Chinese Deep Sea Manned Submersible Research and Technology
An Open Source Analysis of the Scientific Literature

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January 2012

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Section One

Introduction

Manned submersible development began in China little over 25 years ago. Since 1987, several deep-sea AUVs have been developed by the Shenyang Institute of Automation. Cui Weicheng, deputy director of the China Ship Scientific Research Center, Wuxi, recently stated that "We had read only some reference papers, there was no chance for us to see a real manned submersible. We were starting from the very beginning."

To national defense needs and offshore oil exploration, the Shanghai Jiao Tong University and the WuChang shipyard started to develop the deep submergence rescue vehicle (DSRV) in April 1971. The DSRV is 15 m in length, 35 tons displacement, 600 m of maximum submergence depth and a crew of 4. Power is provided by silver-zinc batteries and maximum speed is 4 knots.

A manned submersible named Yu-Ying-1 was operated in 1989. It can dive to a depth of 150 m and is equipped with a special manipulator. Length is 7.3 m, width 2.7 m, and height is 3.35 m. The working depth is 160 m, endurance is 72 hours and carries a crew of 3. Sea trials were carried out in April 1988 and on May 1988 it recovered its first torpedo from the 140 m sea bottom.

In the 1980s and 1990s Chinese researchers built both remotely operated and autonomous underwater vehicles capable of reaching depths up to 6000 meters. From 1990 to 2001, three different deep-sea UAVs were developed by the Shenyang Institute of Automation.

The HR01 was developed and assembled at Shanghai Jiao Tong Institute in 1986. Shanghai Jiao Tong Institute was in charge of researching and developing the vehicle, its performance, structures, propulsion and hydraulic systems, and the Shenyang Institute of Automation was in charge of researching the information transmission and control systems. Overall length of the vehicle was 2.7 m and maximum working depth was 200 m.

On the basis of this research effort, the State Economic Commission decided to establish an ROV research center at the Shanghai Jiao Tong Institute in 1985. The Shanghai Jiao Tong Institute and International Submarine Engineering, Ltd., Canada developed two types of operational ROVs, the SJT-10 and the SJT-40.

Other ROVs developed include JH-01 used for inspecting dams. Reservoir trials began in December 1986 and national approval was given for use in November 1987. China Ship Scientific Research Center developed the heavy tethered ROV 8A4. This ROV has an operating depth of 600 m, length 2.18 m, weighs 1.84 tons and has a maximum forward speed of 3 knots.

The **Explorer AUV** was the first deep-sea AUV in China and was developed under the National High-Tech Research and Development Program (863 Program). The development effort which lasted 4 years was a joint program of the ShenYang Automation Research Institute and the

Shanghai Jiao Tong Institute The vehicle is controlled by six thrusters and has six degrees of freedom motion control. Deep-sea trials were carried out in 1994 in the South China Sea.

Feng Xisheng, a professor at the Shipbuilding Engineering Institute of Harbin Engineering University is said to be the general designer of the Explorer AUV and Xu Huangan (Shanghai Jiao Tong University) was said to be the deputy general designer of the AUV.

Xu Huangan is also said to the designer of the Sea Pole class bathyscaphe and Cui Weicheng is the first deputy designer. The pressure hull of the Sea Pole is made of a titanium alloy and is manufactured in Russia from two hemispherical parts by tungsten inert gas welding. The plate thickness is stated to be 76-78 mm and pressure tests were performed in Russia.

Main Specifications of the Explorer AUV

Dimensions	4.4 (L) x 0.9 (W) x 1.1(H) m
Depth	1000 meters
Speed	4 knots
Power	Lead-acid battery
Weight	2100 kg
Propulsion	4 horizontal thrusters, 2 vertical thrusters

The **CR-01** was the first 6000 meters-level AUV developed in China. It was designed and built by the Shenyang Institute of Automation and the Institute of Marine Technology Problems, Russian Academy of Science in 1995. The CR-01 was developed under the National High-Tech Research and Development Program (863 Program).

Over forty underwater tests of the CR-01 have been completed and it has worked underwater for 8 hours continuously at a speed of 2 knots. Deep-sea trials were carried out in 1995 and 1997. The August 1995 trial reached a depth of 5,200 meters. The CR-01 has been used for multi-metal nodule investigations in the Pacific Ocean and operated six hours on the bottom at a velocity of 2 knots.

Main Specifications of the CR-01 AUV

Dimensions	4.4 (L) x 0.8 (B)
Depth	6000 meters
Speed	2 knots
Power	Silver-zinc battery
Weight	1300 kg
Propulsion	6 thrusters

The **CR-02** AUV was designed and built by the Shenyang Institute of Automation and the Institute of Marine Technology Problems, Russian Academy of Science in 1999. Its maneuver performance is superior to the CR-01 and it employs counter-propellers in its vertical plane and has 8 obstacle avoidance sonars. Lake trials were completed in 2001and then it was used in Deep-Sea Mining Systems tests. The sonar system consists of a bathymetry Side Scan Sonar and a sub-bottom Profiler.

Main Specifications of the CR-02 AUV

Dimensions	4.5 (L) x 0.8 (B)
Depth	6000 meters
Speed	2.5 knots
Power	Silver-zinc battery
Weight	1500 kg
Propulsion	unknown

Jiaolong (Harmony) Manned Submersible

JIALONG COMRA CHINA (www.comra.org)

The JIAOLONG is China's deep ocean exploration submersible, a project undertaken through the State Oceanic Administration. In 2000 a proposal for a deep-sea submersible was submitted to the China Ocean Mineral Resources R&D Association, a government agency. In December 2001, Liu Feng was officially hired as the overall project leader for the 7000 meter manned submersible project. Started in 2002, the Ministry of Science and Technology launched the Jiaolong Project as part of the State Hi-Tech Development Program (863 Program). Contracts were first signed in March 2002. Cui Wei-Cheng states that the project started in 2003. The submersible is a three-person vehicle, similar in concept to other deep vehicles, but with a maximum depth rating of 7,000m. The submersible is 8.2m long and weighs 22 Tons. Maximum mission direction is said to be 12 hours with a 72-hour emergency life support system.

Its 4.8-inch thick forged titanium pressure hull was built by Baltisky Zavod in St. Petersburg, Russia. The main spherical pressure hull is made of 12 separate side sections and 2 bottom sections of spherical shape. Both bottom and side sections were forged from flat plates blanks. According to Cui Wei-Cheng, "the welded hemispheres were placed into a special oven for thermal treatment to relieve residual stresses and eliminate distortions due to the machining of the hemispheres. Manual TIG welding was used." The main framework is said to be a welded titanium space frame structure and was tested to twice the equivalent actual load distributions.

During the period from 1996-2001, Liu Tao carried out a study on the structural analysis and design of a deep manned submersible under the supervision of Weicheng Cui as part of his PhD study. Liu made "a systematic study comparison of the DTMC (David Taylor) and Krylov formulas based on finite element analysis and collected experimental data." Lu, in the design of the spherical pressure for the Jiaolong, applied the finite element method to study the ultimate strength of spherical pressure hulls. Both the DTMB and the Krylov formulas were found to be on the conservative side compared with FE results. Details on the Krlov formula were first presented by Paliy at a 1991 conference in Shanghai.

The Jiangsu University of Science and Technology was subcontracted to investigate the ultimate strength of the spherical hull around the same time. Yu and others studied the influence of the initial imperfections on the ultimate strength of the spherical shell of the submersible. Harbin Engineering University performed a study on buckling strength and its reliability analysis of imperfect cylindrical and spherical pressure hulls. This was the first Chinese thesis to carry out reliability analysis in addition to the buckling strength analysis.

The JIAOLONG will be the deepest rated manned submersible, ahead of the SHINKAI 6500 from Japan, after the dive trials have been completed. More than 100 tests dives were carried out at the China Ship Scientific Research Center, "in an open water tank shaped like a bowl, with a diameter of 85 meters and a maximum depth of 15 meters." Initial testing started in 2009 from August 6th to October 19th with a series of dives to 50m, 300m and 1000m and 3000m. Cui Wei-Cheng states that the 1000 meter sea trial was conducted in 2009 and the 3000 meter sea trial was conducted in 2010. The deepest dive was to 3,759 meters and operated underwater for 9 hours and 3 minutes. During the summer of 2010 from May 31 to July 18, the submersible completed a deeper test regimen in the China Sea completing a series of 17 dives; 7 reaching depths past 2000m and four dives diving below 3000m. In charge of sea trials, Dr. Liu Feng pointed out that the biggest difficulties were due to lack of experience which were compounded by severe weather conditions such as typhoons and storms. The director of the dives is Liu Feng.

The sea trials will continue in a progressively deeper test regime in 2011 and 2012. It will take 5 hours to reach a depth of 7,000 meters and the vehicle can work for as long as 12 hours underwater. The project is led by Dr. Wang Fei, deputy director of the State Oceanic Administration with participation of the National Science and Technology administration, and several Chinese industry associations. In July of 2011 dives of 5057 and 5188 m were accomplished.

In 2005, Tsung Yeh and four other scientists and engineers traveled to the United States to serve on the mother ship (Atlantis) of the Alvin manned deep-sea submersible. A total of 21 dive trips were made in the Alvin by Chinese researchers. In 2006, China began selecting its oceanauts and one of the first was Fu Wentao. Ye Cong, the oceanaut who dived the Jiaolong to 3,759 meters on July 13, also set a set record for operating a submersible underwater at that time. So far there are only three fully qualified and licensed oceanauts and Ye is the only who has the experience of diving as deep as 3,000 meters. Other oceanauts include Tsung Yeh and Tang Jialing.

Main Specifications of the JIAOLONG

Dimensions	8.3m x 3.0m x 3.2m
Maximum operational depth	7000 meters (designed)
Weight	22 tons
Crew	1 pilot and 2 scientists
Power supply	oil filled silver-zinc batteries
Underwater time	12 hours
Speed	2.5 knots

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Jiaolong Submersible

Section Two

Fatigue Related Research for Submersibles

China Ship Scientific Research Center, Wuxi

A 2001 article considered the nonlinear relationship between the material strain and the stress by introducing the elastic modulus in the VonMises elastic buckling formula of the pressure hull. This provided the approximate formula of the material modulus by means of the regression of the material strain test curves and replaced mean diameter by outside diameter. The simplified method and formula given by this paper were verified by a pressure hull test and were used in the primary design phase of the deep sea submersible.

During the period from 1996-2001, Liu compared the DTMC (David Taylor) and Krylov formulas (Paliy) based on finite element analysis and then collected experimental data. A simple calculational method for the elastic-plastic stability of spherical pressure shells of the deep manned submersible was proposed based upon this research.

In the design of the spherical pressure for the Jiaolong submersible, Lu applied the finite element method to study the ultimate strength of the pressure hull. Results from the DTMC and Krylov formulas were found to be on the conservative side compared to FE results.

The pressure hull is the most critical component of a manned deep sea submersible and the pressure hull is subjected to a cyclic load for every diving task. As the number of dives increases, the hull may be subject to low cycle fatigue failure. A 2004 paper carried out the fatigue load spectrum for the Alvin submersible and based on this analysis proposed that the probability distribution for the fatigue load spectrum of deep sea manned submersibles is Gumbel.

A new method for the stress analysis of ring-stiffened cylindrical shells based on the solutions of the web, flange and cylindrical shell was presented in 2004. Numerical results showed the differences in the calculated stresses between the inner-stiffener and the outer-stiffener of the cylindrical shell. The present method was employed instead of the code calculation for stress analysis of the cylindrical shell stiffened by the big inner-stiffener because the code calculation underestimates stresses incurred.

A 2007 paper reviewed the design status of the 6,000m class manned submersible and the design thickness and weight characteristics of the titanium alloy spherical hull were given by the plastic analysis method and design factors including the safety factor, inner diameter, volume density and weight of the spherical hull were discussed.

Based on the theory of the beam on an elastic foundation, an analytical method for the calculation of stresses of openings in a spherical shell was developed. This method proved easier to use than the normal shell theory and was applied to complicated stiffened structures subjected to different loads and the analytical results were similar to results obtained by FEM.

Based on the characteristics of the manned spherical pressure hull in the deep sea submersible, Cui Wei-cheng said that there are contact problems in the locations of the access hatch and the

three viewports. Contact finite element analysis should be used rather than ordinary finite element by assuming that there is no sliding. On the basis of stress-strain analysis results, the effect of the friction coefficient on the stress distribution of contacting parts was studied and the stress was found to be within limits for the access hatch substructure and the viewports substructure.

A comparison of the currently available design rules from various classification societies indicated significant different results among those rules and many existing spherical pressure hulls are found not to be in compliance with most of the current design rules. In order to update these design rules a series of titanium alloy spherical pressure hulls including structural imperfections were modeled and studied by commercial nonlinear FEM programs. New formulas for the ultimate strength of spherical pressure hulls of manned submersibles were developed by Pan and Cui.

The input parameters of design rules can be divided into four kinds: the dimension of the pressure hull which includes the radius and thickness of the spherical shell, material properties which include Young's modulus, yield strength and the Poisson's ratio, structural imperfections which includes overall out-of-roundness and local shape deviation of the spherical surface of the shell from regular round form and lastly additional coefficients which include factors of material properties.

Pan and Cui pointed out that for a perfect spherical shell, as thickness increases, the actual stress values and buckling/ultimate strengths deviate from theory of nonlinear elasticity. This deviation is mainly caused by large deformation and nonlinear material behavior. For a complete sphere with geometrical imperfections, how many independent parameters are needed in defining the imperfections, what is the influence of each parameter on the buckling/ultimate strength on spherical shells are some of the questions that need to be determined. And for spherical caps in addition to the imperfections, the boundary conditions will have a great effect of the buckling/ultimate strength. Design equations are needed based on a series of complex numerical calculations.

Based on ultimate strength formulas, Pan and Cui proposed that additional stress limitations which control the local stress concentrations should be involved to makeup complete design rules. Stress limitations are set to be: the average shell membrane stress at maximum operating pressure shall be limited to two-thirds of the maximum specified yield strength of the material, the highest combined value of average shell membrane stress and bending stress at maximum operating pressure shall be limited to ¾ of the minimum yield strength of the material and the maximum compressive peak stress at any point in the hull, including the effects of local stress concentrations shall be limited to 4/3 of the minimum specified yield strength of the material. The maximum tensile peak stress at any point in the hull, including effects of local stress concentrations, shall be limited to the minimum specified yield strength of the material.

These proposed rules were applied to the design of the 4,500m manned submersible. The internal diameter of the pressure is 2.0m (the same as the Alvin) and is designed to operate under 46.1MPa external pressure with a safety factor of 1.5.

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Dalian University of Technology

Pitting corrosion occurring on the surface of hull structural plate will result in a significant degradation of the ultimate strength of the structural plate. An assessing formula for determining the ultimate strength of hull plate with pitting corrosion damage was developed and applied to actual hull plate with structural damage.

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Fuzhou University

The physical essence and calculation principle of graphic analysis of external pressure hulls in ASME VIII-1, GB 150 and EN13445 standards were shown to be consistent with that of proportional law in combined theory of strength and stability by transforming the graphic charts in these standards into dimensionless charts. An equivalent relationship between the mathematical expression of the proportionality law and graphic charts was illustrated and an analytical equation for nonlinear instability of external pressure was established. The equation was used to calculate the ultimate pressure of five titanium alloy spherical shells under external pressure and the values predicted by this equation agreed with the test results.

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A new analytical algorithm for the design of external pressure vessels, *Journal of Fuzhou University (Natural Science Edition)*, 2011-02

Harbin Engineering University

Harbin Engineering University was the first Chinese university to carry out thesis on reliability analysis in addition to buckling strength analysis for deep sea submersibles. A study on the buckling strength and reliability analysis of imperfect cylindrical and spherical pressure hulls was been carried out in 2007.

Harbin researchers stated that the finite element model was too inefficient to optimize designs and developed a strategy for optimizing the design of a cylindrical shell stiffened by rings. The method used was based on the combined use of the design of experiment and response surface model. The central idea was that parameterization of the finite element model of the shell was set up using the secondary development tool APDL. Design variables were chosen using criterion for structural strength and a FEM corresponding to the samples was built and analyzed. Second-

order polynomial response surface models of structural strength and weight were set up using the samples and responses obtained by FEM and an optimized design result for a cylindrical shell was obtained by RSM using the penalty function method. The results showed that this method can improve the strength utilization of structure and improves the optimization efficiency.

The tangent modulus factor was applied to the analysis of the ultimate strength analysis of the manned deep sea submersible pressure shell. The factor was derived from the combined theory of strength and stability and based on the relationship between stress and strain in a material, the tangent modulus factor can be simulated, reflecting the structure's balance relationship. The curve could also be expressed by an analytical function with four parameters. The function was used to calculate the ultimate strength of a titanium alloy spherical shell and then compared with those from the Taylor Basin formula and the finite element method. The method proposed in this paper was simpler and produced figures acceptable for design and engineering practice. The tangent modulus factor method was shown to be valid for preliminary design and analysis of spherical shell pressure hulls.

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*College of Shipbuilding Engineering, Harbin Engineering University
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*College of Computer Science and Technology, Harbin Engineering University
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Bibliographic Details:

Ai Sang-mao is a PhD student at Harbin Engineering University and his current research interests include fluid-structure coupled analysis and vortex induced vibrations.

Sun Li-ping is a professor at Harbin Engineering University and her research interests include deepwater engineering.

Wang Xiao-tang is a professor at Harbin Engineering University and his current research interests include strength and stability of underwater vehicles, elastic and plastic mechanics.

Huazhong Institute of Technology

Buckling and ultimate strength analysis of spherical pressure hulls were first reported on in China by Zhen and his co-workers. They proposed a formula for calculating the buckling

strength of spherical pressure hulls considering the geometrical imperfections and inelastic behaviors.

The optimum of the three intersecting spheres tangent arc pressure hulls was investigated by the optimization procedure of the out penalty function method. In this study, the thickness-radius ratio, the length-radius ratio of the spherical shell and the angle of intersection of the spherical shell were selected as design variables and the strength, stability and boundary constraints were considered to minimize the buoyancy factor. A sensitivity analysis was also performed to determine the influence of the design variables on the buoyancy, strength factor and stability. This paper provides a reference for the structural design of this new style of pressure hull.

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*Huazhong Institute of Technology
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*College of Communication Science and Engineering, Huazhong University of Science and Technology
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**College of Traffic Science and Engineering, Huazhong University of Science and Technology
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**Wuhan Second Ship Design and Research Institute
***Navy Office of 431 Shipbuilding, Liaoning
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Jiangnan University, Wuxi

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*Yue Kun and *Tian Chang-lu
*School of Mechanical Engineering, Jiangnan University, Wuxi
Stress analysis of deep-sea view-port windows and its optimization, *Journal of Jiangnan University (Natural Science Edition)*, 2011-01

Jiangsu University of Science and Technology

A 2004 article discussed the development state of materials used in the deep sea submersible and provided strength and stability formulas for the pressure shell. Problems relating to the spherical titanium pressure shell were also discussed. In the design of the Jiaolong, Jiangsu University was subcontracted a task to investigate the ultimate strength of the spherical pressure shell. Yu and colleagues first carried out a review and then studied the influence of the initial imperfections on the ultimate strength of the spherical shell for the submersible.

The pressure hull of the deep sea submersible are midthick hulls and the material yields in the location of the hulls before the structure fail. By combining finite element analysis with the typical theory, a 2005 article studied the influence of the eigenvalue-buckling mode imperfection, local imperfection and the deflection of thickness and radius. Results showed that the structures are not sensitive to the initial imperfection and that the critical loads are worst when the range of the imperfection is the critical arc-length.

Results from the Taylor formula were compared with that from finite element analysis (FEA) for a titanium alloy and by combining both the results from the FEA were improved. The ultimate loading capacity of the spherical pressure hull was estimated in the initial design stage using this improved method of analysis.

The material of a ring-stiffened circular cylindrical shell will yield in plastic deformation before the hull structure fails. Using the FEA software ANSYS the influences of the initial deflection on the plastic stability of the ring-stiffened cylindrical shell were simulated under the influence of symmetrical exterior pressure. ANSYS was also used to model and obtain the ultimate strength of the pressure hull with openings and initial imperfections. Calculations showed that the difference between the ultimate strength of the spherical pressure shell with openings reinforced and the ultimate strength of the pressure hull with no openings were small.

A 2009 article presented further details on the use of ANSYS to simulate the pressure hull and discussed the effects of initial defects to the limit load of a pressure cylinder when the amplitude

of the defects vary to some extent. The initial defects did not change the buckling mode of the pressure cylinder shell and were shown to have small effects to the load limit of the structure.

One of the main problems of the deep sea submersible is the stability of the pressurized spherical shell. The shell is moderately thick and in calculations it is necessary to take into account transverse shearing deformation. The influences of out of roundness under machine processing and the interaction between material nonlinear and geometry nonlinear on the stability of the shell were considered. Calculations showed that the instability pressure decreases with the increasing of the radius under the same thickness but then increases with the increasing of the radius under the same radius.

