Proceedings of the Twentieth (2010) International Offshore and Polar Engineering Conference
Beijing, China, June 20–25, 2010

ISBN 978-1-880653-77-7 (Set); ISSN 1098-6189 (Set); www.isope.org

Introduction to A Prototype System of Dense Underwater Wireless Sensor Networks

Shuo Wang *Min Tan*
Lab. of Complex systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences
Beijing, China

ABSTRACT

Underwater Wireless Sensor Networks (UWSN) has a brilliant prospect in many underwater applications, so the researches on UWSN have been paid more and more attention in recent decades. In this paper, a prototype system of dense underwater wireless sensor networks is introduced. Several problems, such as system architecture, node design, acoustic communication protocol and node localization, are considered for the prototype system design. And data collection and network management software is designed and developed for UWSN. Some experiments are carried out to validate the performance of the prototype system. The results show the proposed solutions are valid and the prototype system is feasible.

KEY WORDS: Underwater wireless sensor networks; underwater networking; system architecture; sensor node; acoustic communication; range measurement; network management.

INTRODUCTION

Such underwater applications as offshore exploration, oceanographic data collection, pollution monitoring, disaster prevention, assisted navigation and surveillance need special underwater supervision systems. Underwater sensor networks are studied and developed to deal with these applications for decades. Cabled underwater sensor networks have been applied widely. But the communication in the cabled senor networks is based on wired communication. The deployment of the sensor nodes is difficult in formidable environment. So the underwater wireless sensor networks and mobile underwater wireless sensor networks are studied for solving sensor node deployment and sensor network distribution. As new underwater networked systems, several problems, such as node design, underwater communication, network protocol, node localization, data collection and management, should be considered under some special underwater conditions.
A cabled-network for real-time and long-term underwater observation was introduced (Asakawa, 2004). The research challenges and practical issues in underwater sensor networks were concluded (Akyildiz, 2005; Partan, 2006). MIT robot laboratory presented an underwater sensor network platform (Vasilescu, 2005; Dunbabin, 2006). The sensor network prototype consists of static and mobile underwater sensor nodes. Data muling method is presented for data collection from underwater sensor nodes. Architecture for underwater sensor network is presented (Wang, 2005). And an underwater sensor node design is proposed (Lu, 2006). But underwater networking and localization did not be considered. So a prototype system of dense underwater wireless sensor network is introduced in the paper.
The paper is organized as follow. The system architecture is introduced firstly. Then underwater sensor node design, networking and distance measurement for underwater sensor nodes are described in detail. And software for data collection and network management is designed and developed. The experimental results are shown. Finally, the paper is concluded.

THREE LAYER ARCHITECTURE

The system architecture is considered firstly for a dense underwater wireless sensor network. A three-layered architecture is designed in the paper. As shown in fig.1, three layers of the sensor network include underwater sensor nodes, sink nodes, and remote server.

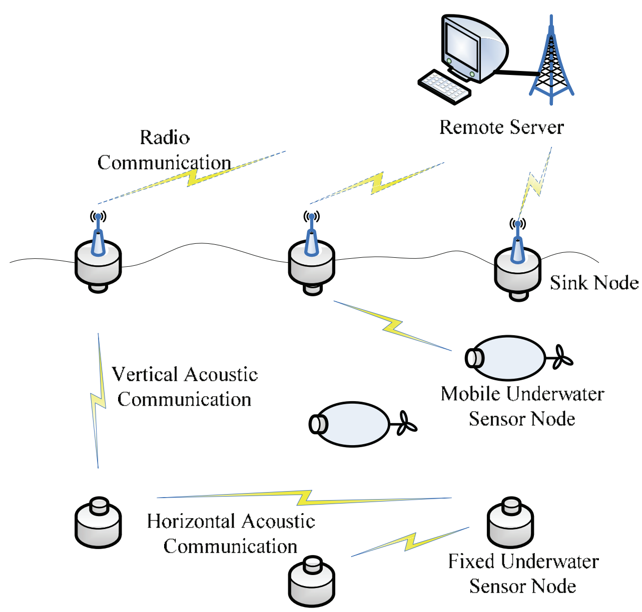


Fig.1 Three-Layer Architecture

Underwater Sensor Nodes

The underwater sensor nodes have sensing and communication functions. And the sensor nodes are divided into two types: fixed wireless sensor nodes and mobile wireless sensor nodes. The fixed wireless sensor nodes can communicate each other and detect their surrounding. The fixed sensor nodes can also work as anchor nodes for other nodes' localization in the network. The mobile wireless sensor nodes can move to and explore the interested areas that are not covered by the fixed nodes. And the mobile wireless sensor nodes may also fulfill some tasks such as sensor node deployment, communication relay between sensor nodes.

