AUVs – A Technology Whose Time Has Come

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***Abstract* - Autonomous Underwater Vehicles (AUVs) were for decades either expensive military systems or very low cost academic research tools. In recent years this technology has evolved into the commercial sector where the number of AUVs being used for offshore surveys and other tasks is increasing at a rapid pace. It is obvious that AUV technology has arrived and the cusp of the transition curve has been reached. This paper will address the state-of-the-art of AUV technology, discuss the systems being employed offshore, and provide a peek into the future of this exciting field.**

I. INTRODUCTION

AUVs have moved from a state of research and development, through operational demonstrations and have now reached the beginnings of commercial acceptance. Although there were at least 66 AUVs being developed in 12 different countries at the end of the last decade, primarily in academic and military institutions, there were basically no commercially operating systems [1, 2]. But AUVs were on the cusp of the commercial acceptance curve, which has recently taken an exponential change upward. Today, commercial acceptance of AUVs offshore has begun. Vehicles such as *Hugin 3000* (Norway), *Maridan 600* (Denmark), *AQUA EXPLORER 2* (Japan), *SAILARS™* (Canada), *ALISTAR 3000* and *SWIMMER* (France), *DeepC* (Germany) and *OSIRIS*, *Sea Oracle* and *CETUS II* (U.S.), are being sold or developed for commercial applications, augmenting those AUVs already being used by academia and the military.

II. WHAT IS THE MARKET?

A. Commercial

In the commercial sector, underwater survey in support of the oil and gas sector will initially dominate the market. The offshore market for AUVs has been analyzed in detail by Douglas-Westwood Limited of the U.K. [3]. The future will not only see subsea installations going deeper and covering larger areas of the seafloor, but the number of installations will have doubled between 1998 and 2003; the value of the subsea market will increase from $4.9 billion in 1998 to $11.8 billion in 2003. They envision two main groups of AUVs—a Survey AUV for data gathering and a Hybrid AUV/ROV for subsea intervention.

The survey systems would be used to survey drilling sites and pipe routes, and they could also take in-situ soil measurements and measure seabed currents along the pipeline route. Douglas-Westwood estimates indicate that subsea drilling site surveys typically cost from $150k-$250k for shallow water, with two deepwater sites costing $900k and $1.4 million [4]. Obviously, reduction of these high survey costs can shave a lot off the bottom line. In the case of the Hybrid AUV, cost savings were not projected, however, the fact that floating production systems are supporting extensive undersea networks of wells, flowlines, risers and other subsea hardware, the potential savings for an AUV-based intervention system, operating from the floater itself, could be significant.

Another analysis by C&C Technologies, Inc. showed that the total cost of a deepwater survey could be cut from $707k using a deep-towed system ($26k/day with ship) to $291k using an AUV ($55k/day with ship) [5]. That is a whopping $416k (59%) savings. A similar conclusion was also reached by the U.S. Navy prior to the development of their 20,000 foot Advanced Unmanned Search System (AUSS). Analysis indicated an order of magnitude reduction in full ocean depth survey time could be achieved if an AUV was used. Thus, even considering the cost of transit time, the increased on-site efficiency of an AUV over towed systems is such that the overall cost will come down. Time is money.

The commercial potential of AUVs for offshore survey was projected in a pre-release of data [6] from *"The World UUV Report."* If AUVs meet industry expectations, sales could reach 30 units by 2004 and they could account for 20% of unmanned undersea vehicle (UUV) operations revenue. The majority of this AUV operational revenue, which could exceed a cumulative total of $200 million by the end of 2004, would be in the survey area. Whereas the ROV revenue is projected to increase by about 63% from 2000 to 2004, AUV revenue is projected to increase by 5,500% during the same period. Obviously, someone believes that AUVs have come of age.

B. Military

On the military side of the equation, AUVs have been under development for decades, and they are now reaching an operational status. Their initial fleet application will be for mine hunting, which was also the case for fleet introduction of ROVs. However, in the case of AUVs, they will operate from a submarine and not a surface ship. The U.S. Navy's submarine launched AUV is the Long Term Mine Reconnaissance System (LMRS), which is scheduled for initial operation in 2003.

An AUV similar to the LMRS is being developed by BAE Systems for the Defense Evaluation and Research Agency (DERA) of the U.K [7]. The *Marlin*, a submarine tube-launched vehicle, began a series of technological evaluations in 2001. Programs are also ongoing in several other countries.