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Naval Architecture and Civil Engineering Department of East China Shipbuilding Institute, Zhenjiang

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*Xie Zuo-shui
*Naval Architecture and Civil Engineering Department of East China Shipbuilding Institute, Zhenjiang
Research on new structural forms of pressure tank, *Journal of Ship Mechanics*, 2002-04

Northwestern Polytechnical University, Xian

The AUV combines ball shell, cylindrical shell, taper shells and other rotary shells by thread coupling, wedge coupling and hoop coupling. A 2007 paper used finite element analysis to present the mechanics mode of an AUV with the analytical method. Complex mathematical analysis was used to model the hydraulic pressure and vibrations endured by a torpedo and an AUV. Further details of this modeling were presented in a companion 2009 paper which looked at how the power system causes vibrations in the shell and noise radiation that is created.

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*College of Marine, Northwestern Polytechnical University, Xian
**Department of Aircraft Structure Overhaul, AMECO Beijing
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Bibliographic Details:

Chen Xiao-li was born in 1982 and got her bachelor's degree from Northwestern Polytechnical University in 2004. She is now studying for her master's degree at Northwestern Polytechnical University and her main research field is structure noise and vibration analysis.

Sheng Mei-ping was born in 1970 and is a professor and doctoral advisor at Northwestern Polytechnical University. Her main research interests are SEA, sound signal treatment, noise and vibration control.

Ocean University of China, Qingdao

The CFD analysis software Fluent was used to measure the force condition of AUV frame construction. These results were applied to the simulation of pressure and velocity distributions in the external flow fields for selected models of the dome on the bow of the AUV.

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*Sun Li, *Liu Gui-jie, *Wang Meng and *He Bo
*College of Ocean Engineering, Ocean University of China, Qingdao
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Science and Technology University of Southern China, Wuhan

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*Science and Technology University of Southern China, Wuhan
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Shanghai Jiao Tong University

New variable transformation formulas were introduced to solve the basic governing differential equations for conical shells in a 2001 paper. By performing magnitude order analysis and then neglecting the quantities with h/R magnitude order, the basic governing equations for conical shells were transformed into a second-order differential equation with complex constant coefficients. Solving these second-order equation provided a simple and accurate solution for conical shells. The solution was simpler than the exact solution because it does not use Bessel's functions and was also shown to be more accurate than the equivalent cylinder solution.

Cui Wei-cheng wrote a state-of-the-art review for fatigue life predictions methods for metal structures in 2002. The review did not specifically address deep sea manned submersible fatigue related issues.

Most of the current research on the pressure hulls for submersibles are based on thin shell theory and there is no analytical theory solutions for thick spherical shells under uniform pressure. In a 2004 article a finite element method was used to study the ultimate strength of spherical pressure in deep sea manned submersibles. By comparing various FE parameters, a validated model was established and using this model, calculations were performed. The calculations were shown to be in agreement with the experimental results. The effect of initial imperfections to the ultimate strength is not significant when the spherical hull is finely manufactured.

The main frame of the deep sea is a complex space rigid frame designed as a structure to install a manned pressure hull, batteries, electric invertors, main ballasting tanks, and buoyancy materials. This 2004 paper described the optimization of the main frame based on two aspects by use of the

FEA software (MSC Patran/Nastran). The static analysis function was used to optimize the preliminary schemes by the Evolutionary Structural Optimization Method. After the first level optimization, the paper went on to size optimization using the modified method feasible directions, sequential linear programming and sequential quadratic programming. The results showed that the weight of the main frame structure could be further reduced without compromising integrity.

Combining the finite element analysis with the typical theory, a 2005 paper studied the influence of the eigenvalue-buckling mode imperfection , local imperfection and the deflection of thickness and radius. The results showed that the structures are not sensitive to the initial imperfection and the critical loads are the worst when the range of imperfection is the critical arc-length.

The structural multi-objective optimal design of the spherical pressure for a deep sea submersible was developed through a combined optimal method, which was based on the Response Surface Method (RSM) and the Genetic Algorithm (GA). Through the use of Design of Experiment (DOE) the response property of design objects was obtained and then the response surface model was fitted to those samples. A Pareto genetic algorithm was used in subsequent optimal design experiments and the multi-objective optimal design of the spherical pressure hull was obtained.

The problem of structural optimization for multiple intersecting spherical pressure hulls was based on the Kriging model. The ultimate strength of the pressure hulls was calculated with nonlinear finite element method a various sample points. Using the Kriging model avoids the problem of large computational costs which occur when the optimization algorithm is directly coupled with finite element analysis.

A mathematical model of Multidisciplinary Design Optimization (MDO) was built for a deep sea HOV general performance design and the BLH framework was suggested for the deep sea HOV project. A Ladin hydrocube of design of experiment method was used to analyze the correlation among the variables and optimal results for a general purpose design presented.

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*School of Naval Architecture and Ocean Engineering, Shanghai Jiao Tong University
**China Ship Scientific Research Center, Wuxi
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**Shipbuilding Engineering Institute, Harbin Engineering University
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**China Ship Scientific Research Center, Wuxi
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**School of Mechanical and Power Engineering, Shanghai Jiao Tong University
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** China Ship Scientific Research Center, Wuxi
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Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang

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Tianjin University

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*School of Mechanical Engineering, Tianjin University
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Yueyang Teachers College, Civil Engineering Department

Journal Articles:

*Chen Jiguang, *Ren Jiatao, **Dou Zhwu and **Li Gangling
*Yueyang Teachers College, Civil Engineering Department
**South China University of Technology, Guangzhou
Study on collapse strength analysis of titanium external pressure vessel in the deep submarine research and rescue boat, *Natural Science Journal of Xiangtan University*, 2001-01

2nd Ship Design and Research Institute, Wuhan

A 2008 article compared the methods used by the US and China in calculating pressure influences on cylindrical shells. A preliminary analysis was then made of possible modifications to the Chinese design rules.

Multiple intersecting spheres of the tangent arc connective pressure hull is a new structural style used in the deep sea submersible pressure hull. The strength and stability of three intersecting spheres of tangent arc pressure hulls with different fR were studied by a finite-element method. Using a least-square procedure, formulas of nonlinear strength and stability for three intersecting spheres of tangent arc connective pressure hulls were proposed.

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*Li Xue-bin
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*Zhang Nai-linag
*Wuhan Second Ship Design and Research Institute
The analyze on the structure weight control technique of deeper submersibles pressure columnar hull, *Ship Science and Technology*, 2008-04

Unidentified Authors

A 1988 paper presented the earliest open source details of the mathematical analysis of the random fatigue load spectrum for submersibles. A mathematical induction method was used to assess the maximum cumulative damage and calculations were performed on a PDP-11 computer. The software described in the paper can be used to find out the cumulative damage ratio within given periods as long as the diving depth record was known.

The openings in the pressure hull of the deep sea submersible will weaken the ultimate strength of the hull and ABAQUS finite element software was used to calculate the impact of opening's size and the connecting wall. The results showed that the increased diameter and wall thickness decreased, the ultimate strength exhibits a downward trend.

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Section Three

Titanium related research

One of the key technologies involved in the building of a deep-sea submersible is the ability to forge and weld large sections of titanium or titanium alloys. The Chinese are working to solve these problems but are still purchasing completed hull sections from Russia. The pressure hull for the Jiaolong submersible is believed to be 4.8 inches thick and was built by Baltisky Zavod in St. Petersburg, Russia.

Published Chinese research has centered on two areas of research: welding technology and ultimate strength calculations. Fatigue life reliability analysis of a titanium spherical shell was performed and the research published in early 2006 as an effort between the School of Civil and Environment Engineering, University of Science and Technology, Beijing and the China Ship Scientific Research Center, Wuxi. The lead author for the Wuxi is Cui Wei-cheng, who is one of main Chinese researchers in the deep-sea submersible area. They first introduced an expression of fatigue crack growth rate and used that to develop a fatigue reliability model. The reliability results were calculated using the Importance Sampling Method in the software routine ISPUD.

A second article was published in the same journal by a group from China Ship Research, Wuxi (lead author Cui Wei-cheng) and focused on developing an experimental method to simulate the working conditions of the titanium framework of the deep-sea submersible. The 3-D framework was difficult to simulate and the paper summarized test experiences such as loads, strain, deflection, safety measurements.

The most recent strength calculations were done for a titanium alloy spherical pressure hull of a deep-sea submersible. The calculations were done by the College of Shipbuilding Engineering, Harbin Engineering University and based on the relationship between stress and strain in a material, the tangent modulus can be simulated. The results from this calculation were compared

to results obtained using the Taylor Basin formula and finite element modeling and the Chinese method was shown to be simpler. The tangent modulus factor method was validated for the preliminary design and analysis of the proposed spherical pressure hulls.

A 2000 review was done by the State Key Laboratory, Institute of Corrosion and Protection of Metals, Chinese Academy of Sciences and summarized advances in titanium alloy welding being done by foreign countries. Earlier research on the laser welding of TC4 alloy has been done at the Naval Aeronautical Engineering Academy, Qingdao, the No. 710 Research Institute of the CSIC, Department of Mechanical Engineering, Tsinghua University, the Beijing Aeronautical Manufacturing Technology Research Institute, the School of Mechanical Engineering, Northeastern University and the State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology. Almost of this research focused on welding TC4 alloy thin plates (Ti6Al4V) using laser technology.

In the welding arena the School of Materials Science and Engineering, Huazhong University of Science and Technology published a 2004 paper on laser beam welding of TC4 alloy and looked at factors which influence microstructure formation, mechanical characteristics and the characteristics of laser beam welding which determine porosity formation.

A 2006 conference paper presented by researchers at the Beijing Aeronautical Manufacturing Technology Research Institute (ITIC International Technology and Innovation Conference) looked a the effects of electron beam local treatment on the fatigue properties of electron beam welded Ti-6AL-4V alloy plates. The fatigue life of the joints was shown to improve up to 30% after heat treatment.

In 2008 joint titanium welding research was performed by the College of Shipbuilding Engineering, Harbin Engineering University, and the Department of Shipbuilding Engineering, Bohai Shipbuilding Vocational College. A welding program was developed in APDL language based on Ansys and numerical welding experiment was modeled. The alloy modeled by this research was not specified for the sake of secrecy but the experiments focused on a three-dimensional numerical experiment of a thick spherical shell structure during welding.

This article was written by Liu Xiang-dong, who is an associate professor and doctorate student at the College of Shipbuilding Engineering, Harbin Engineering University, where he is majoring in the performance and safety of ships and marine structures. The lead author is Yao Xoing-liang, who is a professor at the College of Shipbuilding Engineering, Harbin Engineering University majoring in ship structural mechanics, prediction and control of ship vibration, and structural response under underwater impulsive load. A biography for the third author (Pang Fu-zhen) was available.

Superplastic forming research is being done at the School of Material Science and Engineering, Northwestern Polytechnical University, Department of Materials Engineering, Harbin Institute of Technology, the State key Laboratory for Hot Processing of Metals, Harbin Institute of Technology, Tsinghua University, and the Beijing Aeronautical Manufacture Technology Research Institute.

Earlier this year a paper was published by the College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics on the welding of Ti6Al4V alloy sheets with 0.93 mm thickness using a 2kW Nd:YAG laser machine. The superplastic forming process was simulated using FEM software (MSC.MARC) and the gas pressure vs. forming time curve was obtained.

One thesis in the area of accuracy control of superplastic forming for TC4 alloy was found but the author and university were the research was performed could not be determined. A ZrO2/TiO2 ceramic with adjustable CTE was developed for use as a liner between the refractory steel die and TC4 component. Using the ceramic die, the TC4 denture base was superplastically formed at 930C.

The 2011 World Conference on Titanium was in Beijing on June 19-24 and a number of foreign authors from countries such as the United States, Sweden, Australia, Japan, UK and New Zealand presented papers. Three Iranian researchers (Mehdi Salehi, Mohammad Meehdi Verdian and Keivan Reissi) from the Isfahan University of Technology attended the conference and presented entitled "Synthesis of Amorphous/Nanocrystalline NiTi Biomaterial Powder by Mechanical Alloying.

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Section Four

Ballast and Buoyancy Related Research

Solid buoyancy materials for use in deep sea submersibles were first described in a 1999 review done by researchers at the Marine Chemical Engineering Institute, Qingdao. The review looked the manufacture of chemically foamed plastics, synthetic foams and light fillers for use in synthetic foams. High strength solid buoyancy and hollow glass microspheres were reviewed and methods of their preparation discussed. When the density of the hollow glass microspheres was as low as 0.21 g/cm, the broken particle ratio at 12 MPa was 40.6%. When the density was 0.52 g/cm, its compressive strength reaches 40 MPa. This work was done by the Technical Institute of Chemistry and Physics, Chinese Academy of Science, Beijing.

An earlier review was done by the China Ship Scientific Research Center as part of the 863 Program under project K1430. Using tests for density and pressure, the physical properties of buoyancy materials were determined and this data was being used as the technical basis to formulate Chinese Rules for classification and construction of deep-sea submersibles (both manned and unmanned).

In early 2006 the Civil and Engineering School, University of Science and Technology, Beijing, prepared a solid buoyancy material from epoxy resins and glass hollow spheres. The compressive strength of resin cross-linked with m-phenylenediamine or 4,4'-diaminodiphenylsulfone was above 210 MPa. A coupling agent (aminopropyltriethoxysilane) was used to pretreat the spheres and a density of 0.61 g/cm3 was obtained with a 25% mass filling ration of hollow spheres and the compressive strength remained above 40 MPa. This work was done under the 863 Program under project 2002AA401001-1. Further work on this type of material was published later that year by these same researchers and through system optimization of the factors influencing surface treatment, a buoyancy material was fabricated with a density of 0.61-0.75 g/cm3 and a compressive strength of 40-68.96 MPa.

The Hunan Plastic Research Institute prepared a high strength buoyancy material by mixing surface activated hollow glass microspheres with an unsaturated polyester resin. By increasing the loading level of the microspheres, the density and hydraulic pressure strength of the material decreased. The higher the density of the buoyancy material with homogenous loading of microspheres, the better the hydraulic pressure strength was. Surface activation treatment of the microspheres also increased the hydraulic pressure strength of the buoyancy materials.

A group from the Technical Institute of Chemistry and Physics, Chinese Academy of Science, Beijing found that when the density of the hollow glass microsphere was as low as 0.21 g/cm3, the broken particle ratio at 12 MPa of the microsphere is 40.6%. When the density was 0.52 g/cm3, its compressive strength reached 40 MPa. This work was performed under the 863 Program under project 2006AA09Z209.

A variable ballast system was described that is composed of a pressure vessel, a super high pressure seawater pump, a DC-motor and seawater change-over valves. The work was done by the China Ship Scientific Research Center as part of the 863 Program under contract 2002AA40100. The seawater is either charged into or discharged from the variable ballast tank to adjust the weight of the submersible and raise or lower the vessel. The system is designed to function at a maximum 7000 meters underwater and its buoyancy adjusting range is 0 to 300 kg.

The variable ballast tank and all other parts that come into direct contact with seawater are made of a titanium alloy and can endure a pressure difference to 71 MPa. The tank's capacity is about 310 liters and its internal pressure varies from 0 to 3 MPA. The seawater transducer is a magnetostrictive linear displacement transducer and has a plus-buoyancy ball that moves up and down with respect to seawater level in the ballast tank.

The seawater piston pump is constructed with solid ceramic liners and steel pistons that are coated with a titanium alloy dioxide ceramic. A safety valve with a blowout pressure of about 3 MPa was first tested on land before being installed. An ocean-pressure compensated 8 kW, 110 V DC brushless motor is used to drive the seawater pump. Its working speed is stated to be regulated from 0 to 450 r/m.

A trim system with hydraulic oil pumping mercury has been researched by the China Ship Scientific Research Center and both static amalgamation and dynamic safety tests were performed. As part of this trim system a deep-sea mercury release value was designed and tested.

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Section Five

Deep-Sea Manipulator Related Research

Anhui Key Laboratory of Advanced Numerical Control and Servo Technology, Ahhui Polytechnic University

A research group based at the Anhui Key Laboratory of Advanced Numerical Control and Servo Technology, Anhui Polytechnic University has developed an underwater working dexterous hand. This hand has three fingers and six joints that are driven by hydraulics. The six joints share one fluid motor and the finger joints are driven by a three fluid cylinder. The dexterous hand has a six-dimensional wrist force sensor, three four-dimensional finger forcer sensors, three ultrasonic sensors and one vision sensor. In 2010 the problem and design of improved seals for an underwater manipulator was proposed. A magnetic seal was proposed for the underwater dexterous hand and relative parameters calculated. The work was performed under the 863 Program under contract 2006AA04Z244.

Details of a potential 4-D force sensor for an underwater robotic manipulator based on an E-type membrane were provided in 2010 journal article. The sensor consisted of a fingertip, an upper cover, a seal ring, elastic force-sensing elements and a base frame. The elastic force-sensing elements were made of an aluminum alloy and the other components were made of chromium nickel stainless steel. To help remove the influence of the ambient water pressure, the technique of automatic pressure compensation was applied to the sensor. The operating principle of the prototype was described as when the hydraulic pressure increases, elastic deformation occurs on the lower round plate under the double thin plates of the force-sensing elements. Those elements recognize that the inner pressure of the sensor increases because the silicone rubber adhesive decreases in volume and the pressure in the sensor shell will automatically maintain a constant value equal to the ambient water pressure. Limitations of the sensor were that if the sensor had worked in a full-scale range for a long time the zero point output is offset and secondly the developed sensor is still a prototype and has not been evaluated in a real underwater manipulator. This research effort was supported by the 863 Program under contract 2006AA04Z244.

Further information on a three finger underwater dexterous gripper utilizing hydraulic drive was presented earlier this year. A circuit was designed to limit the range of motion of the three joints. The logic function of the control circuit was controlled by a programmable circuit. This work was performed under the 863 Program under contract 2006AA04Z244.

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Harbin Engineering University

In 2000, Harbin University developed a novel technique using timed discrete event systems supervisory control theory to model the control scheme for a multi-armed underwater vehicle. Harbin University provided details on a 7-function manipulator which is used in underwater applications. The manipulator has six DOF and a paw, including shoulder yaw, shoulder pitch, elbow pitch, forearm roll, wrist pitch and wrist roll. The operating depth is 3000 meters and the forearm roll joint is driven by a swinging cylinder, the wrist roll joint is driven by a hydraulic motor and the other joints are driven by a hydraulic cylinder. A compound control method based on cerebellar model articulation controller (CMAC) was described for the manipulator. The CMAC is used a feed-forward compensator to estimate the system inverse dynamic model and a PID controller is a feedback controller for system stability. Microcontrollers are used to control the sensor and actuator of each joint. The servo system of the shoulder joint is composed of an asymmetrical cylinder and symmetrical servo valve. Moog G761 is used as the servo valve and the cylinder is made by Chinese URANUS Hydraulic Machinery Co. LTD (www.uranushc.com) as a single-rod cylinder. This research was supported by the National High Technology Research and Development Program (863 Program) under contract 2006AA09A105-4.

In 2006 researchers from Harbin University described a method for controlling hydraulic power by use of an asymmetrical cylinder controlled by an asymmetric value, which was applied to the leg control of a six-freedom simulator. Pressure jumps were eliminated by combining the control strategy with the model.

In a 2009 conference presentation described a manipulator which is hydraulically powered, remotely controlled system which is operated in a master slave style operation by an operator on a surface vessel. The master controller is used to operate, configure and diagnose the manipulator system. The position-controlled slave arm is hydraulically powered, electrically controlled manipulator with shoulder pitch and yaw, elbow pitch, forearm rotate, wrist pitch, wrist rotate and jaw open/close functions. Large hydraulic linear actuators control movement of the shoulder, elbow and wrist pitch and each actuator has a position sensor, an actuator control module that contains microprocessor electronics and a servo value. The control telemetry uses a RS-485 serial interface and all slave arm control functions are connected on a common bus. The telemetry is bi-directional and the control of each slave arm function (except for the jaw) utilizes a closed loop.

An IEEE notice regarding a conference paper from Harbin University on underwater navigation was found that casts light on potential problems with the accuracy of information presented by Chinese researchers. IEEE claims the article plagiarized material from a previously published PhD thesis out of Sweden. The IEEE violation notice can be found at http://ieeexplore.ieee.org/freeabs_all.jsp?arnumber=4608195 and is entited:
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Hou Shuping was born in 1972. She received her MS degree in the school of power and nuclear energy of Harbin Engineering University in 2001. She began to work as a PhD candidate in the School of Mechanical and Electrical Engineering of Harbin Engineering University in 2001. Her main research fields are robotics, fault diagnosis and intelligent control.