Sink Nodes

Sink nodes floating on the water surface are the sensor nodes that have devices for both acoustic communication and radio communication. So the sink nodes can collect data from the underwater sensor nodes through acoustic communication and send it to remote server by radio communication. And the remote sever can also send request and commands to the underwater sensor nodes through the sink nodes. The sink nodes equipped with GPS modules can provide their precise position information for the underwater sensor node localization. And the sink nodes can distribute their precise time information to the underwater sensor nodes in time synchronization process.

Remote Server

Remote server is a supervision and management system for the whole underwater wireless sensor network. The remote server can collect and store the sensing data through the underwater sensor network. The network topology and sensor node states should be obtained by the remote server for network management. The underwater sensor nodes' position can be estimated or collected by the remote server too. So the remote server provides an interface for the users to access the underwater wireless sensor network easily and conveniently. And such functions as data fusion, object tracking and estimation, can be integrated in the remote server.

Based on the three-layered architecture, a prototype system for dense underwater wireless sensor networks is designed. The underwater nodes are designed according to fixed wireless sensor nodes and mobile wireless sensor nodes. The MAC protocol is applied to make these nodes networked. And a ranging algorithm is given for distance measurement between sensor nodes. Software is developed to manage the sensing data and the sensor network states.

SENSOR NODE DESIGN

The basic functions of an underwater sensor node are sensing, communication and processing. And the mobility is also important for a mobile underwater sensor node. Because different underwater sensors are related to different applications, sensors are not discussed briefly in this paper. Underwater communication is important and difficult for a cheap underwater sensor node. And efficient and energy-saving propulsive system is helpful for a mobile underwater sensor node. But commercial acoustic communication devices are too expensive for a dense underwater wireless sensor network. Traditional propeller is not satisfied in efficiency and maneuverability for the mobile sensor nodes. In this paper, underwater communication and propulsive system are discussed briefly for the underwater sensor node design.

Acoustic Communication

Acoustic communication is a feasible means of underwater communication. For a dense underwater sensor network, the node communication range which is less than one hundred meters would reduce the transducer and power supply requirements. A low baud rate can reduce the bandwidth requirement of acoustic channel and the difficulty of modulation and demodulation of the acoustic signals.

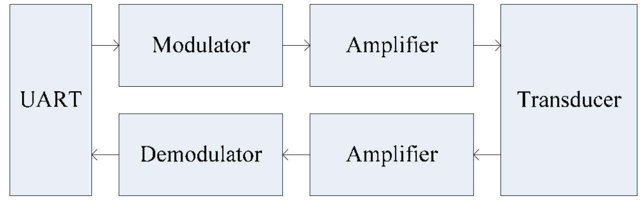


Fig.2 Sensor node acoustic communication module

The hardware design for a sensor node acoustic communication module is shown in Fig.2. The microcontroller of the sensor node sends and receives data through UART. The sending data are modulated by means of Frequency Shift Keying, then amplified, and transmitted through transducer. The acoustic signals received by transducer are amplified and demodulated into a series of bits sent to the microcontroller through UART. A cheap waterproof ultrasonic sensor T/R40 is selected as acoustic transducer. FSK modulator and demodulator chips XR2206 and XR2211 are chosen. The chips can modulate and demodulate acoustic signals with carrier frequency from 10 KHz to 300 KHz. And performance of the acoustic communication module is shown in Table 1.

Table 1. Performance of the acoustic communication module

Parameters	Value
Modulation	FSK
Baud Rate	256 bps
Transducer	Ultrasonic Sensor
Carrier Frequency	32 kHz
Communication Mode	Half-duplex Communication
Communication Range	30 m
Missing Rate	20 %
Power Supply	5 V
Transmitting Power	516 mW
Receiving Power	300 mW
Idle	55 mW