A study of the broader scope of AUV mission applications for the U.S. Navy was recently completed by an ASN/RDA chartered study team [8]. The UUV Master Plan study, which looks ahead 50 years, provides a roadmap for the Navy to use in integrating unmanned undersea vehicles (UUVs) into the battlespace of the future. Critical missions include Intelligence, Surveillance, Reconnaissance, Mine Countermeasures, Tactical Oceanography, Communications, Navigation, and Anti-Submarine Warfare.

The Navy's UUV Master Plan incorporates near-term acquisition efforts while establishing the direction for long-term development and technology investment [9]. The U.S. Navy's Office of Naval Research has already applied the results of this plan to direct their R&D investments, and UUV technology programs exist at most Navy R&D Centers.

C. Scientific

International academic and research organizations are pushing the technology toward useful realization faster than the slow paced introduction into the oil patch or the bureaucratically sluggish military establishment. Because of limited resources and the necessity to launch from small boats or platforms, the academic community must keep vehicles small and economical. Smaller vehicles such as the Woods Hole Oceanographic Institution's (WHOI's) *REMUS*, MIT's *Odyssey*, and Florida Atlantic University's new modular AUV *Morpheus* are showing that cost effective missions can be performed. Small, inexpensive, mass produced AUVs that one can afford to occasionally lose will be the catalyst that pushes operational AUVs from the tens into the hundreds or thousands.

In Japan, the *R-1 Robot* being developed at the University of Tokyo is making great strides with recent operations that include the survey of the underwater volcano Teisi and the tracking of whales. And JAMSTEC's *URASHIMA* AUV has recently completed it first operational trials to the vehicle's design depth of 3,500 meters [10].

III. TODAY'S COMMERCIAL AUVs

A. Offshore Survey

The leaders will begin to clarify as more operational data is acquired, however, the *Maridan* and *Hugin* vehicles are certainly achieving superior results.

The AUVs developed by Maridan A/S, Denmark have had many recent successes. The AUVs are an outgrowth of research originally carried out under the EU's MAST research program. This began with the first prototype *MARIUS* (1991-1993) followed by *MARTIN* (1994-1997). The vehicles have evolved into their first commercial vehicle, the *MARIDAN 600 AUV (M600)*. In January, 2001, De Beers Marine took delivery of an M600, which is conducting surveys for hard minerals off the coast of South Africa in water depths of 110-150 meters.

Recent successes announced by Maridan on their website include surveys in the North Sea (October 2001) and the Gulf of Mexico (January 2002). Surveys were performed using a payload consisting of a Reson 8125 multibeam system, Klein Sidescan sonar and a Geo-Acoustics chirp sub-bottom profiler. Maridan is now providing survey services throughout the Gulf from their new US office. Navigation tests with their latest version of the AUV, *Selandia*, have achieved an error rate of 0.03% of distance traveled.

During their most recent mission, Maridan supported a group of European oceanographic organizations under the CONVECTION project funded by the European Commission. The project used the *MARTIN* vehicle to conduct under ice surveys in the Greenland Sea, Figure 1. The successful surveys were conducted in February, 2002.

Fig. 1. The Maridan AUV *MARTIN* during arctic survey.

The *Hugin 3000* AUV, developed by Norway's Kongsberg A/S for C & C Technologies, Inc, Lafayette, Louisiana, has been operating since January 2001 in the Gulf of Mexico. Since beginning operations, C & C Technologies has completed over 6,000 miles of survey lines for oil and gas companies. During one of the missions conducted for BP and Shell, the *Hugin 3000* discovered the wreckage of the U-166, a long-lost German World War II submarine, Figure 2.

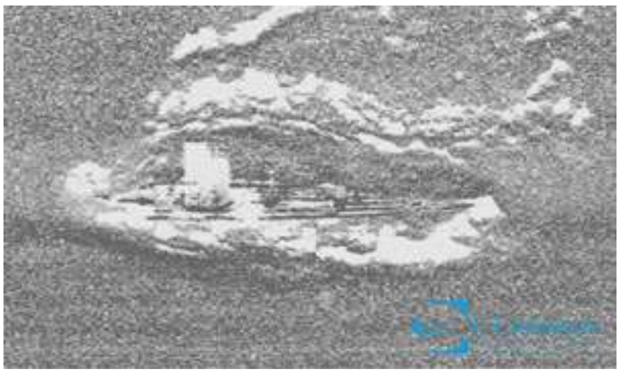

Fig. 2. U-166 submarine.