Huazhong University

In 1995 Huanzhong University researchers presented information on the development of two operation manipulators designed and built in China. The manipulator working depth was said to be 600 meters. A 1998 article introduced the performance and construction of two manipulators built for use on the Blue Whale underwater vehicle. One of the manipulators was used for dragging and had three degrees of freedom operation, maximum depth operation of 2803m and maximum lift capacity of 1500N. Five different types of jaws were developed and the jaws have both locking and discharging functions. Another manipulator was for general use and had six degrees of freedom, 2300m maximum depth and 320N maximum lift capacity. It is capable of cutting cables.

In 1999 the design for a new speed servo-control system for an underwater manipulator was presented. The system utilized a DC motor speed controller with negative and positive voltage

feedback. The software and hardware communication techniques for the distributed control system were described in a 2001 article. A serial programming technique based on the multithreading of Win32 was used in this application. A servo-controller based on PC104 and VxWorks as the hardware and software platforms was described in 2007 and an embedded control system was developed.

A hybrid serial-parallel manipulator based on two kinds of 3-UPU parallel mechanisms was first described in a 2004 Huazhong University of Science and Technology journal article. Each 3-UPU had one platform, one base and one limb and three degrees of freedom. Each limb was comprised of universal and prismatic joints in series for a total of six degrees of freedom. The motion of the serial-parallel mechanism can be decoupled to pure translation and spherical rotation and easily controlled for real-time applications.

A 2006 article from Huazhong University introduced a hydraulic robotic arm with a function of changing tools automatically. A new embedded controller based on PC104 and VxWorks RTOS was designed for the system.

A 2007 article described a sliding mode control scheme based on the exponential approach law. The manipulator consisted of a rotating joint and an extend/withdraw joint driven by electric motors. In order to study the actual performance of the control method, trajectory tracking experiments were done. The sliding mode controller was designed based on the decentralized dynamics of UVMS and uses fuzzy logic to adaptively tune gains. Dynamic models of the motors and thruster will be included in future research. This work was performed under contract 2006AA09Z203 of the 863 Program.

A 2008 article described a gearbox test system based on an automatic shift manipulator. The shift procedure was a complicated nonlinear time varying one and an expert system was used to control the shift operations. This work was performed under the 863 Program under contract 2006AA04Z244.

A recent journal article describes an underwater 3500 m electric manipulator (Huahai-4E) which was developed at the underwater manipulation technology laboratory located at the Huazhong University of Science and Technology. The manipulator was designed to be mounted in the bottom of the underwater vehicle and 6061T650 aluminum alloy was chosen as the manipulator material. The manipulator has modular integration joints, and a layered architecture control system. The joints are oil-filled and pressure-compensated and they utilize a brushless permanent magnetic motor. Further details of the manipulator indicate that it is equipped with an ultra-sonic probe array and an underwater camera. The ultra-sonic sensor system is composed of a micro-computer unit (MCU, msp430), a sending circuit and a receiving circuit. Every probe emits 8us 500K Hz pulses and receives the reflect wave once. The MSP430 then calculates the distance to the target and figures out it approximate location. In tank experiments the range of the ultra-sonic sensor was found to be two meters and due to the attenuation of sound waves, when the target distance was more than one meter, reliability and precision decreased.

Several experiments were done to test the manipulator. The first one was a water tight ability test and the pressure test is done in a hydraulic cylinder filled with water. The second test was

autonomous manipulation which done in a ship tank. From 0 to 900 seconds, the manipulator searched for the target, then to align the jaw with the target took another 20 seconds. This work was performed under the 863 Program under contract 2006AA09Z203.

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The Shenyang Institute of Automation, Chinese Academy of Sciences

The Shenyang Institute of Automation has described a simulator for simulating two underwater problems: underwater perception and autonomous manipulation. A simultaneous localization and mapping algorithm was used to estimate the state of the underwater manipulator system and the target object. An earlier study describes a multi-functional task work package for an underwater robot that was manufactured by the institute. In 2006 a three-function electric manipulator was described along with an algorithm that generated the desired trajectories for both the vehicle and the manipulator. A companion paper describes how the drag optimization function was incorporated into the motion coordination algorithm to minimize energy consumption of the system. A three-function manipulator was described in 2007 as part of an underwater vehicle-manipulator system and a simulation model was presented using the Matlab Simulink toolbox and M-function which helped validate the motion planning and control strategy for the entire subsystem. In 2009 a journal article described work on an underwater rectangle surroundings-based impedance force controller for an underwater work system. By tracking the reference trajectory the end-effectors of the underwater work system one can follow the underwater rectangle surroundings surface. The position and orientation were obtained by estimating the

specific contact point acquired by changing the feedback force. These efforts were performed under the 863 Program under contract 2006AA09Z217.

A three-function underwater electric manipulator test-bed was described which was composed of a claw and two swing joints. The manipulator was developed by The Shenyang Institute of Automation. The claw is a simple mechanism driven by an inside step motor and the shoulder and elbow joints are driven by the same rotary module. The rotary module includes a DC torque motor, a harmonic-drive reducer, a fail-safe brake and an incremental reducer. Two PWM servo amplifiers drive the DC and step motors. A micro-computer PC-104 controls the system and ADT650 is used as the data sampling card. The rotary joint driven module has an inner cable layout.

The Shenyang Institute of Automation introduced an autonomous anchor system for ROVs which can help provide a stable underwater operating environment. The paper addressed the problem of redundancy resolution for an underwater manipulator system. A task-priority redundancy system based on the weighted least-norm solution was adopted and a case study was presented. Simulations were run on a ROV carrying a SIWR-II underwater manipulator arm. This work was performed under the 863 Program under contract 2006AA09Z217.

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University of Science and Technology, Hefei

Novel six-dimensional force/torque sensors were developed as part of a joint effort by the University of Science and Technology, Hefei and the Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Canada. Components of force were measured along three orthogonal axes based on E-type membranes. Qiaokang Liang is the lead on this effort and works in both China and Canada. He has also worked on a micro-scale positioning device based on a two degrees of freedom plane compliant parallel mechanism. The stage utilizes piezo-driven actuators, flexure joints and an integrated/torque sensor that is capable of delivering 2-DOF motions and provides real-time position information for feedback control.

In a presentation at a 2010 IEEE conference Qiaokang Liang described a six degrees of freedom micromanipulator based on a compliant parallel mechanism. The manipulator uses piezo-driven actuators, flexure hinges and an integrated force sensor that can provide the system with real-time force information for feedback control.

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Qiaokang Liang is working towards a PhD in design science and engineering at the Institute of Intelligent Machines, Chinese Academy of Sciences and University of Science and Technology of China, Hefeo, Anhui, China.

Currently, he is a visiting scholar at the Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, ON, Canada, sponsored by China Scholarship council, Ministry of Education of China. His research interests include multidimensional force/torque sensors, underwater manipulator, compliance parallel kinematic mechanisms and simulation-driven development and optimization.

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He is a Canada Research Chair in Robotics and Automation in the Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, ON, Canada. His current research interests include robotics and mechatronics, advanced manufacturing techniques and CAD/CAM.

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Yunjian Ge received a BS degree in computer science from the University of Northeast China, Shenyang, Liaoning, China in 1982 and a PhD degree in computer science from the Institut National des Sciences Appliquees (INSA), Lyon, France in 1989.

Currently, he is a Professor at the University of Science and Technology of China and the Institute of Intelligent Machines, Chinese Academy of Sciences, Anhui. His research interests include information acquisition and processing, robot sensing system, human-computer interaction telepresence, and sport biomechanics. Since 1990, he has assumed and accomplished

more than ten research projects from the National Ascent Project, National 863 Project, National Science Foundation of China.

Hydraulic Research

Deep-sea hydraulic power sources studied included oil hydraulic and sea-water hydraulic systems. Both of these drives were reviewed in a 2010 journal article from the School of Mechanical Engineering, Southwest Jiao Tong University. An open-loop pressure control system based on a linear parameter-varying model for deep-sea extreme work conditions was designed by this school and research showed that the realized output of the hydraulic source pressure control has a permissible range of submerged length and flow media temperature for a specific initial viscosity. This research was performed under the 863 Program under contract 2006AA09Z226. Modeling and application of pressure compensation devices for deep-sea hydraulic systems were reported on by the Laboratory of Fluid Power Transmission and Control, Zhejiang University.

A pressure compensation system for underwater hydraulic systems was summarized in a 2006 review written by the College of Mechanical Engineering, Zhengzhou University and the 715 Research Institute of CSIC. The article analyzed the advantages and disadvantages of conventional pressure compensators and proposed different methods for pressure compensation. Researchers at the China Ship Scientific Research Center, Wuxi, analyzed the characteristics of an American Schilling manipulator and then used this information to develop a principal-subordinate controller for a deep-sea hydraulic manipulator. A six degree function manipulator was then defined from the analysis.

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Section Six

Deep Sea Submersible Guidance and Control Related Issues

Beijing University of Aeronautics and Astronautics

A kinetic equation of 6-degree of freedom for an underwater was designed taking into account gravity, buoyancy, thrust power and ocean current. A nonlinear controller was then designed to track the geometric path and included both inner and outer loops. The inner loop imported nonlinear compensation in order to simplify the robot system to a linear system. The outer loop used negative feedback to correct the wrap between the actual path and the ideal path.

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*Beijing University of Aeronautics and Astronautics
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*School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics
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Central South University, Changsha

Low mapping accuracy for AUVs is affected by the fact that sonar may not be able to detect dynamic objects correctly. In order to build more complete mapping information, a new approach was developed that uses static and dynamic grid maps. The two types of occupancy grid maps are updated through the static maps, sonar observations and dynamic objects detected by a monocular camera.

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*Liu Li-mei, **Cai Zi-xing and **Pan Wei
*Institute of Intelligent System and Software, College of Information Science and Engineering, Central South University, Changsha and College of Computer and Electronic Engineering, Hunan Business College, Changsha
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Map building method based on sonar information, *Computer Engineering*, 2009-07

China Electronics Technology Group Corporation, No. 20th Research Institute, Xian

An inertial navigation system/ global positioning system/Doppler velocity log integrated navigation system fusing multi-sensor data was proposed. A federated kalman filter was adapted and each navigational subsystem was optimized through a dynamic information sharing coefficient to improve overall performance.

Journal Articles:

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*China Electronics Technology Group Corporation, No. 20th Research Institute, Xian
New application of federated filter in INS/GPS/DVL integrated navigation system for AUV, *Torpedo Technology*, 2010-04

China Ship Scientific Research Center, Wuxi

In 1997, a journal article was published that looked at AUV navigation in the deep sea environment. Neural networks were seen as the best solution to the highly nonlinear control problem. The merits of feed-forward and feed-backward systems were evaluated and then a GESA algorithm applied that auto-enhanced the functional-link net.

A virtual simulation model for the deep sea UAV was described and the system included three dimensional track display and collision detection. The powerless descent/ascent motion of a deep sea submersible is an ultra-large attack angle motion and cannot be properly described through traditional motion models for undersea bodies. Variations in buoyancy and weight of the submersible with depth were considered as part of the model.

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Chinese Academy of Surveying and Mapping

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**2715 Research Institute of Shipbuilding Industry Corporation, Hangzhou
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*Chinese Academy of Surveying and Mapping, Beijing
Research on setting 3D network of underwater DGPS, *Science of Surveying and Mapping*, 2006-04

*Bei Jin-zhong, **Zhang Chuan-yin, *Gao Xing-wei, ***Wang Ze-min and *Cai Yan-hui
*Chinese Academy of Surveying and Mapping, Beijing and School of Geodesy and Geomatics, Wuhan University
** Chinese Academy of Surveying and Mapping, Beijing
***715 Research Institute of Shipbuilding Industry Corporation, Hangzhou
Research on time synchronization calibrating in underwater GPS system and its experiment, *Science of Surveying and Mapping*, 2007-03

Dalian Maritime University

The Marine Dynamic and Simulation Control Laboratory provided information on the simulation system for an underwater deep sea vehicle. The system incorporated system-behavioral realism, operating environmental realism, architectural physical realism, and functional features. A 6 degree of freedom hydrodynamic mathematical model of the simulation system based on virtual reality technology was developed. Techniques for modeling deep sea terrain, high efficiency data structure for the visual database, searchlight effects in the deep sea environments, simulation of manipulator operation, sonar simulation, and a synchronization method for the visual system with multi-channel function were all part of the model.

Journal Articles:

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*Marine Dynamic Simulation and Control Laboratory, Dalian Maritime University
Research on simulation system based on virtual reality technology for handling underwater vehicle in deep sea, *Journal of Harbin Engineering University*, 2005-04

Harbin Engineering University

A 1998 conference presented details for the control system of an intelligent underwater vehicle. In China, the Shenyang Autonomous Institute and the China Ship Scientific Research Center have developed the EXPLORER AUV, which can dive to 6000m depth. Harbin Engineering University has developed two autonomous underwater vehicles (HIUV-I and HIUV-II) and studies the intelligent behaviors of AUVs and develops software for intelligent system control.

Experimental verification of the control system for the HIUV-II was carried out in July 1995 in a lake near Harbin. There was no velocity sensor on the HIUV-II , and the information of position sensors is to some extent fuzzy and indistinct and it is important to estimate the velocities of the vehicle and current in order to manipulate the vehicle accurately. A three-layer feed forward neural network was used to estimate velocity of the vehicle from the input and output relations. As of early 1998 a third vehicle, designated HIUV-III, is being developed and will tested in the sea near Dalian.

A mathematical model of an AUV moving near the plane wall was presented on the basis of the principle of hydrodynamic forces disturbed by the plane wall and PID controllers with five-degrees of freedom were designed. The motion control of the AUV under the influence of ocean current and accurate location on the workstation were accomplished by system simulations.

Harbin University researchers have also looked at the mine countermeasure mission for multiple AUV team system. A typical MCM mission included the tightly coupled formation to the mine field and a loosely coupled sub-area target allocation and renaissances. Tasks are injected into the system by sending messages to one of the AUVs, which can deliver the tasks to the other AUVs by negotiation. The complete mission including four AUVs was demonstrated in 2005 in the newly developed multiple AUV simulation environment at Harbin Engineering University. The deep-sea submersibles can be used in a relay mode to send and receive messages from AUV military teams and provide control over missions.

Military applications of AUVs include battle damage assessment, delivery of weapons, target following, and target destroying and reconnaissance. Mission management and intelligent decision are some of the most embodiment of autonomous level of the AUV. Possible submersible operations include terrain scanning, outline following and objective search.

Three steps were shown to be optimal for path planning: establish a cost matrix between each pair of points, using the Dijkstra algorithm to calculate the path of smallest cost value and using the Little algorithm to calculate the Hamilton path of smallest cost value. A survey mission was carried out by an AUV in a lake and the mission zone included obstacles and a forbidden area. The AUV was able to carry out terrain scanning, then followed the outline around the island in the center of the lake, and finally objective scanning. Path optimization and speed optimization were designed to reduce the complexity of the decision process.

Based on the independent characteristics of the AUV, a SINS/DVL integrated navigation system is usually adapted for guidance and control purposes. A June 2005 paper compared two integrated navigation systems (SINS/DVL and the compass status SINS/DVL integrated

navigation system). The compass status of SINS/DVL integrated system's positioning accuracy decreases when the filter processing state is interrupted by the loss of the outer velocity provided by the DVL. A modified Kalman filter has been proposed to improve accuracy when the AUV is in motion.

The Harbin researchers chose positioning error, velocity error, misalignment error, and gyro drift as the states of the state vector according to the error characteristics of SINS in the long-working state. The random time-varying drift caused by the accelerometer was taken into account in the accelerometer noise. The priority estimate of the Kalman filter is not accurate when the vehicle is in motion and increasing the sample frequency does improve performance, but processing time goes up. Simulation showed that SINS can offer very accurate heading information in the short term as a compass and DVL can offer accurate velocity data for the AUV.

A model reference controller based on a fuzzy neural network was proposed for an AUV. To reduce uncertainties in manual adjustments, a hybrid particle optimization algorithm based on immune theory nonlinear decreasing inertial weight was proposed. The algorithm was shown to prevent premature convergence and keep the balance between global and local searching abilities. In the model reference adaptive controller (MRAC), the most important module was the fuzzy network controller, which is part of the motion control system for the AUV. The fuzzy network controller was is a fuzzy system with doubles inputs and outputs, and the inputs are position error and velocity, and the output is the required force or movement at each degree of freedom acting on the AUV.

Earlier research in this area had looked at the use of fuzzy neural network control for the simulation of the motions of a general detection remotely operated vehicle (GDROV). The GDROV is designed as an open-frame structure due to the fact that it equipped with numerous advanced inspecting sensors and does not have a streamlined geometric profile because of this. Because the GDROV runs at slow speeds, the coupling of motion in six degrees of freedom is not severe. In order to make the design of the control system convenient, the coupling function was ignored and the motion of the underwater vehicle considered separately.

Simulation experiments were carried in still water and water with current. The velocity of the current added 0.2 m/s in the northeastern direction and there was a great improvement in response and precision over traditional fuzzy and neural network controls. The steady-state error fell from 2% to 0.04% in longitudinal control and rise-time fell from 46s to 28s in heading control.

Inertial navigation has been the main navigation method for UAVs, but cumulative error of the INS affects navigation precision. Terrain matching aids in the precision of the INS and integrated system provides increased navigation accuracy. The simulation platform of the navigation system of an AUV was developed based on a Windows platform with Visual C++. 6-DOF dynamic modeling for an AUV is a matter of dynamics and should be in inertial coordinates.

Under ideal conditions, the heading and the direction of the AUV should be identical. The heading, pitch and the distance between the center of the AUV and the course are important

parameters for path following. The horizontal and vertical navigators cooperate with the velocity controller, heading controller and pitch controller to realize path following.

The TER-COM algorithm which is based on the profile of the sea-bed terrain was used for terrain matching. The position of the AUV was obtained by comparing the data of the sounder with the data from the ocean chart database. The position information computed by the TER-COM algorithm was shown to be able to amend the errors of inertial navigation.

While S-surface control has proven to be an effective method for motion control of AUVs, there are problems with maintaining steady precision of course due to the constant need of adjusting parameters. An intelligent integral was introduced to improve the precision of the S-surface control. A fuzzy neural network was included to help adjust the production rules for the knowledge base. There were only three controlling parameters of the presented S-surface control model and it was simpler to tune these parameters than those of a fuzzy controller.

Experiments were conducted on the simulation platform of an AUV developed in the Harbin laboratories. The AUV consists of a motion control system, path planning system, navigation system, emergency management system and monitoring system. There are 8 thrusters in the propelling system and this includes 4 ducted propellers located at the stern and 4 tunnel propellers located in the body. The 2 horizontally stern located propellers are used as the main thrusters and the other 2 propellers are used to provide trim movement. The 2 tunnel propellers are used as lateral and vertical thrusters.

The expert S-surface controller had faster response speed and better steady-state precision than that of the S-surface controller. The expert S-surface controller can adjust its parameters on-line in different navigation situations and the ability of anti-inference is enhanced and stability of the system increased.

Research on a similar control system for a mini AUV (MAUV-II) was presented in a 2009 paper. MAUV-II has a single propeller and uses lithium batteries as its power source. There are two horizontal and 2 vertical propellers located at the rear of the AUV. The 6-DOF motion mathematical model was founded by combining kinematics and dynamic equations which are derived from momentum theorem.

The motion of the AUV is not 6 degrees of freedom and it cannot accomplish movements of sway, heave and roll. Because of this the main control motions of the AUV are yaw, pitch and depth. The AUV enters into stabilization in a short time and simulation curves show good turning ability. The larger the deviation is, the quicker the yaw angular velocity is.

In August 2008, IEEE issued a notice of violation concerning a conference paper given by researchers from the College of Automation, Harbin University. The topic of the was terrain navigation for an underwater system and IEEE stated that the paper contains portion of original text from a December 2005 PhD thesis by Ingemar Nygren (School of Electrical Engineering, Royal Institute of Technology, Sweden).

A generalized form of a mathematical model (6-DOF) describing the nonlinear vehicles systems was derived and was applied to a large number of underwater vehicles. The motion control system including speed, position and depth control was investigated for different task assignments of vehicles. An improved S-control based on a capacitor model was developed which can provide flexible gain selections with clear physical meanings. The control system of the model included both position and speed control in the horizontal plane and combined heave and pitch control for dive in the vertical plane.

A new method for the simultaneous location and mapping for an AUV was proposed in 2008. Line characteristics were first characterized from the data scanned by the sonar and then three kinds of geometric constraints were brought into the characteristic matching process in order to guarantee that the observed characteristic would match the model characteristic correctly. By this method the UAV can locate and map in complicated environments only depending on the forward looking sonar and the Doppler dromometer, which corrects the map at the same time.

A 2011 paper by researchers from Harbin and Wuhan Universities presented information on the hardware and software systems used in the position and attitude control systems of a Deep Submergence Rescue Vehicle (DSRV). Two trim tanks and four heel tanks are fixed on the platform and used for pitch and roll control. By controlling the switching time of the pumps and values, the trimming and heeling angles were adjusted automatically. Maximum values obtained in these experiments were 30 and 15 degrees respectively. Force and torque obtained from the controller are transferred to body-fixed coordinates from inertial coordinates and solved the problem of complicated thrust allocation caused by large heeling and trimming angles.