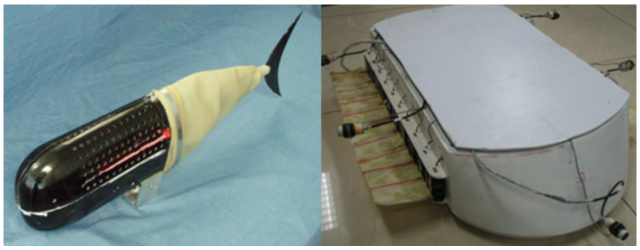
Optical Communication

Acoustic communication has low baud rate, so its data transmission is time-consuming. Data Muling, which a mobile node approaches the fixed nodes and collects data through high-rate communication, is usually adopted. As a high-rate communication means, optical communication is considered as point-to-point communication with high baud rate between a mobile underwater sensor node and a fixed sensor node. The blue-green light has better transmission performance in water, so it is chosen as media for optical communication. The communication protocol is based on IrDA standard protocol. Luxeon III Emitter is selected as the emitter, and photodiode SLD-70BG2 is selected as the receiver. Because the IrDA protocol is half-duplex communication protocol, two encoder/decoder chips MCP2120 supported IrDA Version 1.3 are adopted to make the optical communication full-duplex. In the optical communication module, power supply for emitter is 3.12 V, the external clock for MCP2120 is

8 MHz, and the baud rate reaches 125 Kbit/s within 2 m in clear water.

Biomimetic Propulsion

For mobile underwater wireless sensor nodes, the propulsion would consume most energy of the system. So an efficient and maneuverable propulsion means is very important for energy-saving of the mobile sensor node. Biomimetic robotic fish has been studied for decades to mimic the efficient maneuverable fish-like propulsion. So fish-like propulsion means is selected for underwater mobile sensor nodes. The swimming modes BCF (Body and Caudal Fin) and MPF (Median and Pectoral Fin) are considered.



(a) BCF propulsion system (b) MPF propulsion system

Fig.3 Biomimetic propulsion means for mobile sensor nodes

In Fig.3 (a), the oscillating body and caudal fin produces vortices in water to generate thrust. In Fig.3 (b), the undulating long-fin can also generate thrust. Both of these propulsion means can be used for the design of the mobile underwater sensor nodes.

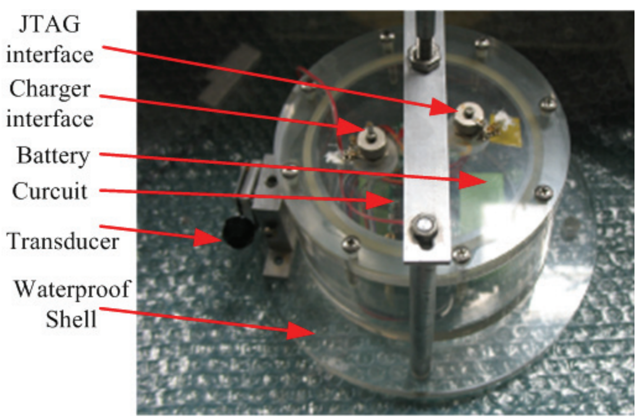


Fig.4 Developed underwater sensor nodes

As shown in Fig.4, a fixed underwater sensor node with the acoustic communication module is developed for the prototype system. The sensor node's microcontroller is ATMega128 which is a high performance and low power MCU with abundant peripheral interfaces, such as SPI, UART, and ADC. The MCU sends and receives data through UART to acoustic communication module. And the analog and digital sensing information can be obtained through the microcontroller peripheral interfaces. Now, only the fixed underwater sensor nodes are involved in the prototype system. The mobile underwater sensor node with acoustic and optical communication is still under construction, and will be integrated into the prototype system step by step.

NETWORKING FOR SENSOR NODES

For a dense underwater wireless sensor network, how to organize these sensor nodes to build the communication network is a very important problem. The optical communication introduced in the former section is point-to-point communication in very short distance, so it can not be used to build communication network for underwater sensor nodes. The acoustic communication can cover a larger area and be suitable to make the sensor nodes networked. But the communication bandwidth is limited; the neighbor nodes have to share the acoustic channel to avoid collision. So Media Access Control is a difficulty to overcome. Compared with such MAC protocols as FDMA, CDMA, CSMA, TDMA with good performance in energy efficiency and collision freedom is more suitable for the underwater acoustic networks. In order to make these underwater wireless sensor nodes networked, node discovery is considered firstly. Then time synchronization for sensor nodes is discussed. And time-slot re-assignment for a special case is also discussed to improve network communication efficiency.