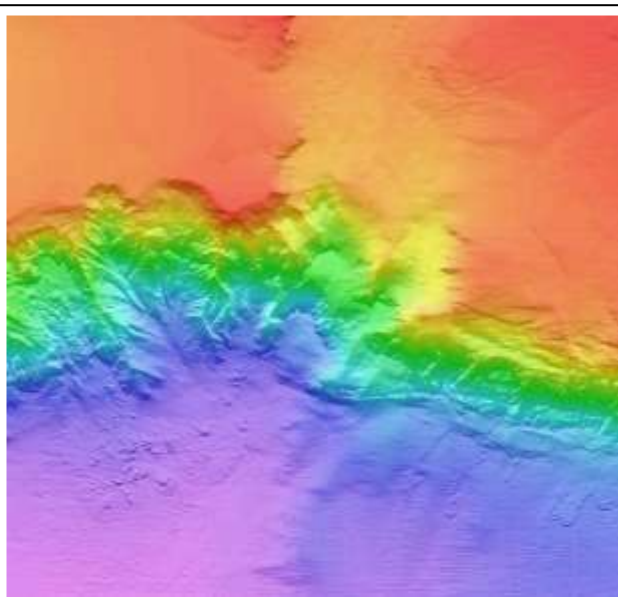

Fig. 3. *Hugin* AUVmultibeam bathymetry data.

The *Hugin 3000* can run surveys at 4 knots in water depths to 3000 meters for up to 45 hours using its aluminum oxygen fuel cell. The vehicle's survey sensors include multibeam bathymetry and imagery, side scan sonar and a subbottom profiler. The *Hugin 3000* AUV is capable of very high resolution multibeam surveys when compared to hull mounted multibeam systems, offering an improvement in resolution of over 30 times according to survey data provided by C & C Technologies. In 2000 meters of water, the bathymetry can be improved from 7.0 meters of vertical noise to about 0.2 meters, an improvement of over 30 times. Similarly, the calibrated backscatter from the multibeam sonar would improve from a 40 meters pixel size to a pixel size of less than 1.0 meter. Figure 3 depicts post-processed multibeam bathymetry data taken at the Sigsbee Escarpment in the Gulf of Mexico with depths ranging from approximately 1100 to 2200 meters. The depth resolution achieved by the Hugin 3000 AUV was on the order of 20 cm (8 in), or 0.02% of the water depth. The data are color-coded at one-meter contour intervals.

Japan is also in the running in the area of offshore cable surveys. The *Aqua Explorer* line of AUVs has been under development for nearly a decade by KDD R&D Laboratories. Their latest version is the *AQUA EXPLORER 2* (AE2), Figure 4, operated by Kokusai Marine Engineering Corp. (K-MARINE). The AE2, which recently completed a survey of a buried cable in the Taiwan Strait that exceeded 400 km [11], is now available for hire in the UK through an agreement between K-MARINE and Oceanscan Ltd.

Fig. 4. *AQUA EXPLORER 2*

B. Offshore Survey – In the Queue

The previous three vehicles (or at least their predecessors) are out there working with quoted day rates or sales prices. But what other contenders are lining up?

Thales GeoSolutions Group Ltd's *Sea Oracle*, Figure 5, is the next AUV intended to go into the commercial survey market. A team of Thales GeoSolutions and Bluefin Robotics engineers is developing the *Sea Oracle*. The AUV is based on the *Odyssey* vehicle technology, which has been a real workhorse in the academic sector. Bluefin Robotics Corp. was founded in 1997, based on technology developed at MIT's AUV lab, which owns shares of the corporation.

Another stakeholder in Bluefin is the Monterey Bay Aquarium Research Institute (MBARI), which has asked Bluefin to commercialize all the AUV technology MBARI will develop over the next decade [12].

Fig. 5. Thales GeoSolution's *Sea Oracle*

The *Odyssey* vehicles, now at the *Odyssey III* stage of development, have completed thousands of dives worldwide to depths exceeding 3,400 meters. At least twelve *Odyssey* vehicles have been built to date. Thales GeoSolutions has agreed to purchase two *Sea Oracles* with an option for six additional units. The vehicles will be capable of 3,000-meter operations.

International Submarine Engineering Ltd., Port Coquitlam, BC, Canada, developers of such AUVs as the *Theseus* and *ARCS*, has teamed with Mentor Subsea Technology Services, a unit of J. Ray McDermott, S.A, to develop the prototype unmanned semi-submersible vessel that will deploy a remotely operated vehicle. The system, called *SAILARS™*, Figure 6, will be able to cost effectively accomplish a variety of subsea intervention tasks. The 19-meter long vehicle will operate for up to 96 hours and can travel at a speed of nine knots to a distance of 28 km from an offshore platform. Once on location, the vehicle can deploy the ROV on 3,000 meters of cable in up to a sea state 6.