Underwater image segmentation is the premise to image analysis and understanding of and visual recognition for AUVs. In the current segmentation, the threshold method is one of the basic skills of image segmentation due primarily to its briefness and stability. In the traditional FCM algorithm the optimal solution is obtained by minimizing the objective function. By using the statistical characteristics of the histogram of gray images, Harbin researchers developed a fast and effective FCM underwater image segmentation algorithm. Particle swarm optimization was introduced to the algorithm and makes up for the shortcomings of the FCM algorithm.

Analysis of the FCM algorithm showed that one of the main factors affecting the computational time was that the update frequency of the cluster center was too low. In the FCM algorithm, each cluster center must wait until all the input mode are transversal. Through the analysis of fuzzy C-means algorithm and then full utilization of the statistical properties of the histogram of the gray image, a fast and effective clustering algorithm was developed. Modifying the membership degree matrix and the clustering center matrix cuts down a large amount of data processing and storage during the computation process of the traditional algorithm and speeds up the efficiency of the segmentation and improves the quality of image segmentation. Average calculation speed is ten times quicker than the traditional FCM algorithm.

Path-planning was optimized in 3-D space by developing a novel spiral particle pathway searching approach and particle swarm method. The concept of the grid method and a spiral particle pathway searching approach was used to search for particles in the pathway in the plane of parallel subspace. MATLAB was used to calculate the particles in order to search for the best

pathway to the target points in three-dimensional space. This was then optimized using a PSO algorithm to improve underwater control of the AUV.

An improved method of generating underwater terrain was developed in which the electric chart was used as the data source. A Laplace interpolation was used in the data interpolation of the water depth on the electronic chart and used to generate a three-dimensional environment. The data storage capacity of the Roam algorithm was redesigned and improved. A height factor was also introduced and these improvements reduced the geometric complexity and increased the accuracy of the method.

Underwater path finding must be three-dimensional path planning and this requires a large amount of three-dimensional terrain data in order to construct a three-dimensional space environment for path planning. Real terrain data for the undersea environment is limited and often the data cannot be directly applied to path planning. The Roam algorithm can be used to draw terrain at high speed but has some basic drawbacks. The Roam algorithm stores data based on Patch and terrain resolution cannot be adjusted overall and is not conducive to the query of elevation data. In addition, the level of detail resolution of terrain mapping is determined by the terrain roughness and the distance to the point of view.

A method for simplifying and improving the data structure was developed and simulated. Each point in the tree structure of the Roam triangle is correspondent to the mid-point of the grid data and the relationship between tree structures can be abstracted from the terrain data and then stored separately. This changes the size of the Patch corresponding to the needs of the display and simplifies data query. The underwater elevation data is regular grid and can be stored directly in a one-dimensional array.

Experiments on different heights were carried out and the discrete depth data was extracted from the electronic chart and the Laplace algorithm was used to generate regular grid data. Then the terrain generated algorithm was used to generate a 3D underwater terrain simulation. The realism of the terrain can be enhanced by pasting the realistic texture for the terrain model and then increasing the lighting effect to enhance the true extent of the scene.

A fault-tolerant controller was designed after analyzing variations in state-feedback gain. Operating conditions and the design method were then analyzed and the control problem expressed as a mathematical optimization problem. This allowed the use of linear matrix inequalities to be used to solve for the controller for the system.

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A real-time test system of semi-physical simulation was designed to access the performance of an AUV attitude control system. The VMI bus test platform of the ATS is composed of a MC, VXI bus mainframe with 13 slots of C-size and VXI bus modules. An IEEE1394 interface was responsible for data exchange between the MC and the VXI bus test system.

A program-controlled rotary estrade (PCRE) can provide attitude angles with three degrees of freedom in accordance with AUV performance requirements. The PCRE is a relatively independent high-precision positioning servo system which uses a PC/104 embedded PC module. A separation-type integral PID control method was used to improve control accuracy and response speed.

The program-controlled pressure device was composed of a hydraulic circuit and the PLC. The pressure, which simulates seawater pressure change and pressure conditions of the AUV at different water depths, was generated in real time under computer control. A fuzzy control method was used to control the hydraulic nonlinear system and correct system error.

Test results showed that the specifications of the ATS were in good agreement with design requirements. The ATS saved more than 70% of test time compared to traditional systems but because ATS works in the serial mode, a great of time is spent unnecessarily. Parallel processing techniques are currently being studied in order to reduce test times.

Based on local path planning, a fuzzy control algorithm was adopted for use by an AUV with variable velocity. Based on a formation control method and the geometrical kinematic relation of the formation order, the multi-AUV formation of obstacle avoiding was translated into the path planning of a virtual AUV. A fuzzy control policy was developed for the AUV to avoid obstacles.

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Sonar processing of images based on the TMS320C30 high-speed DMS was shown in the mid-1990s to be an important intelligent system for the autonomous underwater vehicle. DSP was used to realize sonar image compression and underwater object parameters calculations including real-time obstacle recognition.

Wang Yuling (Wang Yu-ling) is believed to be the leader of the team developing sonar technology for AUVs and has developed a ray theory based method to explain the principle of waveform variance as applied to correlation of sonar. Two approaches (temporal and spatial correlation) to the design of correlation sonar were explored. The prototype correlation sonar has

undergone two tests at the West Pacific Ocean and the South China Sea. Comparing the velocity results obtained by the correlation sonar with those obtained by acoustic Doppler current profiler and differential GPS illustrated the feasibility of the correlation sonar for measuring current and vehicle velocity.

The major issue associated with Synthetic Aperture Sonar with a large mapping width is the real-time processing of large amounts of data. This processing uses computing instruments, mapping algorithms and the system structure to produce high resolution maps. A parallel processing method was implemented on a computer cluster and used for high-frequency SAS signal processing and verified by a lake test. Recent results indicated that a range resolution of 4 centimeters, an azimuth resolution of 5 centimeters and a mapping width of 200 meters can be met by the current system.

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*Institute of Acoustics, Chinese Academy of Sciences, Beijing
Velocity measurements with correlation sonar and sea test verification, *Technical Acoustics*, 2005-02

*Jiang Ze-lin, *Liu Wei, *Li Bao-li, *Liu Ji-yuan and *Zhang Chun-hua
*Institute of Acoustics, Chinese Academy of Sciences, Beijing
A parallel processing method for high-frequency synthetic aperture sonar based on clusters, *Applied Acoustics*, 2011-03

Institute of Automation, Chinese Academy of Sciences, Beijing

The particle swarm approach aimed at mobile robots in a structured environment was examined and information on environmental constraints and path length was integrated into the fitness function, which was computed by the neural network. A hybrid particle swarm algorithm was developed and shown to be usable for real-time mobile robot navigation.

Journal Articles:

*Zhao Xian-zhang, *Chang Hong-xing and *Zeng Jun-fang
*Institute of Automation, Chinese Academy of Sciences, Beijing
Path Planning Method for Mobile Robot based on Particle Swarm Algorithm, *Application Research of Computers*, 2007-03

Lanzhou University of Technology

Two of the most common methods integrated AUV nagination are dead-reckoning (DR) and kalman filtering. The unscented kalman filter was applied to AUV navigation and shown to be accurate with comparable system cost.

Journal Articles:

*Yang Ping, *Zhang Cui-ying and *Zhang Shu-zhen
*College of Mechano-Electronic Engineering, Lanzhou University of Technology
Operational principle and dynamic analysis of a new-type water-jet propeller, *Journal of Lanzhou University of Technology*, 2009-03

National University of Defense Technology, Changsha

Ring laser gyros can be used to determine the position and azimuth of deep sea submersibles and a simulation program was implemented. Results of a 72-hour position and azimuth determining experiment were reported in a 2009 journal article. The velocity error was below 0.9 $m.s^{-1}$ and the position error was below 29.9 km.

Journal Articles:

*Lian Jun-xiang, *Wu Wen-qi, *Li Tao and *Hu Xiao-ping
*College of Electromechanical Engineering and Automation, National University of Defense Technology, Changsha
Application of unscented Kalman filter in AUV integrated navigation, *Journal of Chinese Inertial Technology*, 2005-01

*Hu Chun-sheng, **Qin Shi-qiao, *Wang Xing-shu and *Huang Zong-sheng
*College of Optoelectric Science and Engineering, National University of Defense Technology, Changsha
**College of Science, National University of Defense Technology, Changsha
Simulation and experiment of precise position and azimuth determining system based on ring laser gyro for deep ocean work, *Journal of Tropical Oceanography*, 2009-04

*Peng Peng-fei and *Liu Zhong
*School of Electronic Engineering, Navy University of Engineering
An Independent Ups and Downs Control Method Underwater Submersible Vehicle Based on Adaptive Fuzzy Control, *International Conference on Intelligent Human-Machine Systems and Cybernetics*, 2009

*Peng Peng-fei, *Liu Zhong and *Jiang Jun
*School of Electronic Engineering, Navy University of Engineering
Ups and down control of underwater submersible vehicle based on fuzzy control, *Electronic Design Engineering*, 2011-05

Naval University of Engineering, Wuhan

Real-time precision simulating signals were generated by a program-controlled signal source and based on these the true controlled performance of an AUV was examined. Attitude angle resolving power was 0.001^0, velocity was 0.002^0/s, depth was 0.8 meters and target angle was 0.02^0. Phase differences between attitude angles and velocities were eliminated and the design simulation validated.

Journal Articles:

*Huang Wenling, **Yao Wangsheng, *Xie Shunyi and *Zhao Jun
Department of Weaponry Engineering, Naval University of Engineering, Wuhan
Department of Computer Engineering, Naval University of Engineering, Wuhan
Simulating and testing design for an AUVs attitude control system, *Computer Automated Measurement & Control*, 2005-1

North China Institute of Water Conservancy and Hydroelectric Power, Zhengzhou

In order to improve the accuracy of an AUV, a terrain passive integrated navigation system, which consisted of a strapdown inertial navigation system, underwater terrain map, bathometer, magnetic compass and doppler log was developed. The parameters of the system were estimated using a UD factorization-based adaptive kalman filter, which adjusted the measured noise to suit the changes of measured course, inhibiting the error divergence of the navigation system. In simulations, the adaptive kalman filter was able to compensate for location errors by about 50%.

Further simulations were carried using Visual C++ tools and the storage format of the digital maps was quadrant grip data. The integrated navigation had two modes: matching time, in which the system uses the mode of SINS/DVL/MCP/TAN and the non-matching mode, in which the terrain matching location information did not participate in the measuring process. That system used the mode of SINS/DVL/MCP. AUV position error was greatly reduced from the simulation experimental results and the precision of underwater navigation also improved.

Conference Papers:

*School of Mechanical Engineering, North China Institute of Water Conservancy and Hydroelectric Power, Zhengzhou
**Party Organization Department, Henan Institute of Engineering, Zhengzhou
Multi-sensor data fusion approach for terrain match navigation of autonomous vehicles, *2nd International Conference on Industrial Mechatronics and Automation*, 2010

*Zhang Tao
*School of Mechanical Engineering, North China Institute of Water Conservancy and Hydroelectric Power, Zhengzhou
Autonomous underwater vehicle navigation using an adaptive Kalman filter for sensor fusion, *29th Chinese Control Conference*, July 29-31, 2010, Beijing

Northwestern Polytechnical University

In 2003 an integrated navigation and control scheme was proposed for a long distance autonomous underwater vehicle. The scheme included both a gyrocompass and a Doppler velocimeter. Semi physical simulation was shown to suffer from a number of problems including the fact that the Doppler velocimeter cannot be used in the laboratory test environment. A PC104 industry control computer was used to perform the following tasks: calculate the integrated navigation and control model of the AUV, send out information on the heading, pitch and roll of the AUV model to simulate the gyrocompass via RS232, send out the sates of the AUV model to the portable computer via Ethernet network by TCP/IP protocol, send out the depth of the AUV to simulate the depth sensor via D/A, send out the "begin" command to the navigation system to simulate the launch of the AUV, and receive the "stop" command from the navigation and control system to simulate the parking of the AUV. Extensive simulation proved the performance characteristics of the system and were shown to reduce both experimental costs and debugging time.

The traditional model of the AUV suffers from two shortcomings. The first is the fact that when the local earth coordinate is selected as an inertial one, the model does not consider the curvature and rotation of the earth. Secondly, geographic parameters such as longitude and latitude are not included in the model. In order to overcome these shortcomings, a new hydrodynamic model of a long-distance AUV, earth-centered inertial coordinates, earth-centered earth-fixed coordinates, navigation coordinates, body-fixed coordinates, and velocity coordinates was developed. The hydrodynamic model consisted of six-degree-of-freedom dynamic equations in earth-centered inertial coordinates based on the theory of momentum and movement and six-degree-of-freedom kinematic equations by coordinate transformation among earth-centered inertial coordinates, earth-centered earth-fixed coordinates, navigation coordinates and body-fixed coordinates. Simulation results showed that because the model is established in earth-centered inertial coordinates, the new model is suitable for global guidance system simulation for a long range AUV and can be used for precision analysis of the navigation and control system sensors.

A path planning algorithm for an AUV going across an underwater minefield was proposed. The path planning included global and local path planning. A Voronoi diagram of mine distribution was established and then a local optimal path was planned using a genetic algorithm. A fuzzy inference system was designed to derive the obstacle-avoiding angle based on the position of the AUV and the obstacle and forward looking sonar was used as the measuring instrument while the AUV tracks the global optimal path.

In a 2007 paper presented results on a real-time strapdown inertial navigation system/Doppler velocity log integrated navigation system for AUVs. The design system was based on the PC104 computer and the navigation system was designed by setting up a model of the AUV. The system passed simulation tests and meets the requirements for a long range AUV.

The nonlinear movement model of an AUV under the action of unknown ocean currents was modeled. The properties of both kinematic and dynamic models were used to develop the model and a horizontal dynamic positioning algorithm based on adaptive back-stepping slide mode control was simulated. The current speed was estimated online and simulation results verified the

global asymptotic stability of the tracking control system and its robustness to boundary external force and movement.

Depth control by fins is one of the difficulties for an AUV in motion control and is indirect due to the freedom coupling between trim and axial motion. By considering current speed and depth deviation, a comprehensive interpretation was used in the object-planning instruction. Expected depth was transformed into expected trim and dynamic output fluctuation can be avoided (caused by the linear mapping of deviation). The feasibility of this system was demonstrated in both pool and natural environments.

In 2008, results were presented for a satellite assisted navigation simulation system for an AUV. The system consisted of a satellite positioned GPS satellite simulator, a GPS receiver and a simulation computer. The scheme was shown to be suitable for hardware-in-the-loop simulation of an AUV navigation and control system.

In 2009, a new method was outlined for a automatic pilot for a long –range AUV. A distributed frame was used and in the hardware design, a CAN bus was adopted for use. The CAN bus made communication more quickly and reliable. The software system used a real-time operation system (uC/OS) to solve time-delay problems.

An AUV uses an algorithm to plan its path to distant objects and targets. The efficiency of the algorithm decreases if the global environment is presented by regular grids with all of them at the highest resolution. A framed quadratic data structure is able to more efficiently represent the environment and improves the ability of the AUV to follow and track an object. From the construction of a discretized representation of a map, the size of the grid is limited and may not represent the best representation of the environment. The structure of the map may be improved by different shapes but the generated path may become worse.

A new type of flexible hot sensor array for underwater applications was developed based on nickel thin film resistors deposited on a polyimide film substrate. Polymer compatible micromachining technology for the flexible array was developed and optimized. The nickel thin film thermal sensors were sputtered and patterned on the polyimide substrate. The thin film resistor and its array were patterned with lift-off or etch-back processes suing photo resist as a processing mask with sputtering or etching. Alumina was used as a waterproof coating due to its good thermal conductivity and high-endurance to the harsh underwater environment. Hydrodynamic experiments were conducted in various water tunnels and indicated that dynamic wave flow can be sensed promptly with the sensor.

Conference Papers:

*Binghe Ma, *Jinzhong Ren, *Jinjun Deng and *Weizheng Yuan
*Northwestern Polytechnical University, Xian
Flexible thermal sensor array on PI film substrate for underwater applications, *International Conference on Micro Electro Mechanical Systems (MEMS)*, January 24-28, 2010, Wanchai, Hong Kong

Journal Articles:

*Kang Feng-ju, *He Jun-hong, *Li Hao, *Gao Li-er, *Yang Hui-zhen and *Li Xiang-jun
*Northwestern Polytechnical University, Xian
Research on distributed interactive simulation technology for underwater vehicle system, *Acta Simulata Systematica Sinica*, 2001-02

*Song Zhi-ming, *Kang Feng-xu, Tang *Kai, Gao Li-e and *Chu Yan-jun
Marine College, Northwestern Polytechnical University, Xian
Research on visual simulation system of autonomous underwater vehicle, *Acta Simulata Systematica Sinica*, 2002-06

*Yan Weisheng, *Gao Jian, *Song Baowei and *Pan Guang
*College of Marine Engineering, Northwestern Polytechnical University, Xian
Real-time navigation and control simulation system for a long-distance autonomous underwater vehicle, *Journal of Northwestern Polytechnical University*, 2003-04

*Li Jun, *Shen Anwen, *Song Baowei and *Xu Demin
*College of Marine Engineering, Northwestern Polytechnical University, Xian
The methods and shipping trial of the navigation of autonomous underwater vehicles based on Doppler dead reckon, *Journal of Huazhong University of Science and Technology*, 2004-01

*Li Jun, *Xu De-min, *Song Bao-wei and *Yan Wei-sheng
*College of Marine Engineering, Northwestern Polytechnical University, Xian
Development and prospect of AUV navigation technology, *Shipbuilding of China*, 2004-03

*Yan Weisheng, *Xu Demin, *Li Jun and *Zhang Fubin
*College of Marine Engineering, Northwestern Polytechnical University, Xian
A new method for modeling long distance autonomous underwater vehicle (AUV), Journal of Northwestern Polytechnical University, 2004-04

*Yuan Xing, *Shi Xiu-hua, *Xu Hui and *Jia Rui
*Northwestern Polytechnical University, Navigation College, Xian
AUV navigation system model at low cost, *Journal of Transluction Technology*, 2005-01

*Wang Ting and *Song Bao-wei
College of Marine Engineering, Northwestern Polytechnical University, Xian
Control of dynamic position system for AUV with multiple thrusters, *Acta Armamentarii*, 2006-05

*Cui Ron-xing, *Xu De-min and *Yan Wei-sheng
*National Key Laboratory of Underwater Information Processing and Control, Northwestern Polytechnical University
Path Planning Algorithm for Autonomous Underwater Vehicle, *Journal of System Simulation*, 2006-12

*Lu Shu-juan, *Yao Yao and *Li Hui-ping
*College of Marine Engineering, Northwestern Polytechnical University, Xian
Design and implementation of integrated navigation simulation system for autonomous underwater vehicle, *Torpedo Technology*, 2007-05

*Gao Jian, *Xu Demin and *Yan Weisheng
*College of Marine Engineering, Northwestern Polytechnical University, Xian
Backstepping sliding mode control of dynamic positioning of an autonomous underwater vehicle, *Mechanical Science and Technology for Aerospace Engineering*, 2007-06

*Zhang Li and *Yang Huizhen
*School of Marine Engineering, Northwestern Polytechnical University, Xian
Research on assembled underwater terrain matching algorithm based on ICCP and TERCOM, *Journal of Projectiles, Rockets, Missiles and Guidance*, 2008-03

*Wang Yan-kai, *Kang Feng-ju, *Duan Shi-mei, *Wang Jiao-yan and *Wei Wei
*College of Marine Engineering, Northwestern Polytechnical University, Xian and National Key Laboratory for Underwater Information Processing and Control, Xian
Assisted navigation hardware-in-loop simulation of autonomous undersea vehicle based on GPS satellite simulator, *Torpedo Technology*, 2008-03

*Zhang Li-chuan, *Xu De-min and *Liu Ming-yong
*College of Marine, Northwestern Polytechnical University, Xian
New automatic pilot design for long-range autonomous underwater vehicles, *System Simulation*, 2009-01

*Zhang Li-chuaan, *Xu De-min, *Liu Ming-yong and *Yan Wei-sheng
*College of Marine Engineering, Northwestern Polytechnical University, Xian
Cooperative navigation and localization for multiple's UUVs, *Journal of Marine Science and Application*, 2009, 8, p216-221

Bo Gao, *De-min Xu and *Wei-sheng Yan
*College of Marine Engineering, Northwestern Polytechnical University, Xian
Framed-quadtree path planning for an underwater vehicle with the task of tracking a moving target, *Journal of Marine Science and Application*, 2010, 9, p27-33

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Wei-sheng Yan is a professor at Northwestern Polytechnical University and his research interests include precision guidance and control of AUV.

