-propelled, autonomous side-scan sonar.

VI. THE FUTURE

The number of institutions, including universities, that are actively involved in underwater technology research has stabilized over the last decade . Of the important technology areas identified as requirements for the success of AUV development the trend for these institutions other than example such as FCT has been to concentrate, by choice, on the technology areas other than power systems. This has been a common trait in underwater vehicle development since the advent of the nuclear-powered submarine [1,29].

The commercial and military use of AUVs and in some cases groups of AUVs in concert has begun and truly commercial products are now available. Many of the power systems technologies are reaching technical maturity. The Stirling Engine has proved itself in operational sea service for close to two decades with the Royal Swedish Navy and the closed-cycle diesel and fuel cell systems have undergone extensive testing. Nevertheless the battery-electric system whose use was first attempted in the mid 19th century for a torpedo is still the power system of choice.

With the advanced electronic and navigational technologies now available it can be said that AUVs in terms of the Klevebrant and Lindström [3] definition are now autonomous to a greater extent than ever before but the key to full autonomy is still arguably the onboard energy and power systems. Whilst battery systems have to be used there will almost always be a limit to the scope of a mission unless some onboard in situ battery charging is available. Nuclear isotope and reactor systems could be used in an AUV to provide energy and power autonomy but is unlikely to happen not least because of the costs involved. Similarly fuel cells and semi-cells can extend the range of most battery powered AUVs by at least a factor of three and in some instances an order of magnitude [34]. Once again cost is the major obstacle.

However, in the past few years two novel power systems have been proposed using renewable energy sources. The first the idiosyncratic Solar powered AUV [34], the second the more futuristic ‘thermocline’ engine [35]. With respect to the concept of in situ battery-charging, in the latter part of the 1990s details about the Solar powered AUV concept began to appear in the technical literature . The concept is to attach solar panels to the vehicle which can be used to recharge onboard batteries, Fig. 9. The system is now under joint development by the AUSI and Institute of Marine Technology of the Russian Academy of Sciences started sea trials at the end of the 1990s[36].

Fig. 9. Solar Powered AUV [36]

The other renewable energy AUV is the SLOCUM, described by its inventors and developers as an underwater glider [34]. The basic concept is that a thermal engine system using a phase-change fluid absorbs energy from the higher temperature surface water and rejects it to the cooler deep during the vehicle glide down the thermocline. The stored energy by using a system of hydraulic valves and bladders can then be used to alter the buoyancy of the glider enabling it to descend and ascend. 'Hotel' load is provided by the batteries. This novel system has apparently been proven at sea but very few precise details of the thermocline engine have yet been provided.

VII. CONCLUDING REMARKS

The origins of AUV power systems can be traced back to the beginnings of recorded underwater technology in the times of Herodotus, Alexander the Great and Aristotle. However, it was only in the 18^{th} and particularly the 19^{th} century that ideas and concepts began to become reality and actual prototypes and in the case of the Whitehead-type and Howell torpedoes were commercial products. Bushnell, Fulton, Bauer, Nordenfelt, Holland and others demonstrated the practicality of underwater military vehicles and in so doing provided or prompted the provision of much of the fundamental technology and science.

Once the private inventor and the commercial shipbuilders had at last attracted the attention of the leading navies and nations the development of underwater vehicles and their associated power systems passed almost exclusively into the hands of the military until the foraging for oceanic liquid hydrocarbons in the 1960s. From that time on the scientific and commercial communities entered the fray of underwater vehicle development. Much of the knowledge gained by the military in some fifty years of research and development was not available to the non-military communities especially with regard to design methodologies [28,37,38].

Over the last four decades or so, the viability and the need for unmanned underwater vehicles to carry out work tasks have been clearly demonstrated by those outside the military. The success and in some instances the inventiveness of the civilian underwater sector, e.g., the human-powered submarine designs, has attracted the attention of the military such that today there appears to be closer relationships and technology-transfer type collaborations between universities, industry and the military. Nevertheless, these type of affiliations do not always lead to the results or advances anticipated. In the cold-war era the military, understandably, were very focused upon *mission-effectiveness* whereas private enterprise and commercial operators are invariably focused on *cost-effectiveness*.

Thus, many exotic power stems were developed or proposed which proved to be either too expensive for normal non-military use, e.g., closed-cycle heat engines using metal combustion, or which required colossal R&D investments to ensure that the system had the reliability required by the military. This scenario often led to both the military and the non-military returning after some novel excursions to the use of battery power for many applications. The operational success of the survey data gathering AUTOSUB and Autonomous Benthic Explorer [4] AUVs have further strengthened the case for battery-power.

Hence, after over three decades of AUV development following the breach in the exclusive use of the oceans by the military it has become clear that no single AUV concept meets all user needs. Nevertheless great strides have been made in technology developments and in design methodologies. Indeed one of the world's leading independent underwater vehicle companies, International Submarine Engineering of Canada, now has a website[5] which includes a downloadable AUV design package highlighting perhaps that access to underwater vehicle technology is now truly in the public domain.

As AUVs evolve and become truly commercial products there is no doubt that power systems and power systems integration will also evolve. This evolution will be greatly enhanced once the power system development becomes as much the bailiwick of underwater vehicle designers as the other key technologies. However, as this short paper has illustrated the power system is often more of an afterthought in the AUV evolution process than a primary concern.

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