In another recent development, the Boeing Company, Fugro GeoServices, Inc. and Oceaneering International, Inc. have partnered to provide advanced underwater survey services. The venture combines Oceaneering's and Fugro's marine experience and Boeing's unmanned vehicle and autonomous guidance technologies. The new 18.5 ft long AUV, with a 10,000-foot depth capability, targets the oil and gas exploration and telecommunications markets. The vehicle is presently undergoing sea trials in the Gulf of Mexico.

France and Germany are also entering the commercial arena. ECA, of France, has spun off their *Olister* vehicle technology into two AUVs: the *ALISTER 300* (mainly for military use) and the *ALISTAR 3000*, a deep water (3000 meter) version for civil applications. The vehicles are existing and have already been extensively tested at sea in France with successful results. Further sea tests under all possible configurations will continue during 2002.

Germany's new venture in to the AUV arena, *DeepC*, is still in the design stage [13]. The 4000 meter vehicle will incorporate the latest fuel cell technology, advanced carbon-fiber reinforced composite pressure hulls, and sophisticated simulation/control software. The project is backed by the Federal Ministry of Education and Research; STN ATLAS Elektronik GmbH (Bremen) will lead the impressive consortium.

Fig 6. ISE's *SAILARS™* Vehicle

France is also working on a hybrid AUV/ROV system called *SWIMMER* (Subsea Works, Inspection and Maintenance with Minimum Environment Rov) [14]. The vehicle can maneuver like an AUV in the oil field, dock at the work site where it receives power and communications, and then launch the integral ROV to perform required work operations. The vehicle development, which is supported by the European Commission, is being run by Cybernetix, a French Company specialized in robotics and a subsidiary of the Comex Group. The *SWIMMER* development has been underway since 1997 under a partnership with IFREMER, University of Liverpool and TOTAL FINA ELF. The operational prototype has undergone demonstration and shallow water sea trials.

C. Other Commercial Players

There are many other vehicles that have been developed and delivered commercially. These vehicles cover size ranges from 3 to 30 feet long. A sampling is provided below.

On the large-scale vehicle end, ISE has the *ARCS* and the *Theseus* vehicles and Perry Technologies has the *MUST*. These vehicles have each performed some dramatic operations including the deployment of fiber optic cables. In the case of *Theseus*, the fiber optic cable was deployed under the ice pack.

Mid-size vehicles include those from the Institute of Marine Technology Problems (IMTP), Russia. Based on their *MT-88* AUV, the IMTP has built and delivered the *CR-01* and *CR-01A* in conjunction with the Shenyang Institute of Automation (SIA) and the Chinese Academy of Science. They have also developed the *OKPO* AUV for Daewoo Heavy Industry, Korea.

Smaller vehicles are commercially available such as the *CETUS II* from Lockheed Martin. The *CETUS II*, the follow-on to the *CETUS* vehicle developed by the MIT AUV lab for Lockheed Martin, is 33% smaller than the original and has a base price of $35K-$45K. Three systems have been built to date for U.S. Navy organizations.

Another small size vehicle that has seen considerable success is the *REMUS*, which was built by WHOI under ONR and NOAA funding. It is estimated that around 15-20 *REMUS* vehicles have been sold to data. The base price is in the $175K range. The vehicles are now being developed by Hydroid, Inc., a company founded by the inventors of the *REMUS* to allow commercial marketing of the vehicle.

D. Non-Commercial Scientific

There is also a wide spectrum of operational AUVs that are not necessarily looking at the bottom line. These vehicles, which are used for scientific missions, are amassing impressive track records.

The leader in this area appears to be the Southampton Oceanography Centre's *Autosub*, which continues to complete successful science missions under the funding of the Natural Environment Research Council. After a decade of development and exploration, *Autosub 2* is now in the wings with an increased depth rating to 2.5 km and range up to 1,000 km.

In the US, WHOI's *ABE* vehicle has acquired impressive data and is also going into the *ABE II* phase. Florida Atlantic University has the *Ocean Voyager II* and *Ocean Explorer* series of vehicles and their new modular *Morpheus* vehicles.

JAMSTEC of Japan has unveiled their 9.7-meter long, 1.5-meter high, 3,500-meter depth AUV the *Urashima*. This vehicle will join JAMSTEC's *UROV 7K* AUV/ROV and their Marine Robot *MR-X1* that is under development. The University of Tokyo continues to conduct research with their *R-1 Robot* which recently dove on an erupting underwater volcano.

The vehicles mentioned above are not the only players. There are many other AUVs that are being used by military, academic and commercial organizations, however, those mentioned above are performing a significant amount of work.