Ocean University of China

A localization system was described for AUVs that used a Doppler velocity log sensor and an attitude and heading reference system sensor (AHRS) to measure depth, attitude, and velocities relative to the sea bottom. A mechanically scanning imaging sonar was employed to obtain acoustic images of objects in the ocean environment. The resulting scan was distorted due to the motion of the AUV and this presented difficulties for use of the system. Point features for the SLAM algorithm were used in this research because the researchers thought it was more suitable for AUV cruising in the undersea natural environment than lines features.

Conference Papers:

*Bo He, *Ke Yang, *Shuai Zhao and *Yitong Wang
*School of Information Science and Engineering, Ocean University of China
Underwater simultaneous localization and mapping based on EKF and point features, *IEEE International Conference on Mechatronics and Automation*, August 9-12, 2009, Changchun

Journal Articles:

*Song Wen-jie, **Sun Jia, **Cheng Wen and **Ji Yan
*Shandong Provincial Key Laboratory of Ocean Environment Monitoring Technology, Shandong Academy of Sciences, Institute of Oceanographic Instrumentation, Qingdao and School of Engineering, Ocean University of China, Qingdao
**Shandong Provincial Key Laboratory of Ocean Environment Monitoring Technology, Shandong Academy of Sciences, Institute of Oceanographic Instrumentation, Qingdao
Design of laser gyroscope navigation system hardware platform, *Ship & Ocean Engineering*, 2011-03

Second Institute of Oceanography, Hangzhou

Journal Articles:

*Li Shou-jun, *Tao Chun-hui and *Bao Geng-sheng
*Key Laboratory of Submarine Geosciences, SOA, Second Institute of Oceanography, Hangzhou
INS/USBL underwater navigation system based on Kalman filter, *Ocean Technology*, 2008-03

Shanghai Maritime University

Sensor systems, especially data filtering, of underwater vehicles are seriously affected and degraded by the environment. A Kalman filter model based on a Genetic Algorithm was proposed as a solution, measurement noised was reduced and the filtering precision of underwater vehicle measurements was improved. The filtering method was tested for the Gyro

Sensor of the OUTLAND 1000 underwater vehicles by pool measurement simulation and found to be effective.

Journal Articles:

*Hu Wee-li, *Wang Cui-cui and *Liu Jing
*Laboratory of Underwater Vehicles and Intelligent Systems, Shanghai Maritime University
Underwater vehicle signal processing based on genetic algorithm Kalman filter, *Computer Knowledge and Technology*, 2009-19

*Chen Ai-qin, *Liu Qian and *Zhu Da-qi
*Laboratory of Underwater Vehicle and Intelligent Systems, Shanghai Maritime University
A fault identification algorithm of thrusters for unmanned underwater vehicles based on BP neural network, *Computer Knowledge and Technology*, 2009-19

Tao Wang, Hengyu Li and Shaorong Xie
*School of Mechatronics and Automation, Shanghai University
Design of shipborne underwater inertial stabilized pan-tilt system based on fuzzy PID controller, *Computer Science for Environmental Engineering and Ecoinformatics, Communications in Computer and Information Science*, 2011, 158(2), p97-103

Shanghai Jiao Tong University

A 2005 paper proposed a robust path following control law for a deep-sea manned submersible maneuvering along a predetermined path. The submersible is underactuated in the horizontal plane and is actuated by two perpendicular thrusters in this plane. An advanced non-linear terminal sliding mode (NTSM) was designed for the path following controller and the closed-loop stability was proved Lyapunov's stability theory. Numerical simulations were provided to verify the control law for path following of the deep-sea manned submersible.

The nonlinear hydrodynamic forces on a deep manned submersible at a low forward speed and large drift angles were determined by a model test based on a new fuzzy sliding mode control strategy. The fuzzy sliding control method was developed by combining sliding mode controllers, responsible for stabilizing the system within different drift angles, by using Takagi-Sugeno fuzzy inference. Simulation illustrated the value of the proposed system.

A general design method for a federated Kalman filter based on mutli-sensor fusion was developed and applied to an integrated navigation for underwater systems. The adapted system included SINS, electronic compass and depth gauges. SINS is the self-determined navigation and is independent of external signals. The system is sensitive to angular velocity and linear acceleration in order to position, velocity and attitude of the carrier. The electronic compass is a heading attitude sensor which measures geomagnetic signals. A federated filter algorithm which uses NR structure (which abolishes the information distribution step) was adopted and shown to have real-time and system reliability.

Conference Papers:

*Zhang Hong and **Song Zhen-hua
*Electrical Engineering College, Northeast Dianli University, Jilin
**Institute of Aerospace Science and Technology, Shanghai Jiao Tong University
Research on Multi-sensor Fusion of Underwater Robot Navigation System, *International Conference on Robotics and Biomimetrics*, December 19-23, 2009, Guilin, China

Journal Articles:

*Ma Ling-a and **Cui Wei-cheng
*School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University
**China Ship Scientific Research Center, Wuxi
Path Following Control of a Deep-Sea Manned Submersible based upon NTSM, *Unknown Chinese Journal*, 2005-04

*Wang Zhong-hua, *Ge Tong and *Zhu Ji-mao
*Underwater Engineering Research Institute, Shanghai Jiao Tong University
Vega based virtual collision avoiding technology in simulation system of deep-sea ROVs near-ocean-bottom operation, *Acta Simulata Systematicia Sinica*, 2005-12

Wang Zhong-hua, Ge Tong and Zhu Jia-mao
*Underwater Engineering Research Institute, Shanghai Jiao Tong University
Vega based virtual collision avoiding technology in simulation of deep-sea ROVs near-ocean-bottom operation, *Acta Simulata Systematica Sinica*, 2005-12

*Ma Ling and **Cui Wei-cheng
*School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University
**China Ship Scientific Research Center, Wuxi
Heading control study of a deep manned submersible at a low speed and large drift angles based upon fuzzy sliding mode control, *Ocean Engineering*, 2006-03

*Ke-qiang Zhu, *Hai-yang Zhu, *Yu-song Zhang, *Jie Gao and **Guo-ping Miao
*Maritime Collge, Ninbo University
**School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University
A multi-body space-coupled motion simulation for a deep-sea tethered remotely operated vehicle, *Journal of Hydrodynamics, Series B*, 2008, 20(2), p210-215

*Liang Yan, **Bao Jin-song, **Jin Ye and **Feng Hong-kui
*School of Mechanical Engineering, Shanghai Jiao Tong University and Shanghai Zhenhua Heavy Industry Co., Ltd.
**School of Mechanical Engineering, Shanghai Jiao Tong University
Study of simulation system of deep submergence rescue based on virtual reality, *Journal of System Simulation*, 2010-03

Shenyang Institute of Automation, Chinese Academy of Sciences

A 2005 conference reviewed the composition of a manned submarine, disposal of the thruster and the equation of thruster force allocation was examined. Motion control of the manned submarine was described and a motion control system was tested on a semi-physical simulation platform and the performance and results of motion control were said to be excellent.
A semi-physical simulation system related to manned submersible vehicle's sensors, actuators and motion status in the deep sea environment was designed and tested. The system is currently being used to "debug" the manned submersible's control systems and is funded under the 863 program.

A proposed control system for the deep sea manned submersible consists of a neural-network-based direct adaptive controller and a dynamic control allocation module. A control energy function was used as the optimization criteria for the control allocation module and weighed pseudo-inverse was to find the optimal solution of the control allocation problem. Stability of the closed-loop control system was proved with Lyaponov theory and the feasibility and validity of the control system was verified through experiments conducted on semi-physical simulation platform.

A 2009 article reviewed and simulated experiments in the area of permanent magnetic propulsion systems. A chaos controls strategy was developed to increase stability and reliability of the system. Simulation indicated that it is possible for the system to rapidly leave the chaotic state under the influence of the functioning of an auto-adapted controller.

Conference Papers:

*Guo Wei and *Wang Xiao Hui
*Shenyang Institute of Automation, Chinese Academy of Sciences
Manned submarine and its motion control, 2005, *Unknown conference*

*Zhu Puqiang, **Wang Xiaohui, **Guo Wei and *Liu Kaizhou
*State Key Laboratory of Robotics, Shenyang Institute of Automation
**State Key Laboratory of Robotics, Shenyang Institute of Automation and Chinese Academy of Sciences, Beijing
Manned submersible vehicle surface monitoring system, 2008, *Unknown conference*

*Zhu Puqiang, **Wang Xiaohui, **Guo Wei and *Liu Kaizhou
*State Key Laboratory of Robotics, Shenyang Institute of Automation
**State Key Laboratory of Robotics, Shenyang Institute of Automation and Chinese Academy of Sciences, Beijing
Manned submersible vehicle information display and data storage technology, 2008, *Unknown conference*

**Baoju Wu, *Shuo Li, *Junbao Zeng, *Yiping Li and *Xiaohui Wang
*Shenyang Institute of Automation, Chinese Academy of Sciences
Graduate School of Chinese Academy of Sciences
ARV navigation and control system at Artic research, *OCEANS 2009*, October 26-29, 2009, Biloxi, MS.

*Zhang Hong and **Song Zhen-hua
*Electrical Engineering College, Northeast Dianli University, Jilin
**Institute of Aerospace Science and Technology, Shanghai Jiao Tong University
Research on multi-sensor fusion of underwater robot navigation system, *IEEE International Conference on Robotics and Biominetics*, December 19-23, 2009, Guilin, China

Journal Articles:

*Sun Maoxiang, *Wang Yanhong and *Wu Xueman
*Department of Electrical Engineering, Shenyang Polytechnic University
Underwater robot path planning with dynamical compensation, *Robot*, 1993-02

*Cheen Hong-hai and **Li Yi-ping
*Shenyang Institute of Automation, Chinese Academy of Sciences and Graduate School, Chinese Academy of Sciences, Beijing
*Shenyang Institute of Automation, Chinese Academy of Sciences
Sliding mode fuzzy control on AUV, *Control and Decision*, 2002-S1

*Guo Wei and *Wang Xiao-hui
*Shenyang Institute of Automation, Chinese Academy of Sciences
Manned submarine and its motion control, *Chinese Journal of Scientific Instruments*, 2005-S1

*Meng Xian-weil, **Wang Xiao-hui, *Liu Kai-zhou, **Guo Wei and *Yang Lin-xuan
*Shengyang Automation Institute, Chinese Academy of Sciences and Graduate School of Chinese Academy of Sciences
** Shengyang Automation Institute, Chinese Academy of Sciences
Semi-physical virtual simulation system for manned submersible vehicle and system performance analysis, *Journal of System Simulation*, 2006-01

*Li Yi-ping and **Yan Kui-chen
*Research Center of Underwater Vehicles, Shenyang Institute of Automation, Chinese Academy of Sciences and Graduate School of the Chinese Academy of Sciences
**Research Center of Underwater Vehicles, Shenyang Institute of Automation, Chinese Academy of Sciences
Application of autonomous underwater vehicle in lake test of deep-sea mining system, *Ocean Engineering*, 2006-02

*Yu Jian-cheng, *Zhang Ai-qun, *Wang Xiao-hui and *Wu Bao-ju
*Shenyang Institute of Automation, Chinese Academy of Sciences
Adaptive neural control with control allocation for a manned submersible in deep sea, *Ocean Engineering*, 2007-01

*An Yuejun, *Wang Shaohua, *Meng Zhaojun, *Sun Changzhi and *Wang Peng
*School of Electrical Engineering, Shenyang University of Technology
Permanent magnet propulsion system control of chaos for underwater robot, *Electrical Engineering*, 2009-03

*Au Yuejun, *Wang Shaohua, *Meng Zhaojun, *Sun Changzhi and *Wang Peng
*School of Electrical Engineering, Shenyang University of Technology
Permanent magnet propulsion motor system control of chaos for underwater robot, *Electrical Engineering*, 2009-03

Southeast University, Nanjing

The iterated closest point (ICP) algorithm is used for terrain mapping method based on correlation analysis. A chaotic BP neural network was developed to reduce the local minimization problem associated with the traditional ICP algorithm. In the new algorithm, a searching area of real position was plotted centering on the indication of refer navigation system, then terrain altitude data was extracted from the refer terrain map. The ICP algorithm can converge at optimum solutions rapidly when the terrain feature is obvious. Theoretically, the ICP algorithm can only converge to a local minimum respect to mean-square error object function and is limited to applications in terrain height mapping. Computational simulation was carried out using Matlab/VC6.0 tools and latitude and longitudinal errors were limited in extent to 0.3".

Conference Papers:

*Zhang Tao and *Xu Xiao-su
*Department of Instrument Science and Engineering, Southeast University, Nanjing
The application of chaotic BP neural network in underwater terrain matching navigation, *Control & Decision Conference*, June 17-19, 2009, Guilian, China

Journal Articles:

*Wang Qi and *Xu Xiao-su
*School of Instrument Science and Engineering, Southeast University, Nanjing
Application of multi-sensor information fusion to underwater integrated navigation system, *Journal of Chinese Inertial Technology*, 2007-06

Tianjin University

Journal Articles:

*Zhang Hong-wei, *Hou Wei-shuxin, *Wang Xiao-ming, *Wang Shu-xin and **Liang jie
*School of Mechanical Engineering, Tianjin University
**National Ocean Technology Center, Tianjin
The multibody modeling and dynamic simulation of the UAV with the capacity of soft landing, *Ocean Technology*, 2006-04

Wuhan University

A new synthetic navigation system for underwater use based on the integration of INS and multibeam bathymetric system was studied and results presented at a 2009 conference. They first studied the method drawing contours with MBS bathymetric data, by means of image matching technique they studied developed a fast image matching algorithm based on wavelet transformation and a sequential similarity detection algorithm.

Conference Papers:

*Hongmei Zhang, *Xiankuo Meng, *Jianhu Zhao and *Nan Shao
*School of Power and Mechanical Engineering, Wuhan University
Study on underwater synthetic navigation system based on inertial navigation system and multibeam bathymetric system, *9th International Conference on Electronic Measurement and Instruments*, August 16-19, 2009, Beijing

The 705 Research Institute, China Shipbuilding Industry Corporation

Journal Articles:

*Lei Jiang-tao, **Nie Wei-dong, *Qu Da-wei and ***Zhou Hua
*Military Representative Office, Xian Dongfeng Instrument Factory
**The 705 Research Institute, China Shipbuilding Industry Corporation
***91439 Unit, The People's Liberation Army of China, Dalian
Modeling and simulation of AUV thermal propulsion system based on EASYS, *Torpedo Technology*, 2010-01

No. 715 Research Institute of China Shipbuilding Industry Corporation, Hangzhou

This institute reviewed the principles of the high-precision Doppler velocity log and built a prototype using funding provided under the 863 program.

Journal Articles:

*Fu Ju-ying and *Shen Bin-jian
*No. 715 Research Institute of China Shipbuilding Industry Corporation, Hangzhou
Development of high precision Doppler velocity log used in underwater vehicle, *Ocean Technology*, 2008-04

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Zhu Hai and Mo Jun, National Defense Industry Press, 2002
Data fusion technology in underwater technology

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Gu Guochang and Du Mei
Area-based 3D global path planning for AUV, *Proceedings of the 2nd Asian Conference on Robotics*, 1994

Wang Lirong, Liu Jiancheng, Yu Huanan and Xu Yuru
Sliding mode control of an autonomous underwater vehicle, *International Conference on Machine Learning and Cybernetics*, 2002, Beijing

Li Lu and Wan Lei
Applied navigation system of "SY-1" small AUV, *Proceedings of the 13th International Symposium on Unmanned Untethered Submersible Technology*, 2003, New Hampshire

Li Juan, Bian Xinquan, Shi Xiaocheng and Qin Zheng
Simulation system of gravity aided navigation for autonomous underwater vehicle, *Proceedings of the IEEE International Conference on Mechatronics and Automation*, 2007, Harbin

Lin Yi, Yan Lei and Tong Qingxi
Underwater geomagnetic navigation based on ICP algorithm, *IEEE International Conference on Robotics and Biomimetics*, 2008

Jianli Cao and Chaoyi Sun
A mission planning system for an autonomous underwater vehicle, *7th World Congress on Intelligent Control and Automation*, 2008, Chongqin

Ge Yang, Rubo Zhang and Dong Xu
A fuzzy-Q method to improve the adaptability of AUV in variable ocean current environment, *Proceedings of the 2009 WRI Global Conference on Intelligent Systems*

S. Guo, B. Gao and N. Xiao
Path-planning of underwater microrobot in 3-D by spiral particle pathway searching approach, *IEEE International Conference on Automation and Logistics*, August 5-8, 2009, Shenyang

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Zhong Rubo and Lin Desheng
A study on real-time map-building for automatic underwater vehicle, *Ship Engineering*, 1998-04

Liu Xuemin and Xu Yuru
S control of automatic underwater vehicle, *Ocean Engineering*, 2001-03

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Wu Yong-ting, Zhou Xing-hua and Yang Long
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Section Seven

Underwater Sensor and Communication Related Research

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The characteristics of underwater sensor networks exhibit limited available bandwidth, large propagation delay, and high bit error rates. Many different mechanisms have been proposed to improve energy efficiency in underwater networks and these existing mechanisms are mainly based on the assumption that sound decays as the propagation distance increases, but ignore the noise attenuation in the deep underwater environment. In a 2010 conference presentation researchers from Dalian University proposed a smart Layered Multi-path Power Control Scheme (LMPC) which manages to establish the energy-efficient tree-based multiple path from the source node to the surface gateways and controls hop-to-hop propagation power. The main aim of LMPC is to improve energy consumption and enhance communications reliability by reducing packet retransmission over the acoustic channel. Multiple copies of the same packet are transmitted independently along multiple paths from a source node to the surface gateways using the acoustic channel with the aim of avoiding retransmissions. Different copies of the packet are relayed and forwarded to the sink using a radio channel. Then the copies are combined to generate the original packets in the sink.

A network simulation platform (NS-2.29) was used to evaluate the proposed scheme and in order to support the underwater acoustic network they adopted a common underwater module for it. During the experiments it was observed that the simulations can reach steady state within the period of 1000 seconds. Energy consumption is almost dependent on the data packet size but depends on the data rate. They also found that as the data doubled or tripled, energy consumption increased little. Overall the LMPC scheme was observed to save between 20-40% in energy consumption compared to Multi-path Communication scheme.

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Interaction between current and underwater bottom topography modulates roughness of the sea surface and this leads to variations of the radar scattering echo. Using a continuity equation and weak hydrodynamic interaction theory in the relaxation time approximation, the spatial variation of the radar scattering cross-section was proved to be proportional to the gradient of the current velocity. The current direction was first determined by using a 2D correlation of spatial variation by backscattering measured by SAR imagery. An inverse algorithm to gradually derive he underwater bottom topography from SAR was developed and images over a sea area of Hong

Kong were studied. A companion 2000 presenetation used the SAR SIR-C image at L band with HH polarization, the underwater bottom topography was inverted.

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Guilin researchers introduced a method of PPM modulation that improves the synchronization process of the underwater laser communication system and improves the coding efficiency of the communication system. A double-frequency adjusted Q laser pumped by a xenon lamp was used in the experiments with wavelength of 532nm, maximum operational frequency of 50Hz, width of the light pulse was 10ns and the maximum pulse energy was 200mJ. Large area collecting apertures were used to focus the optical signal on to large area sensitive detectors. The results which were presented indicated that the modulator was successful and has a stable level of working reliability.

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The Institute of Information and Communications and the College of Underwater Acoustic Engineering are the two centers for underwater sensor and communications related research at Harbin Engineering University. Liu Yuntao and Yang Shenyuan developed a waveform design method that improves the performance of high speed underwater communication by restraining the multipath effect. This was achieved by placing the signal on the zero point of the wavefront filter and then keeping the information rate. Lake experiments performed using this method exhibited a lower error code rate than traditional waveform design methods. The improved waveform design restrains the multichannel effect of the underwater channel and increases transmission distance and reliability of the underwater communication system.

OFDM (orthogonal frequency division multiplexing) systems were shown to be sensitive to frequency offset and this degrades system performance. In a 2007 article Wang Ming-Hua and Sang En-Fang analyzed the effect of frequency offset in an underwater acoustic channel and then proposed a frequency synchronization method that had high estimation precision and could track a wide range of frequency offset. The method was tested in a lake and was shown to be effective in a variety of conditions.

In a 2008 conference presentation Sang and others examined CP-OFDM and ZP-OFDM and showed that ZP-OFDM using a complicated channel equalization on the premise of the Toeplitz transfer matrix used lower power in the transmission area. Monte Carlo simulation showed that this method had better performance and reliability than CP-OFDM.