IV. THE FUTURE

AUVs are now at an early stage of acceptance. As they work their way into the phase of operational acceptance on a commercial level, their numbers will grow. Academia is not only using AUVs but also spinning off firms to supply commercial versions. And the US Navy is gearing up to push the technology, ensuring that cost-effective systems are available for use by the fleet in the future.

But the future will hold more than the acceptance of the "standard" AUV, it will begin to see the Hybrid AUV/ROV emerge. Today, the number of all electric ROVs, such as the Quest ROV developed by ALSTOM Schilling Robotics, is increasing. These more efficient vehicles will increase system reliability and eventually provide cost-effective components that will become available for use by AUVs. Along with this will come the fusion of the AUV and the ROV into the Hybrid AUV that is projected by many to be the future vehicle in the offshore oil and gas industry.

The previous information leads to one definite conclusion: AUV technology is a technology whose time has come. As more operations are conducted by AUVs, their impressive record of accomplishments and excellent data quality continues to grow. The "inner space race" has begun and the commercial leaders are fighting to see who will be there to capture first prize in the future billion-dollar AUV market.

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REFERENCES

1. R.L. Wernli, "AUV'S—The Maturity of the Technology," OCEANS '99 MTS/IEEE Conference Proceedings.

2. R.L. Wernli (editor), *The Operational Effectiveness of Unmanned Underwater Systems* (CD-ROM), Marine Technology Society, 1999.

3. J. Westwood, "Future Prospects for AUVs," A presentation to the Maridan 'PING' symposium, Copenhagen, September 16, 1999.

4. J. Westwood, "Future Markets for UUVs," Douglas-Westwood Associates.

5. T. Chance, A. Kleiner and J. Northcutt, "The Impact of Autonomous Underwater Vehicles upon Deepwater Survey Costs," C&C Technologies.

6. "Strong growth forecast in underwater vehicles market," Press Release at the Offshore Technology Conference, Houston, Texas, 1 May 2000.

7. A. Tonge, "Marlin, The UK Military UUV Programme—A Programme Overview," Proceedings of the International UUV Conference, Newport, RI, 24-27 April 2000, pp. 31-38.

8. P. Dunn, "Navy UUV Master Plan," Proceedings of the International UUV Conference, Newport, RI, 24-27 April 2000, pp. 82-92.

9. B. Fletcher, "UUV Master Plan: A Vision for Navy UUV Development," OCEANS 2000 MTS/IEEE Proceedings, Providence, RI, September, 2000.

10. H. Nakajoh, "Sea Trial of AUV "Urashima"," Underwater Intervention Conference Proceedings, New Orleans, LA, Feb. 27-Mar 2, 2002.

11. T. Asai, J. Kojima, K. Asakawa, T. Iso, "Inspection of Submarine Cable of over 400km by AUV 'AQUA EXPLORER 2'," Proceedings of the 2000 International Symposium on Underwater Technology, Tokyo, Japan, 23-26 May 2000, pp. 133-134.

12. F. Van Mierlo, "AUV Technology," Oceanology International 2000 Conference Proceedings, Brighton, UK, 7-10 March 2000.

13. W. Hornfeld, "DeepC – The German Development Project for an Intelligent Deep Sea Robot," Underwater Intervention Conference Proceedings, New Orleans, LA, Feb. 27-Mar 2, 2002.

14. Y. Chardard, "Work AUV for deep water intervention: Dream or reality," Underwater Intervention Conference Proceedings, New Orleans, LA, Feb. 27-Mar 2, 2002.

Web Sites of Interest:

www.dw-1.com – Douglas-Westwood Associates
www.maridan.dk – Maridan A/S
www.cctechnol.com – C&C Technologies
www.kongsberg-simrad.com – Kongsberg Simrad

www.bluefinrobotics.com – Bluefin Robotics Corporation
www.fgsi.fugro.com – Fugro GeoServices Inc.
www.hydroidinc.com – Hydroid, Inc.
www.ise.bc.ca – International Submarine Engineering Ltd.
www.oceanscan.co.uk – Oceanscan Ltd.
www.k-marine.co.jp – Kodusai Marine Engineering Corp.
www.whoi.edu – Woods Hole Oceanographic Institute
www.soc.soton.ac.uk/autosub/ - Southampton Oceanography Centre, Autosub
www.jamstec.go.jp – JAMSTEC
http://underwater.iis.u-tokyo.ac.jp/Welcome-e.html – University of Tokyo, Ura Lab.
http://www.oe.fau.edu/AMS/auv.html – Florida Atlantic University AUVs
http://auvserv.mit.edu/ – MIT AUV Lab
www.thales-geosolutions.com – Thales GeoSolutions
www.eca.fr – ECA
www.cybernetix.fr – Cybernetix SA