Turbo code was proposed for underwater acoustic communication based on orthogonal multiplexing. Performance of the code under different modulations were studied and simulated. Turbo code is a special class of concatenated code where an interleaver is used between two parallel or serial encoders. The existence of the interleaver results in very large code word lengths with excellent performance, particularly at low signal to noise ratios (SNRs). Monte-Carlo simulations in different modulation methods were processed in a shallow ocean channel. It was shown that the error performance deteriorated in low SNR because of the high original bit error. In higher SNR, the performance was significantly improved. The anti-jamming performance of an underwater communication system based on OFDM was significantly improved using Turbo coding. With the same bandwidth utilization and the acceptable SNR of underwater communication, system reliability was improved. A combination of the turbo code and OFDM improves transmission rate and reliability of the underwater system.

In 2008 results were presented of a transmission system based on Amplitude-Phase Shift Keying (APSK) modulation and OFDM. The system was designed to solve problems associated with bandwidth efficiency, power efficiency and reliability for high-speed underwater communications.

Processing underwater acoustic signals attracted the attention of researchers and a method was developed to extract useful information from the processed data. An algorithm capable of extracting features from the radiated noise of underwater targets based on bispectrum estimation was developed and then the extracted features were passed into a radial basis function neural network classifier. The results showed that the bispectrum was capable of restrain Gaussian noise and at the same time capable of obtain the non-Gaussian feature of the signal and reducing the number of dimensions of the feature space.

The College of Underwater Acoustics showed that an underwater vehicle with USBL can be navigated by a single transponder moored on the ocean floor. Trials results from the southern China sea were undertaken and examined. A brief analysis was also conducted that examined different errors introduced in system performance on the operation of the navigation system. Because sound velocity is not constant in the deep sea an algorithm was developed that corrects for sound ray bending. Results of a deep sea trial showed the feasibility of the algorithm in correcting sound ray bending.

A large-scale network was proposed for the positioning and navigation of underwater vehicles by both wireless radio communication and underwater acoustic remote control communication. The system can track the underwater object's three-dimensional movement by the cooperation of a shipborne range finder, surface radio remote buoy, underwater transponder array, and radio base station. The remote underwater transponder was controlled by a combination of radio and underwater acoustic remote control communications. Sea trials showed that the system was both feasible and reliable.

The tunnel effect and its mechanism of production in a multibeam bathymetry sonar was studied and side lobe interference was shown to be an important factor in the tunnel effect. The tunnel effect leads the bathymetry sonar to mistake the relatively flat seabed floor for concave-up horizontal half cylinder terrain. An adaptive beamforming algorithm based on GSC structure was developed that showed the ability to eliminate side lobe interference in edge beams of multibeam bathymetric data.

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A 2007 presentation addressed the navigation problem of coordinating a team of heterogenous vehicles that includes autonomous underwater vehicles (AUVs). The employment of multiple AUVs has significant military advantages and a team of underwater vehicles could survey large ocean areas more rapidly than can be accomplished by a single ship or AUV. By utilizing the underwater DGPS concept, together with a set of intelligent surface sonobuoys, the precise location of the AUV carrying an acoustic pinger could be estimated by the measured time-of-arrival of acoustic signals and the DGPS position of sonobuoys. Compared to an INS/GPS

navigation system, an AUV utilizing this system does not need to come to the surface to calibrate their position periodically.

Onboard INS systems were stated to not maintain required accuracy over the long time vehicle maneuvering and are expensive and require calibration for different AUV systems due to its vehicle-specific characteristics. A prototype of an acoustic navigation system consisted of a set of light surface buoys with a DGPS receiver integrated on board. The hydrophone and the ARM CPU are synchronized before deployment with the DGPS clock datum. The core of the DGPS intelligent sonobuoy is an ARM7 CPU known as the S3C44B0. An extended 16M is for data storage as well as data buffer and the acoustic module is based on a Motorola DSP. A two way radio link with 20M radio reference allows for communication within ranges up to 40/50 km.

For underwater exploration a surface vessel can control a number of AUVs motivated by this GPS method. The surface vessel communicates with the AUVs via 3-5 kHz acoustic modem for long range bidirectional communication. The time-of-arrival method also makes it possible for the sonobuoys to get the position of multiple underwater vehicles within different time frames. The surface vessel can then collect all of the positions of the AUVs via radio link to the sonobuoys.

The acoustic navigation system was tested by proposing that there were four sonobuoys pre-deployed in a given square geometry of 10x10 Km in the X-Y plane and the AUV of interest in the coordinated team was at a depth of 500m. The performance of the navigation method could then be examined by computing the trajectory tracking error with noisy range measurements. Future work is looking at the development of a version of the system that can operate in the presence of multi-path effects, acoustic outliers and in-water validation of the system.

Monte Carlo simulation was used to model the blue-green atmosphere-ocean laser communication channel. Through this simulation method they were able to set up a series of the complete communications channel environment. The Monte Carlo code simulates the process by which the photon propagates in the medium and simulations were used to determine the path of each photon that is incident from the sun until it is either absorbed or scattered back to space. Simulation results were presented for the channel response waveform with different types of clouds and their impact determined. As the sea water scattering and adsorption increases the number of photons that arrive on the receiving plane go down. The laser energy attenuation in atmosphere-ocean laser communications channels can be divided into the attenuation of clouds, the attenuation of atmospheric molecules, the attenuation of the atmosphere-ocean interface and the attenuation of sea water. The use of this system for communicating with deep sea submergence vessels is improbable due to attenuation effects and the actual range of the system needs to be determined through continued experimentation.

The degradation of the underwater image obtained by range gated pulsed laser imaging system is mainly caused by scattering and absorption by in-water particles. Studies showed that the knowledge of in-water optical properties and their relationship to the image formation can be exploited to restore the image by using point spread function as an estimation of image degradation based on Well's small angle approximation.

Test image sets were obtained using the range gated underwater imaging system. The target was located underwater at a distance of 30m from the imaging system and the angle of field of view was approximately 4 degrees. The attenuation coefficient of water was measured to be $0.27m^{-1}$ and the albedo was 0.8. Noise reduction using an arithmetic mean filter was first performed on the image in order to obtain the initial guess input of the blind deconvolution algorithm. It was found that different edge detectors lead to different maximum value results. A global blur metric method was incorporated to determine the iteration time for objectively evaluating the restoration result. Results showed that noise reduction preprocessing is necessary and the local blur metric is efficient in seeking the best iteration time in order to obtain the restored image objectively with balance in noise restraint and deblurring. The weak pint of the system was in automatic image restoration and further studies were planned in this area.

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SEANAR, an energy-efficient and topology-aware routing protocol was proposed for use in the underwater sensor networks. SEANAR relies on topology information and degree information of neighboring nodes for making routing decisions. The geographical routing protocol is considered a promising approach for underwater sensor networks but geographical routing protocols used in land-based WSN do not work well in the 3D underwater environment.

All nodes were assumed to be randomly deployed in the 3D area with sparse density. The node can move freely in the horizontal 2D plane and move slightly in the vertical direction, which is a widely adopted mobility pattern for underwater sensor networks. The sink is stationary and fixed at the center of the surface and each node sends packets to the sink throughout multihop routing. SAENAR adopts a greedy approach in which every intermediare node collects informnation of its neighbors and then forwards the packet to the candidate with the highest weight. In SEANAR the nodal degree information is the critical criterion of the weight. The nodes with higher degree are assigned higher priorities and are assumed to have a higher probability of delivering the packet to the sink.

A customized simulator with C++ was developed for the evaluating the performance of SEANAR. Sensor nodes were randomly deployed in a 240m x 240m x 120m 3D area and the communication range of each node was 30 meters. In terms of packet delivery SEANAR gave better results than either VBF or GF. The overhead energy efficiency of VBF was about three times higher than that of SEANAR and GF. When the nodes are densely deployed, the deterioration in delivery slows down and to keep the delivery ratio stable in more dynamic scenarios requires getting the neighbors information more frequently.

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The multipath effect causes synchronous position offset in the underwater acoustic channel. Improvements to the equalization algorithm were obtained by adopting the theory of early-late integration phase and then using this to track the sampling position on the basis of the more steady normalized constant modulus algorithm. This was achieved by using a least squared technique, which showed a strong capacity for beter convergence and stability and resisted disturbances in the network.

Sensor network structures were presented for a 2D underwater acoustic network, a 3D network and an integrated network. In the 2D network all of the UUV sensors were deployed on the seafloor or at a predetermined depth and every underwater team has a special underwater transceiver which can be used to transmit detection data from sensors to surface stations or transmit instructions from from stations to sensor nodes. The transceiver must have two acoustical transceivers in the vertical and horizontal. The vertical takes charge of communications and the horizontal is used to communicate ewith the surface station or buoy. Links among the nodes take be direct or through a multi-hop mode.

In the 3D network, sensor nodes are deployed at different depths and ensure adequate detection coverage and and efficient communication range, each node should cooperatively adjust its depth on a real-time basis. This preserves the integrity of the network topology and at least one path can be used to link sensors node with the surface station at random instantances.

In the integrated network all UUVs are divided into certain groups and all UUVs among the same group work at the same depth with different groups working on different depths. In each group there are several sensor nodes and an underwater transceiver, which is similar to the 2D network. The configuration saves energy and also can achieve 3D target detection.

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College of Marine Engineering, Northwestern Polytechnical University

Researchers at this university showed that one of the major problems in applying OFDM to underwater channels is the motion-induced Doppler distortion which creates non-uniform frequency offset in the case of a wideband acoustic signal. A novel Doppler estimation technique (SPM) was proposed for OFDM communication over an underwater acoustic channel. By using

null subcarriers they exploited the intrinsic structure of OFDM signals to derive a Doppler estimator based on the signal-phase matching principle. The acquisition of this algorithm was compared with ESPRIT algorithm and ESPRIT was shown to be unsatisfactory when the SNR is low and that was probably due to its poor in anti-inteference of inter-subcarriers of OFDM. The main advantages of SPM are its computational simplicity and high accuracy.

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The propagation delay in underwater communications is fiver orders of magnitude higher than in radio frequency terrestrial channels and this is a critical issue in the area of surveillance. Controlling transmission in an efficient and time sensitive manner is a crucial issue according to researchers the Ocean University of China, Shandong. Underwater acoustic channels are usually low-bandwidth and the bit error rate associated with packet transmission is very high due to the influence of the underwater environment. One solution was that each underwater sensor node should have more caching ability than the terrestrial sensor mode however more collisions will happen because of the caching packets retransmission.

One of the easiest ways to address these problems is to minimize the number of collisions but protocols are used in terrestrial sensor networks are not suitable for the underwater environment. In the 2008 an Adaptive Transmission Control Mechanism (ATC) was proposed to control the transmission based on a novel feed-back based scheduling scheme. This mechanism was built on the following two steps: the first step was to get the WF of all the nodes and this is worked out according to the BER and topology of the network. The second step is to work out the

transmission time of each node and the time was worked out according to the WF and the limitation of the propagation delay.

The topology of the network was assumed to have a tree-structure and all nodes are assumed to collect and transmit data at a fixed frequency in the underwater communications network. For a comparative study of the different proposed schemes the ATC was simulated using the ns-2 network simulator. The experiments assumed that 50 nodes were randomly placed in a 600x600 m^2 area and f=12.5 KHz and 802.11 was chosen as the MAC layer protocol. BER is reflected by the signal-to-noise (SNR), the BER between neighbors was adjusted by a period interference and changing the width of channels. With limited power resources available it is vital for sensor nodes to minimize energy consumption during radio communication in order to extend the lifetime of the sensor network. ATC consumes less energy than the other two algorithm considered in this set of simulations and this means that the retransmission caused by channel contention is minimized by ATC. Energy consumption was shown to be 40.91% of CT and 51.41% of the PS scheme. ATC reduces energy consumption without sacrificing end-to-end delay.

Underwater sensor nodes are mobile due to underwater currents and use acoustic channels for communication. Traditional ARQ series are not suitable for use in this environment due to their frequent feedbacks. Pure FEC can't be applied to underwater sensor networks because of its complexity and the need for feedback. The Ocean University group studied transport protocol in underwater sensor networks and then implemented a reliable lightweight RFEC-based encoding and decoding algorithm. They then combined that algorithm with ARQ to create a transport protocol which can advantage of FEC to deal with the high error rate and ARQ to avoid feedback.

Another conference presentation considered the effect of transmission range of the sensor to prolong the network lifetime of underwater acoustic sensor network. The network model assumed that group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors and the nodes are interconnected to one or more underwater sinks by means of wireless acoustic sensors. All of the sensor nodes were assumed to use power controls to adjust the amount of transmission energy and each node has the computational power to support different MAC protocols and to perform signal processing functions.

The maximum energy consumption in one node per round was found and data propagation was multi-hop transmission. If the total energy consumption is minimized such that each un-sensor sends the data to the un-sink then the energy consumption of the underwater acoustic sensor network is minimized. The research model is a two-dimensional underwater sensor network model and can also be employed in a three-dimensional underwater sensor network. Details of the three-dimensional network were not provided in the results presented for this study.

Details of an energy balanced chain (EBC) were proposed which can efficiently prolong network lifetime by actively controlling the node's hop distances and the analysis focused on linear sensor networks. The energy balance for the entire was considered to forward data by multi-hops towards the sink or by sending data by one hop directly to the sink.

The presentation proposes a data transmission algorithm for the underwater network and analyzed the algorithm. A two-dimensional communication architectures was considered in the analysis and as described earlier the nodes are anchored to the sea bottom and are interconnected to one or more un-sinks by wireless acoustic links. The simulation modeled a sensor network of nodes distributed over a disk area with a radius R and the un-sink is in the center. The initial energy of each node is 3000 J and each round every sensor generated a 200-bit packet that gets propagated to the uw-sink. Energy consumption decreases because of the increasing of the transmission energy in the direct transmission mode. The average energy spent on the selected annulus closest to the un-sink is the largest in the Minimum Transmission Energy algorithm and the average energy spent on the selected annulus farthest to the un-sink is the largest in direct transmission which was in agreement with the presented simulations.

Another communication discussed a probability-based energy balancing scheme in which the sensor nodes report the data to the link by singe-hop direct transmission or multi-hop transmission. A centralized probabilities algorithm was used to generate a set of transmission probabilities to better balance the energy consumption. Then a suboptimal distance-based data transmission scheme was proposed which operates in a distributed mode and operates on each sensor node. This optimized the slice width and helps in selecting the relays near their optimum transmission range.

A medium access control (MAC) protocol named C-MAC was proposed for underwater sensor networks. C-MAC is a TDMA-based MAC protocol which divides networks into many cells. Each cell is considered a time slot and nodes in a cell can only transmit packet's in the cell's time slot. In this protocol an acoustic sensor network was divided into many cells by their physical position and the whole network behaved like a beehive.

Experiments showed this protocol can avoid collision, minimize energy consumption and increase throughput efficiency. In a MAC protocol based on TDMA time is segmented into many cycles which are repeated continuously and where each cycle consists of seven time slots. Each time slot is made up of the data transfer phase and the protection phase and the length of the protection phase is equal to the largest expected propagation delay in the network. Each data transfer phase is long enough to transmit a maximum length packet. The simulation analysis area is divided into many cells and nodes were placed in a random manner in each cell. The network was simulated for different transmission ranges varying from 500m-1000m. The TDMA-based MAC protocol is inherently collision free and saves energy by allowing nodes to turn off the radio to rule out idle listening. Additionally the protocol does not need control packets and this saves energy compared to the contention based protocol.

Anchor nodes are difficult to deploy at precise location in underwater environments and to achieve 3D localization, localization schemes need to deploy anchor nodes underwater. The precision of the anchor deployment affects the location accuracy of the nodes directly. Distance measurements underwater suffer from large errors and this makes most range-based localization schemes inaccurate. Time of Arrival (TOA) and Time Difference of Arrival (TDOA) schemes require precise time synchronization which is difficult to achieve in underwater environments and are vulnerable to the speed of sound which is affected by water temperature, pressure and salinity.

In order to meet these and other challenges a 3D localization scheme (LDB) using directional beacons for underwater networks was proposed. The network is anchor free and utilizes a moving AUV. An acoustic directional transducer which uses multiple ceramic or piezoelectric elements to create a conical shaped directional acoustic beam was mounted under the AUV to aid in underwater localization. An AUV can move slowly underwater following a predefined trajectory and can be used to collect sensed data from a node mounted on the ocean floor. When an AUV sends a directional beacon towards the sensor field those nodes that hear the beacon fall in the conical beacon beam and the beam forms different circles with different node depths. When an AUV transits at fixed depths of water sending beacons, the nodes can be mapped from 3D to 2D with these predetermined circles. In practice, the AUV sends beacons with time intervals because the node that hears the beacons must differentiate between those beacons.

Te performance of the LDB was evaluated through extensive MATLAB simulations and the sensor nodes were randomly deployed in 100m x 100m x 100m 3D space. The AUV followed a pre-determined trajectory at fixed depth with a constant speed over the 3D deployment space and the mounted transducer has the fixed acoustical radiating power to reach the furthest nodes that may be deployed on the bottom of the 3D space. The speed of the AUV was set at 2 knots and the radius of the node's restrained movement at 0.5m. The results of the simulations demonstrated that the ratio of localized nodes does not change much when more sensor nodes are deployed in the volume. The reason for this is this scheme does not depend upon communication between sensor nodes it only depends on the beacons sent out by the AUV. Further research is directed towards the application of LDB to real testbeds using a directional acoustic transceiver that is being constructed at Ocean University of China.

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A new technique for the detection of underwater targets using a matched biorthogonal wavelet was shown to enhance target detection and eliminate noise. Results showed that this method for single frame detection (signal to noise ratio ≥ 1.25) provided better performance than classic wavelets and morphological filtering.

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For an underwater sensor network there are three layers to be considered: water surface, underwater and water bottom. The different physical environments present different requirements to the nodes in underwater sensor networks. Fixed nodes on the surface include buoys that can make use of GPS localization, satellite or radio communication and solar or wind power for charging batteries.

Mobile nodes are considered to be AUV or ROV. Because these platforms are mobile they are able to move between the water surface and the bottom surface. The 2004 conference paper stated that these platforms use wireless communication when they go to the surface and may also use short range communications methods when they are close to fixed nodes located on the water bottom. These mobile nodes are important in the reconfiguration of sensor networks.

In the design of function modules for reconfigurable underwater sensor networks the basic functions can be divided into several classes: sensing, communication, data processing, relay, gateway and control/cooperation. The sensing module is used for temperature measurement, pressure, pH, turbidity, image, distance to target, acoustic data and related functions. In order to keep sensor costs as low as possible some nodes have very basic functions such as sensing module, communication module and control/cooperation module. Research from this institute focused on the development of low-cost, miniature and wireless communications for underwater platforms such as biomimetric fish robot. The mobile sensor on the robot is used for environmental monitoring and the underwater sensor network can reconfigure or self-organize the system's geographical topologies.

A 2005 presentation provided additional details on the sensor network architecture and its ability to change their topology and configuration according to the situation. An automatic testing language was developed for evaluating underwater acoustic sensor networks (UASNs) and allowed end-to-end networking experimentation to be done on the platforms. A 2007 paper noted that UASNs are envisioned for assisted navigation and tactical surveillance applications. The unique characteristics of the underwater acoustic channel include limited bandwidth capacity, high propagation delays and low reliability. A physical experimental platform was developed for UASNs that consisted of a system control module, sensing module, automatic communication testing module, networking module and an evaluation module, which can complete automatic point-to-point communications performance tests and end-t-end networking experiments.

The experiment system is composed of one gateway node and multiple underwater nodes. The gateway node consists of an underwater transducer, a surface station and a network adapter. The underwater node consists of a sensor, underwater acoustic telemetry modems, and a network adapter. The automatic testing language was known as ATM Automatic Testing Language (ATM-ATL) and consists of four different kinds of instruction sets. The simple instruction set includes the standard AT instruction set, the multiple and composites instruction sets are similar to the single circulating sentence in advanced programming language, and the special instruction set is used for controlling and management tests.

Experiments were made in the Qipanshan reservoir and deployed three nodes. The first node consisted of a Benthos Acoustic Telemetry Modems (ATM891 and ATM 408) and is a stationary gateway node. The second node is a Benthos ATM885 Modem and works as an underwater relay node. The third node is an underwater sensor node and consists of a Benthos ATM885 and CTD sensor measuring water temperature, salinity and depth. The modem works in the 9-14kHz frequency band, average transmission energy was 40W and the sampling interval was 30s. Results for networking experiments were presented in a series of charts where the distance between nodes was about 1600m, communication rate was 600bps, the data packet was 112 byte,

the control packet was 16 byte and the relative moving speed between node was from 0 to 1.5m/s.

Traditional inter-communication systems for underwater vehicles are generally organized as a three-layer architecture: device layer, control layer and an application layer. Device layers belong to the low-level control layer and there are many functions associated with this layer network. These include supplying power to sensors and actuators, collecting digital data through sensors, receiving commands and then sending them to actuators.

The control layer belongs to the middle-layer control layer and navigation control CPU lies in this layer. This layer is responsible for navigation control, signal processing and error tolerance. And the application layer belongs to the high-level control layer. The function of this layer is to monitor the overall system, perform advanced task management and to issue commands for task planning and sea situation estimation. The application layer is often used in semi-autonomous underwater vehicles for intervention missions, manned submersible vehicles and remotely operated vehicles.

The three-layer network has a number of disadvantages due to different networks and protocols. The different protocols may not be compatible with each other and this increases the difficulty of development. Secondly the application of different networks leads to a lack of transparency between the different layers and this leads to increased hardware and software costs.

A typical underwater vehicle has about 100 sensor and actuators signlas that need to be transmitted on the network within a control cycle. The overall data communication system hardware architecture for a manned submersible was designed on the basis of an industry Ethernet. The Industry Ethernet takes the place of traditional control layer networks. All of the submersible's sensors in the data and control commands are available for through the Ethernet.

In order to test the performance of the overall system a platform was built to simulate the network traffic within a control time cycle. The simulation platform included both real and virtual devices. The virtual devices simulation computer simulates hydrodynamic motion of the vehicle, sensor data, actuators and equipment such cameras, lights and sonar. Experiments and tests showed the system has good real-time performance. Future research efforts will focus on the development of real-time control systems that can resist the effects of deep underwater surroundings.

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With the help of Karush-Kuhn-Tucker (KKT) conditions the group was able to derive a simple and explicit, but accurate, approximate solution under reasonable assumptions to an optimization problem. The optimization problem aimed to minimize energy consumption and at the same accounts for other performance metrics such as data reliability and the communication delay. The approximate solution provides theoretical guidelines for designing durable and relaiable underwater sensor networks.

Utilizing rigorous theoretical determinations, the issue of energy efficient transmission was addressed. The effect of four different parameters (node distance, communication frequency, packet and SNR) on the performance of the network was determined and then an explicit solution to the optimization problem according to KNT conditions was evaluated.

A 2010 conference presentation considered two scenarios concerning energy efficient operations in underwater sensor networks. The first scenario was non-cooperative diversity and the second was cooperative diversity. In both cases there is a source node and a destination node. The source node sends out a package repeatedly until the destination node receives it correctly. These scenarios are seen as the basis components of a multi-hop network. The cooperative scheme achieved a near-optimal energy savings especially when the source and the destination node are close.

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A Gabor transfer was used to localize the target echo signal in both the time and frequency domain for a laser underwater target detecting system. The laser emitter radiates the laser perpendicularly into the water from the atmosphere and is reflected by a reflector placed at 45^{o}. The experiment used a Q doubled frequency Nd:YAG 532nm laser, with wavelength stability of 0.05nm, pulse width of 10ns, laser pulse peak power of 2MW, repetition frequency of 100Hz, and a power stability of+/-5%.

In the underwater laser target detection system target echo signals fold into the sea backscattering and can express the geometric structure and medium properties of the targets. There are differences in pulse-width and magnitude among distinct targets which are reflected in the instantaneous frequency changes. Analysis and description of the echo signal Gabor transform coefficients can provide a basis for the qualitative and quantitative analysis of the echo signal and recognizing targets. Experiments showed that there was an obvious difference in the characteristics parameters of different signals and that target echo signals' first and second eigenvalues are much larger than other eigenvalues. There also exist distribution differences in the traces and eigenvalues of targets in different materials and colors. Application of the time-frequency characteristics parameters description based on Gabor transforms have reduced target-specific requirements and the dependence on artificial pre-knowledge. The system can be improved through the use of an underwater range gate imaging system with appropriate trigger, signal, gate-controlling delay and gating-time width time that can be used to control ICCD gating.

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In 2007 researchers from this institute reviewed developments in the area of underwater laser imaging technology. Applications included underwater high-speed imaging, underwater laser imaging, and underwater laser scanning. Applications of wave optics in the underwater environment include underwater laser holography, underwater laser communications, and illumination and detection of target using Raman spectra. The review did not present any information to Chinese developments in these areas.

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In order to improve the performance of the underwater acoustic OFDM communication system, the use of an irregular repeat accumulate (IRA) code as a channel coding scheme was proposed. Computer simulations were followed by sea trials in shallow water acoustic channels near Xiamen port. The simulation results showed that the IRA coding scheme improved the SNR performance of the system in the range of 14 to 16 dB. The bit-error-rate (BER) performance of the IRA code gets improvement with the increase in code length and the iteration of decoding to a certain degree which then tends towards stability.

The permissible BER range for an underwater acoustic communication system is from 10^{-3} to 10^{-5} and a 1000-bit IRA code with with about 5 to 8 iterations is suited to meet the basic requirements of the underwater communication system. The sea trial results showed that the BER of the system was decreased by an order of magnitude via the IRA coding schemeand some

BERs were found to be equal to zero, which confirmed that the scheme can improve the performance of an underwater acoustic OFDM communication system.

Underwater acoustic communication channels vary from stationary with sparse arrivals to rapidly varying and fully reverberant present fading, multipath and refractive properties which impede UWA data transmissions. To solve this problem a receiver with the iterative soft-input/soft-output equalization and decoding that employs a Repeat-Accumulate coding joint adaptive decision feedback equalizer was proposed. Simulations showed that the UWA communication system with the proposed channel coding scheme can get about 6 dB coding gain compared to a system without coding.

A recent presentation proposed a frame synchronization method for underwater acoustic communications on mobile platforms. The proposed method involves the transmission of signals based on hyperbolic frequency modulated signal as a preamble of the frame, and the receiver uses a correlator which is matched to the transmitted signal. The proposed method works with a robust correlation of the Doppler effect and is suited to handle the presence of dense multi-path channels. In an underwater acoustic hop frequency communication system, each user's information is modulated by a special code on the transmitter and the information is then demodulated by the same code at the receiver. The performance of chaotic and RS sequences was evaluated in a 2010 presentation and both are considered as good candidates for spread sequence in CDMA systems because of their excellent performance. Multiple access communication requires the number of sequences to be as many as possible and there should be no limitations on the number of users that could be accommodated by anti-jamming communications. Simulation showed that the average interval of the RS sequence is less than the theoretical value of the chaotic sequence but was still good enough to be used in an underwater acoustic hop-frequency communication system.

Late in 2010 the design and analysis of a DFT-spread OFDM system for an underwater acoustic channel were presented in a journal article. Low peak-to-average power ratio and a diversity gain in frequency-selective channel are two of the resons why the research group chose a DFT-spread spectrum system for data transmission. The power ratio can improve power efficiency of the transmitter and frequency-selective channel reduces the bit-error-rate of the system. Experiments were carried out in the experimental pool at Xiamen University and the distance between transmitter and receiver was 10m. The average bit-error-rate of the OFDM system was neary 10 times the rate of DFT-spread OFDM system.

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Section Eight

Notes on Data Sources and Methodology

There are two main databases of Chinese engineering and scientific research available for use: http://www.en.cnki.com.cn/ (Tsinghua Tongfang Knowledge Network Technology Co., Beijing) and http://www.wanfangdata.com/index.asp. Both of these databases are available in English and Chinese and are searchable by author, subject and title. Each result includes the title of the journal, date and issue, authors and their affiliation, abstract, key words, funding details (optional), and a list of references, co-references, and conference related references. Clicking on each individual reference brings you to that new reference and allows the collecting of related material of relevance. Clicking on the conference related links only brings up information on conferences held in China and in Chinese. The use of Google Translate allows for translation but the accuracy is in question.

By careful evaluation of these and other scientific databases it is possible to compile a large list of activities that have been funded under the National High Technology Research and Development Program of China (863 Program). One of activities funded by this research fund is the National Defense Key Laboratory of Autonomous Underwater Vehicle Technology located at Harbin Engineering University. It was possible to crosslink these two activities through a careful reading of the Chinese literature.

Another program that funds submersible related activities is the National Defence Science and Industry Committee Foundation. Grant No. 40104050101 funds research on the "Study of station and attitude maneuver of submergence rescue vehicle" performed at the College of Automation, Harbin Engineering University. An 863 plan "deep-sea manipulator key technique" and "underwater work tool" project has been found at the Underwater Technology Laboratory, College of Traffic Science and Engineering, Huazhong University of Science and Technology. A Chinese reference lists this work as being funded by the 863 Program under Grant No. 2006AA09Z203 and the State Commission of Science and Technology for National Defense Industry Project "micro underwater work tool" and the National Natural Science Foundation of China. This reference illustrates the links between submersible research funded by the Chinese National High-Technology 863 Program and National Defense Projects.

These databases have provided a reference to Chinese technical reports and books on deep sea submersibles. The National Defence Industry Publishing Company in 2001 published a book by Sun Yuan-qian and Ma Yun-yi entitled "Modern Maneuver Theory and Application of Submarine and Deep-Diving Submarine Vehicle." In 2003 to technical reports on deep-sea manned submersible and a 2004 CSSRC report (ZQXWQ001) by Zhang Hua entitled "The design and calculating of manoeuvere of manned submersible vehicle."

Another valuable source of information on Chinese journal articles, conference presentations and conferences held in Chinese is the IEEE database. IEEE can be searched by author, key work, date and the conference. By clicking on the conference you are able to bring up the individual papers or abstracts of papers presented at the conference. It should be noted that it is not uncommon for authors to submit a paper for presentation at a conference but cancel their actual presentation. This allows their names to show up in the proceedings without them actually presenting a talk.

Two important Chinese scientists (Jian-Hu Liu and You-Sheng Wu, Chinese Ship Scientific Research Center) have attended the annual Shock and Vibration Information Analysis Center (SAVIAC) Shock and Vibration Symposium since at least 2002. At the 2002 conference Jian-Hu Liu presented a paper entitled "Dynamic Responses of Submarine to Underwater Explosion." At the 2003 conference they presented a paper entitled "A Method for Analyzing Interactions Between Underwater Shock Wave and Acoustic Structure." Searching the Chinese scientific and engineering literature reveals that both Jian-Hu Liu and You-Sheng Wu have been with the China Ship Scientific Research Center, Wuxi since at least 2000 and authored a paper entitled "A Simplified Method for Analyzing the Response of GRP Ship to Underwater Explosion."

Jianhu Liu, Yousheng Wu, Jianqiang Pan and Haikun Wang (all from the China Ship Scientific Research Center) are scheduled to present a paper at the upcoming 82nd Shock and Vibration Symposium which will be held on October 30 – November 3rd. The title of the paper to be presented is "Research on the Shock Protection of Surface Ship Crews Subjected to Underwater Explosion."

Using the full search features available through IEEE one can retrieve a number of relevant conference papers. Some are in Chinese with abstracts in English. IEEE does not provide translation of those papers although the reference section of many papers may be in English.

Chinese authors are now publishing in refereed IEEE journals such as IEEE Sensors Journal and these papers often provide additional information that is very useful. First the articles are refereed and the quality is higher than usual. Secondly and more importantly at the end of an IEEE paper or journal article there is usually a brief bibliography of each author along with a recent picture. As an example in the July 2011 IEEE Journal of Oceanic Engineering an article entitled "A New Hydraulically Actuated Titanium Sampling Value for Deep-Sea Hydrothermal Fluid Samplers" appears and contains short biographic data on each of the authors. This research was funded by the National High Technology Research and Development Program (863) under Grant 2010AA09Z202.

ScienceDirect, WileyOnline and other commercial scientific and engineering have been searched and material retrieved. Important journals include: Applied Ocean Research, China Ocean Engineering, Journal of Marine Science and Application, Ocean Engineering and Science China (Earth Science). Co-authored papers with Western scientists have recently appeared in journals such the Journal of Sound and Vibration. This particular series of articles, focused on dynamic response and acoustic radiation from an underwater structure, was written by Q. Zhou (Ship

Science Department, Wuhan) and P.F. Joseph (Institute of Sound and Vibration Research, University of Southhampton, UK).

It is also possible to find short bibliographies at the end of some journal articles. The Journal of Marine Science and Applications usually carries short biographies of authors at the end of the article and these are being collected and added to the database of scientists and engineers working in the submersible area. A 2008 article from this journal entitled "Research on numerical welding experiment of a thick spherical shell" gives a short biography and photographs for Liu Xiang-dong and Yao Xiong-liang but not for Pang Fu-zhen. Biographies are available for both Liu Xiang-dong and Yao Xiong-liang in earlier articles from this journal.

A 2004 article in this journal provides a short biography on Zeng Gunag-Wu, a senior professor at Huanzhong University of Science and Technology, and indicates that he was the former chairman of the Department of Naval Architecture and Ocean Engineering. His main fields of interests are listed as "structure analysis and the design of marine and rocket."

A 2007 article in this same journal provides a short biography on Liu Xiang-dong. He is an associate professor in the College of Shipbuilding Engineering, Harbin Engineering University. His co-author, Yao Xiong-liang, is a professor and dean of the College of Shipbuilding Engineering, Harbin Engineering University. His interests include ship structural mechanics, prediction and control of ship vibration, and structural response under underwater impulsive load.

http://www.china-papers.com/ is a site that claims to provide full text PhD thesis from Chinese universities. It can be searched by subject only and the returned reference only provides an abstract for each thesis. Author's name, university and date of the thesis are not included.

Abstracts for the following theses have been found at the site:

Research on Preliminary Design of Deepwater Semisubmersible
Analysis and Design and Deep-Sea Submersible Structures
Research on the Variable Vector Propeller of Submersible
Research on the Pressure Compensation for External Hydraulic Systems of Submersible Vehicles
Application of USBL Positioning Technology on Underwater Submersible Interfacing
Application of MDO Method to 7000 HOV General Design
Bi-level Integrated System Collaborative Optimization Method and Its Application to the Overall Conceptual Design of Deep Sea Space Station
Research on Underwater Mating Key Technology of Manned Submersible
Studying on Hydrodynamic Characteristics of AUV with Numerical Model and Experiments

Three book chapters from a 2008 book relevant to underwater vehicles have been located and added to the reference collection. The book is entitled "Underwater Vehicles," the editor is Alexander V. Inzartsev, published by I-Tech, Vienna, Austria and the ISBN is 978-953-7619-49-7.

Chapter 10 is entitled "Experimental Research on Biorobotic Autonomous Undersea Vehicle" and the authors are Jianhong Liang, Hongxing Wei, Tianmiao Wang, Li Wen, Song Wang and Miao Liu (all with BEIHANG University).

Chapter 27 is entitled "Cooperative Acoustic Navigation Scheme for Heterogenous Autonomous Underwater Vehicles" and the authors are Xianbo Xiang (CNRS –LIRMM – University of Montpellier and Huazhong University of Science and Technology), Lionel Lapierre (CNRS –LIRMM – University of Montpellier), Bruno Jouvencel (CNRS –LIRMM – University of Montpellier), Guohua Xu Huazhong (University of Science and Technology) and Xinhan Hunag (Huazhong University of Science and Technology). This work was funded in part by the National Natural Science Foundation of China under grant 69585003 and the National 863 Hi-tech Research and Development Program of China under grant 2006AA09Z203.

Chapter 28 is entitled "Dynamic Modelling and Motion Control for Underwater Vehicles with Fins" and the authors are Xiao Linag, Yongjie Pang, Lei Wan and Bo Wang (all with Harbin Engineering University).

A 2010 entitled book entitled "Motion Control," edited by Frederico Casolo, (published by INTECH, Croatia, ISBN 978-953-7619-55-8) includes a chapter (9) entitled "Terrestrial and Underwater Locomotion Control for a Biometric Amphibious Robot Capable of Multimode Motion." Authors are Junzhi Yu, Qinghai Yang, Rui Ding and Min Tan (all with Laboratory of Complex Systems and Intelligence Science, Institute of Automation China Academy of Sciences). This work was supported in part by the National Natural Science Foundation of China under Grants 60775053 and 60505015, in part by the Municipal Natural Science Foundation of Beijing under Grant 4082031, in part by the National 863 Program under Grant 2007AA04Z202 and in part by the Beijing Nova Programme (2006A80).

Resumes are another important source of information. Resumes of interest obtained so far include Professor Yu Yandong (School of Materials Science and Engineering, Harbin University of Science and Technology). Her specialty is metal forming of advanced alloys focusing on aluminum and magnesium. Portions of this research have been funded under the National 863 Hi-tech Research and Development Program of China.

The website of the Laboratory of Oceansense Network (http://osn.ouc.edu.cn/joomal/) provides a list of select publications in the area of underwater acoustic and sensor networks going back to 2003. The website also contains descriptions of work performed under the National 973 Project, National 863 Project and the National Number Marine 908 Project. Further information on these projects will be included under the funding section of this report.

Another useful site Arnetminer (http://arnetminer.org/) which includes useful features such as professional network graphs for university researchers worldwide. Although the disambiguation of transliterated Chinese names is difficult, the linkage diagrams show professional relationships of various kinds.

Section Nine

Implications and Conclusions

One current weakness of the Chinese manned deep sea submersible program is the ability to fabricate large titanium alloys components. This is rapidly changing through interactions with Russian and Western instutions. Technology transfer has aided and will continue to aid the submersible program and is an area of concern.

The 908 Project of the State Oceanic Adminstration is closely associated with the 863 Program and has produced details underwater maps of the waters surrounding China. The Jiaolong will be able to utilize these mapping details in the employment of underwater communication and sensor networks. These networks will be employed at strategic chokepoints throughout Chinese controlled waters.

The Jiaolong and other manned submersibles will be used to control remotely operated AUVs for the combat and surveillance purposes. The Jiaolong will not be used as a weapons platform but may be used to control sensors that guide and control underwater systems. Limited open source reports are available in these areas and future collection efforts should focus on known key institutions and researchers through datamining and detailed interaction networks mapped.

Appendix A

Selected Chinese Submersible Researchers

Wang San-de was born in 1974. He received the BS degree in physical education in 1997 from Yanbei Normal College and received the MS degree in acoustics from Shanxi Normal University, China. He received the PhD in underwater acoustic engineering in 2005 from Harbin Engineering University. Now he works at the Dalian Scientific Test and Control Technology Institute. His main research interests are in vibration of structures and noise control.

Yang De-sen was born in 1957, professor, supervisor of PhD students in underwater acoustic engineering, member of Acoustical Society of China, vice president of Harbin Engineering University. He received the MS degree and PhD degree in underwater acoustic engineering in 1988 and 1996 from Harbin Engineering University.

Liu Ning was born in 1979. He received the BS degree and MS degree in underwater acoustic engineering in 2003 and 2006 from Harbin Engineering University. His current research interests include vector signal processing and noise control.

Tao Guo was born in 1982. He is an engineer at Dalian Scientific Test and Control Technology Institute. His current research interests include beam forming and noise measuring.

Xiyou Li was born in 1975. He received the MS degree in optical communication technology in 2005 from Harbin Engineering University. His current research interests include digital communication and system control technology and noise signal processing.

Ziynag Yu was born in 1978. He received the MS degree in underwater acoustic engineering in 2007 from Harbin Engineering University. His research interests are research and exploitation of the radiation noise of underwater machine.

Yao Xoing-Liang is a professor and dean of the College of Shipbuilding Engineering, Harbin Engineering University. He was born in 1963. His current research includes explosion, noise and vibration control and fluid-structure analysis.

Liu Qing-Jie is a Master of Engineering in the Major of Analysis of Structural Dynamics, College of Shipbuilding Engineering, Harbin Engineering University.

Yu Xiu-Bo was born in 1982, is a Master of Engineering in the Major of Ship Structural Dynamics and Explosion, College of Shipbuilding Engineering, Harbin Engineering University.

Guoyong Jin was born in 1980. He received his PhD degree from Harbin Engineering University in 2007. He is an associate professor at Harbin Engineering University. His research interests include vibration and noise analysis, and active noise and vibration control.

Xiaoling Liu was born in 1980. She received her MS degree from Harbin Engineering University in 2008. She is now an engineer at the China Shipbuilding Information Center. Her

current research interests include vibration and noise analysis and control and shipbuilding information.

Zhigang Liu was born in 1956. He received the BS and MS degrees from Harbin Ship Engineering Institute in 1981 and 1987 and then received his PhD from Harbin Engineering University in 2000. He is the president of Harbin Engineering University and a professor and supervisor for PhD students. His main research interests include vibration and noise control and diesel dynamics.

Zhang Bo was born in 1979. He is a PhD candidate at Northwestern Polytechnical University, majoring in weapon firing theory and technology.

Zhang Yu-wen was born in 1946. He is a professor and doctoral supervisor at Northwestern Polytechnical University, majoring in weapon and expert engineering, fire theory and technology and trajectory and control.

Yuan Xu-long was born in 1977. He is an instructor at Northwestern Polytechnical University, majoring in firing theory and technology and trajectory and control.

Zhang Yu-li was born in 1967, is currently studying for a doctorate from Huanzhong University of Science and Technology. His main research interests are in the fields of structure analysis and manufacture of ship and marine architecture.

Zeng Guang-Wu was born in 1937, is a Senior Professor at Huazhong University of Science and Technology, former chairman of Department of Naval Architecture and Ocean Engineering. His main research interests are in the fields of structure analysis and optimization design of marine and rocket. He developed new technology of design rule of submarine structure, structure optimization design method and applications for surface craft, direct design method for marine structure feature analysis and optimization of rocket structure used in designing new type naval craft and research of rocket with great efficacy.

Fang Wang was born in 1985. She is a PhD candidate at the State Key Lab of UAV, Harbin Engineering University. Her current research interests include simulation and motion control of Autonomous Underwater Vehicle.

Lei Wan was born in 1964. He is a professor at the State Key Lab of AUV, Harbin Engineering University. His main research fields are motion and underwater control and navigation of underwater vehicles.

Yu-min Su was born in 1960. He is a professor at the State Key Lab of AUV, Harbin Engineering University. His current research interests include fluid dynamics and marine propeller design and system integration of underwater vehicles.

Yu-ru Xu was born in 1942. He is the subject leader of Naval Architecture and Ocean Engineering, the national key discipline of Harbin Engineering University. For more than 30 years he managed and fulfilled many creative engineering research projects, especially for the

fast development technology of Autonomous Vehicles in China. He has made important contributions to the system simulation, intelligent control architecture and system integration in this field.

Bo Gao was born in 1982. He is a candidate for the PhD at the Northwestern Polytechnical University. His current research interests include path planning for robot and industrial control.

De-min Xu was born in 1937. He is an academician of Chinese Academy of Engineering. He is a professor at the Northwestern Polytechnical University. His current research interests include precision guidance, and control and simulation of fish torpedo.

Wei-sheng Yan was born in 1968. He is a professor at the Northwestern Polytechnical University. His research interests include precision guidance and control of AUV.

Wang Bo was born in 1982. He received his MS degree in the Design and Construction of Naval Architecture from Harbin Engineering University in 2008. His research interests include control and simulation of underwater vehicles.

Wan Lei was born in 1964. He is a professor in the school of Shipbuilding Engineering, Harbin Engineering University. His main researches include motion control and navigation of underwater vehicles.

Qin Zai-bai was born in 1953. He is a senior engineer in the school of Shipbuilding Engineering, Harbin Engineering University. His current research interests include design of experimental facilities of underwater vehicles.

Zhang Lei was born in 1983. He received his MS degree in the Design and Construction of Naval Architecture and Ocean Structure in 2007. His current research interests include intelligent control and simulation of underwater vehicles.

Su Yu-min was born in 1960. He is a professor at Harbin Engineering University. His current research interests include design of underwater vehicles and bionic robots.

Zhao Fu-long was born in 1981. He received his MS degree in the Design and Construction of Naval Architecture and Ocean Structure in 2008. His research is focused on the motion control of underwater vehicles.

Liang Xiao was born in 1980. He received the MS in Fluid Mechanics in 2006. His current research interests include intelligent control and simulation of underwater vehicles.

Li Ye was born in 1978. He is a Doctor of Design and Construction of Naval Architecture and Ocean Structure in Harbin Engineering University. His current research interests include intelligent control and path programming of underwater vehicles.

Qin Zheng was born in 1981. He is a PhD candidate for control theory and control engineering of College of Automation, Harbin Engineering University. His current research interests include autonomous control and simulation technology for AUV.

Bian Xin-qian was born in 1941. He is a professor and PhD supervisor for the College of Automation, Harbin Engineering University. His current research interests include overall technology for AUV and dynamic positioning.

Pang Yongjie was born in 1955. He is a professor and supervisor for PhD candidates in the school of Shipbuilding Engineering, Harbin Engineering University. His main research fields include design of underwater vehicles and exploiting systems of resources in deep ocean, underwater virtual world simulation and multiple AUVs cooperation and coordination.

You Guangxin was born in 1976, received his BS degree in Ship Building Engineering in 1999 at Harbin Engineering University. His main research interests focus on multiple AUVs cooperation and coordination.

Guo Zhen was born in 1980 and received her PhD in the school of Automation, Harbin Engineering University in 2005. Her main research interests include navigation guidance and control.

Sun Feng graduated from precise instrument major of Harbin Institute of Technology in 1967. He is a professor at Harbin Engineering University and has been engaged in the research work of precise instrument and machinery for many years.

Ning Liu was born in 1979. He received the MS degree in underwater acoustic engineering in 2003 from Harbin Engineering University. His current research interests include vector signal processing and noise control.

Sande Wang was born in 1974. He received the PhD degree in underwater acoustic engineering in 2005 from Harbin Engineering University. His main interests are in vibration of structure and noise control.

Appendix B

Projects with Known Chinese 863 Naval Research Funding in Chronological Order

Design and Application of the Underwater Recovering System for the Untethered Underwater Vehicle "Explorer", *Robot*, 1996-03
*Yu Kaiyang, *Xu Fen'an, *Wang Ditang, and *Yang Lei
*Shenyang Institute of Automation, Chinese Academy of Science, Shenyang
863 Program

From Remotely Operated Vehicles to Autonomous Undersea Vehicles, *Engineering Science*, 2000-12
*Feng Xisheng
*Shenyang Institute of Automation, Chinese Academy of Science, Shenyang
863 Program (863-3-512-15)

Inversion of Underwater Bottom Tomography by using the SAR Imagery, *Geoscience and Remote Sensing Symposium*, July 24-28, 2000
*Ya-Qiu Jin and *Wei Zhang
*Center for Wave Scattering and Remote Sensing, Fudan University, Shanghai
863 Program (863-818-06-05)

Two-Dimensional Topography Inversion of Underwater Bottom by using SAR Imagery, *Antennas, Propagation and EM Theory*, August 15-18, 2000
*Wei Zhang and *Ya-Qiu Jin
*Center for Wave Scattering and Remote Sensing, Fudan University, Shanghai
863 Program (863-818-06-05)

Basic Motion Control of Free-Swimming Biomimetic Robot Fish, *42nd IEEE Conference on Decision and Control*, December 2003
*Junzhi Yu, *Shuo Wang and *Min Tan
*Laboratory of Complex Systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences, Beijing
863 Program (2001AA422370)

Development of Research on the Pressure Shell Structure of Deep Manned Submersible, *Journal of East China Shipbuilding Institute (Natural Science Edition)*, 2004-04
*Yu Ming-hua, *Wang Zi-li, *Li Liang-bi, *and Wang Ren-hua
*School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang
863 Program (2002AA401002-007)

Development of a Biomimetic Robotic Fish and its Control Algorithm, *IEEE Transactions on Systems, Man and Cybernetics*, 2004, 34(4), 1798-1810
*Junzhi Yu, *Min Tao, *Shuo Wang and *Erkui Chen
*Laboratory of Complex Systems and Intelligence Science, Chinese Academy of Science, Beijing
863 Program

Research on Architecture for Reconfigurable Underwater Sensor Networks, 2005
*Shuo Wang and *Min Tan
*Institute of Automation, Chinese Academy of Sciences, Beijing
863 Program (2003AA404190) and National 973 program (2002CB312200)

A high precision ultrasonic docking system used for automatic guided vehicle, *Sensors and Actuators A*, 2005, 118, 183-189
*F. Tong, *S.K. Tso and **T.Z. Xu
*Consortium for Intelligent Design, Automation and Machatronics (CIDAM), City University of Hong Kong
**Oceanography Department of Xiamen University, Xiamen
863 Program (863-512-10-21)

Manned Submarine and Its Motion Control, *Chinese Journal of Scientific Instrument*, 2005-S1
*Guo Wei and *Wang Xiao Hui
*Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang
863 Program (2003AA401003)

Velocity measurement with correlation sonar and sea test verification, *Technical Acoustics*, 2005-02
*Feng Lei, *Wang Chang-hong, *Wang Yu-ling and *Qiu Wei
*Institute of Acoustics, Academy of Sciences, Beijing
863 Program (2003AA604030)

Preparation and Characterization of Solid Buoyancy Materials Based on Epoxy Resins, *Fine Chemicals*, 2005-03
*Wang Qi-feng, **Du Zhu-wei, ***Chen Xian, **Li Hao-ran and *Sun Chun-bao
*School of Civil and Environmental Engineering, Beijing University of Science and Technology
**National Key Laboratory of Biochemical Engineering, Institute of Process Engineering, Chinese Academy of Sciences, Beijing
***Marine Research Institute of Chemical Industry, Qingdao
863 Program (2002AA401001-1)

A developed Ethernet-based communication system for manned submersible vehicle, *OCEANS 2005*
*X.W. Meng, *K.Z. Liu, **W. Guo and X.H. Wang
*Shenyang Automation Institute, Chinese Academy of Science, Graduate School of CAS
**Research Center of Underwater Robots, Shenyang Institute of Automation, Chinese Academy of Science
863 Program

Influence of initial deflection on plastic stability of manned deep-sea submersible's pressure sphere hull, *Ocean Engineering*, 2005-04
*Wang Ren-hua, *Yu Ming-hua, *Li Liang-bi and *Wang Zi-li
*School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang
863 Program (2002AA401002-07)

Research on the Ultimate Strength of Pressure Spherical Shell with Openings in Manned Dee-Sea Submersible, *Shipbuilding of China*, 2005-04
*Yu Ming-hua, *Wang Ren-hua, *Wang Zi-li and *Li Liang-bi
*School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang
863 Program (2002AA401002-07)

Nonlinear Finite Element Analysis of Pressurized Shell for Manned Deep Submersible, *Shipbuilding of China*, 2005-04
*Li Liang-bi, *Wang Ren-hua, *Yu Ming-hua and *Wang Zi-li
*Department of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang
863 Program (2002AA401002-07)

Path Following Control of a Deep-Sea Manned Submersible Based upon NTSM, *Untranslated title of Chinese journal*, 2005-04
*Ma Ling and **Cui Wei-Cheng
*School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University
**China Ship Scientific Research Center, Wuxi
863 Program (2002AA401002)

A waveform design method for improving high speed underwater communication performance, *Acta Acoustica*, 2005-05
*Liu Yuntao, *Yang Shenyuan and **Cai Huizhi
*Institute of Information and Communication, Harbin Engineering University
**Institute of Acoustics, Chinese Academy of Sciences, Beijing
863 Program (863-818-09-09)

Palette's Continuous Coding Method for Sonar Image Pseudo-color Processing, *Acta Simulata Systematica Sinica*, 2005-07
*Liu Wei, *liu Ji-yuan, *Huang Hai-ning and *Chang Chun-hua
*Institute of Acoustics, Academy of Sciences, Beijing
863 Program (2002AA631110)

Structure Design of Mechnical Hand Based on the Typical Underwater Operating Assignment, *Modular Machine Tool & Automatic Manufacturing Technique*, 2005-08
*Liu Zheng-shi, *Zhu Guang-sheng, *Wang Yong, and **Ge Yunjian
*School of Mechanical and Automotive Engineering, Hefei Technology University, Hefei
**Hefei Institute of Intelligent Machines, Chinese Academy Institute, Hefei
863 Program (2001AA423300)

Study of 1-3-2 Type Piezoelectric Composite Transducer Array, *Ultrasonics*, 2006, Volume 44, pe673-e677
*****Li Guang, ***Wang Li-kun, *Luan Gui-dong, *Zhang Jin-duo and ***Li Shu-xiang
*School of Electronics Engineering and Computer Science, Peking University
**Tianjin High-Sea Acoustics Instrument Company, Tianjin
***Sensor Technology Research Center, Beijing Information Technology Institute
****Underwater Acoustic Research Branch, National Ocean Technology Center, Tianjin
863 Program

Ultimate Strength Analysis of Pressure Spherical Hull of Manned Deep-Ocean Submersibles, *Journal of Jiangsu University of Science and Technology (Natural Science Edition)*, 2006-04
*Wang Renhua, *Yu Minghua, *Wang Zili and *Li Liangbi
*School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang
863 Program (2002AA401002-07)

Design Method Research of Lighter Exostructures Made by Composite Material on Deep Human Occupied Vehicle, *Ship Building of China*, 2007-01
*Hu Yong, *Zhao Jun-hai, *Liu Tao and *Cui Wei-Cheng
*China Ship Scientific Research Center, Wuxi
863 Program (K1430)

A Model for Calculating Magnetic Field of Underwater Pipe, *Hydrographic Surveying and Charting*, 2007-01, *Ren Lai-ping, *Huang Mo-tao, *Zhai Guo-jun, Ouyang *Yong-zhong, **Deng Zhi-jun
*Naval Institute of Hydrographic Surveying and Charting, Tianjin
**92292 Troops, Qingdao, Shandong
863 Program (2004AA639710)

Research on the Design of Spherical Pressure Hull in Manned Deep-Sea Submersible, *Journal of Ship Mechanics*, 2007-02
*Liu Tao
*China Ship Scientific Research Center, Wuxi
863 Program (2002AA40100)

Classification of simulant sonar signals base on BP network, *Journal of Marine Sciences*, 2007-02
*Zhou Jian-ping, *Tao Chun-hui, *Lu Wen-zheng, *He Yong-hua and *Gu Chunhua
*Second Institute of Oceanography, SOA, Laboratory of Submarine Geosciences, SOA, Hangzhou
863 Program (2002AA615130)

Trial of deep sea navigation with a single transponder, *Ocean Engineering*, 2007-02
*Lan Hua-lin, *Sun Da-jun, *Zhang Dian-lun and *Li Xiang
*College of Underwater Acoustic Engineering, Harbin Engineering University
863 Program (2002AA613010)

Research on time synchronization in underwater GPS system and its experiment, *Science of Surveying and Mapping*, 2007-03
*Bei Jin-zhong, *Zhang Chuan-yin, *Gao Xiong-wei, **Wanf Ze-min and *Cai Yan-hui
*Chinese Academy of Surveying and Mapping, Beijing
**715 Research Institute of Shipbuilding Industry Corp, Hangzhou
863 Program (2001AA613050 and 2003AA613050)

Path Planning Method for Mobile Robot Based on Particle Swarm Algorithm, *Application Research of Computers*, 2007-03
*Zhao Xian-zhang, *Chang Hong-xing and *Zeng Jun-fang
*Institute of Automation, Chinese Academy of Sciences, Beijing
863 Program (2005AA420050)

Experimentation and investigation of chirp sonar for dam inspection, *Journal of Naval University of Engineering*, 2007-04
*Wang Ji-sheng, *Guo Yuan-xi and *Qiao Gang
*School of Underwater Acoustic Engineering, Harbin Engineering University
863 Program (2002AA420090)

A New Motion Control Scheme for Underwater Vehicle-Manipulator System, *Robotics, Applications and Telematics*, 2007
Y. Guo, G. Xu, X. Xiang and Z. Ziao
863 Program

An algorithm for precise calibration of absolute position of a transponder moored on seabed, *Journal of Naval University of Engineering*, 2007-05
*Lan Hua-lin, *Sun Da-jun, *Zhang Dian-lun and *Lu Feng-chun
*College of Underwater Acoustic Engineering, Harbin Engineering University
863 Program (2002AA613010)

Shallow Water High Resolution Bathymetric Side Scan Sonar, *OCEANS 2007*
*Xiaodong Liu, *Weiqing Zhu, **Changle Fang, **Wen Xu, *Fangsheng Zhang and *Yujia Sun
*Institute of Acoustics, Chinese Academy of Sciences, Beijing
**Teledyne RD Technology, Shanghai
863 Program

Research of PWM control technology of submarine trim regulating system, *Mechanical and Electrical Equipment*, 2007-08
*Yang Shen-shen, *Xu Guang-qing, *Cheng Fei and *Wang Lei
*No. 702 Research Institute, CSIC, Wuxi
863 Program (7000-XX), funding for nation 863 momentous special item 7000 m human-loaded submarine

Development and Depth Control of Biomimetric Robotic Fish, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, October 29-November 2, 2007
*Le Zhang, *Wei Zhao, *Yonghui Hu, *Dandan Zhang and *Long Wang
*Intelligent Control Laboratory, Center for Systems and Control, College of Engineering, Peking University
863 Program (2006AA04Z258)

Modular Design and Motion Control of Reconfigurable Robotic Fish, *IEEE Conference on Decision and Control*, December 12-14, 2007
*Yonghui Hu, *Long Wang, *Wei Zhao, *Qi Wang and *Le Zhang
*Peking University
863 Program

Coordinated Control for Multi-AUV Systems based on Hybrid Automata, *International Conference on Robotics and Biomimetics*, December 15-18, 2007, Sanya, China
*Xianbo Xiang, *Guohua Xu, *Qin Zhang, *Zhihu Xiao and *Xinhan Huang
Department of Marine Engineering, Huazhong University of Science and Technology, Wuhan
863 Program

Trajectory Tracking for Underwater Manipulator Using Sliding Mode Control, *International Conference on Robotics and Biomimetics*, December 15-18, 2007, Sanya, China
*Guohua Xu, *Zhihu Xiao, *Ying Guo and *Xianbo Xiang
Underwater Technology Laboratory, College of Traffic Science and Engineering, Huazhong University of Science and Technology
863 plan “deep-sea manipulator key technique” and “underwater work tool” projects

General Performance MDO of a Deep Sea HOV based on BLH Framework, *Journal of Ship Mechanics*, 2008-01
*Liu Wei, *Cao An-xi, *Gou Peng, and *Cui Wei-cheng
*State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University
**China Ship Scientific Research Center, Wuxi
863 Program (2002AA401002)

Optimum Transmission Range for Underwater Acoustic Sensor Network, *Information Networking*, January 23-25, 2008
*Dou Jinfeng, *Guo Zhongwen, **Cao Jiabao and *Zhang Guangxu
*Computer Science Department, Ocean University of China, Shandong
**Lucent Technologies Qingdao Telecommunications Systems, Shandong
863 Program (2006AA09Z113)

Development of an Artificial Fish-Like Robot and its Application in Cooperative Transportation, *Control Engineering Practice*, 2008, 16(5), 569-584
*J. Shao, *L. Wang and **J. Yu
*Peking University, Intelligent Control Laboratory, College of Engineering
**Laboratory of Complex Systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences, Beijing
863 Program

Development of High Precision Doppler Velocity Log Used in Underwater Vehicle, *Ocean Technology*, 2008-04
*Fu Ju-ying and *Shen Bin-jian
*No. 715 Research Institute of Chinese Shipbuilding Industry Corporation, Hangzhou
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Laboratory of Oceansense Network 908 Research

"For feature data and semantics of the marine information, 908 Subject will design and develop a set of XML application standards for distribution and exchange of marine applications and based on this, design the marine information exchange and integrated model based on XML, and put it as base of service system of distribution and exchange of marine information network. For the application of marine basic information, develop the information exchange and integrated application system based on XML, implement marine information exchange and integration based on XML."

http://osn.ouc.edu/joomal/index.php/projects

Selected 908 Funded Chinese Researchers

Guangxu Zhang was a graduate student in computer science at the Ocean University of China. Her main research interests include routing protocols and algorithms for sensor networks.

Dr Jiancheng Luo graduated from the State Key Laboratory of Resources and Environmental Information System, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences with a PhD degree in 1999. He is a Professor at the Institute of Remote Sensing Applications, Chinese Academy of Sciences.

Jiabao Cao received his MS degree in 2001 in Manfacture and Engineering from Shandong University. He works at Alcatel-Lucent Technologies, Qingdao and his main research interests are computer networks and VOIP.

Jinfeng Duo received her BS degree in 1998 in Automatization Engineering from Shandong University of Technology and her MS degree in 2001 from Shandong University.She is currently a PhD candidate at the Ocean University of China and is an instructor in computer science there. Her main interests are computer networks, distributed ocean information processing techniques,

with special interests in protocols and algorithms for ad hoc, wireless sensor and underwater acoustic networks.

Dr Sihai Li is a Professor and the Deputy-General of the 908 Project Management of National Marine Data & Information Service, State Oceanic Administration, China.

Professor Tianhe Chi is Director-General of the National Engineer Center for Geoinformatics (NCG) at the Institute of Remote Sensing Applications, Chinese Academy of Sciences. His main research interests include Geographical Information Sharing, Digital City and Digital Province.

Dr Wen Dong graduated from the Institute of Remote Sensing Applications, Chinese Academy of Sciences with a PhD degree in 2010. She is an Assistant professor at the Institute of Remote Sensing Applications, Chinese Academy of Sciences.

Dr Xin Zhang graduated from the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences with a PhD degree in 2004 and completed postdoctoral work at the Institute of Remote Sensing Applications, Chinese Academy of Sciences in 2006. He is currently an Associate Professor at the Institute of Remote Sensing Applications, Chinese Academy of Sciences.

Zhongwen Guo received his PhD in 2005 and is currently a Professor in computer science at Ocean University of China, Qingdao. He is the Vice President of the Information Science and Engineering Institute of Ocean University of China. He was the project manager for XML-based marine information exchange and integration, the National Digital Ocean Program 908 (908-03-01-07) and also was a member of the expert tank on ocean information techniques domain of the National High Technology Program 863. His main research interests are computer networks, distributed ocean information processing techniques, and routing protocols and algorithms for sensor networks.

Appendix D

Graphic from China Ship Scientific Research Center, Wuxi – Submersibles