Node Discovery

After deployment of the underwater sensor nodes, each node has to discover its neighbors. In the developed prototype system, TDMA with fixed time slot is adopted for node discovery. Each underwater sensor node is assigned a special ID and a unique time slot. If the quantity of the sensor nodes is large, the quantity of the time slots should be large enough to make each node have one unique time slot. If the quantity of time slots is not enough, the possibility of transmission collision will increase with decreasement of time slots.

In the discovery process, one underwater sensor node broadcasts its information in its own time slot. Other sensor nodes listen to the acoustic communication channel and receive the sender's information. After several periods, most of the sensor nodes obtain its neighbors' information. The information includes their neighbor nodes' ID, time slot, communication quality and their neighbor's neighbor nodes' ID, time slot, and communication quality. For different applications, more neighbor nodes' information such as position may be collected by the sensor node in node discovery process. And the collected information can be used for time slot re-assignment and route.

The quantity of time slots does affect the communication efficiency of the underwater sensor network seriously. When the underwater sensor network has a small quantity of nodes, consumed time of node discovery process may be acceptable and tolerable. But when the underwater sensor network has a large quantity of nodes, the node discovery process would be very time-consuming. The above method can process the node discovery problem really, but it also needs to be improved further. And the node discovery should be paid more attention, especially in dense underwater wireless sensor networks.

Time Synchronization

Identical time is very important for dense underwater wireless sensor networks. The sensing data with time stamp will be more meaningful for special applications. And the identical time is also important for all the sensor nodes to access the acoustic channel. All the local clocks of the underwater sensor nodes are set to be same before deployment. But each node's local clock biases gradually in long duration work. And the large difference of each node's local time will cause the failure of TDMA. So time synchronization has to be considered. But the propagating delay of acoustic channel makes time synchronization hard. How to compensate time delay is the key problem to time synchronization of the underwater sensor networks.

The time delay T_D is analyzed and divided into three parts: sending time T_S, propagating time T_P, and receiving time T_R. The sending time which is spent in assembling a packet and queuing can be estimated based on baud rate of acoustic communication. The propagating time between sensor nodes can be estimated based on the distance between nodes. The receiving time which is spent in processing the received packets and delivering the packets to the microcontroller is similar to sending time. The whole delay time is the summation of the three parts as shown in Eq. 1.

$$T_D = T_S + T_P + T_R \tag{1}$$

The time synchronization process begins when the sink nodes send time synchronization commands to all the underwater sensor nodes. And each underwater sensor node sends its own local time in its own time slot, and other underwater sensor nodes receive the time information, calculate time value and update their local time. After enough time synchronization cycles, the local time of all the underwater sensor nodes would converge to an identical value. Then the time synchronization process ends. Because the time delay of the acoustic communication channel is very large compared to that of the radio communication channel, the delayed time must be compensated when the underwater sensor nodes synchronize their local time. Assumed that a sensor node i sends its local time and sensor node j receives the time information of the node i, the local time of the node j will updated according to the following equation.

$$T_j^{update} = \frac{(T_i + T_D) + T_j}{2} \tag{2}$$

where T_j^{update} is the updated local time of the underwater sensor node j which listens the local time information of sensor node I; T_i is the local time information sent by sensor node i; T_D is the compensated value for time delay, which can be obtained according to Eq.1; and T_j is the sensor node j local time that the node j receives the time information of node i.

Time Slot Reassignment

Because TDMA is used in the underwater sensor networks, the network efficiency of the TDMA-based system is very important. As described in the above section, each node is allocated a unique time slot number before deployment. The more the underwater sensor nodes are, the lower the TDMA network efficiency is. Because the communication range and connectivity of the sensor nodes are limited, same time slot can be re-used in the different area. Reassignment of TDMA time slot in the underwater sensor network would improve the efficiency and throughput. The reassignment algorithm had better be simple to realize and suitable for different topologies. But the reassignment algorithm of TDMA time slot is a hard problem. In order to simplify the problem, a special case is studied and the reassignment algorithm of TDMA time slot is given for this special case. The considered special case is a 4-connectivity network. If there are enough mobile underwater sensor nodes, the 4-connectivity network can be realized by nodes' mobility. And the 4-connectivity network is also helpful to localize a node in 3-dimension environment.

The 4-connectivity network is shown in Fig.5. 9 time slots are used for re-assignment of the network. 9 templates are designed for nodes to select their time slots. The un-assigned node can determinate its time slot based on its assigned 1-hop neighbor nodes and 2-hop neighbor nodes according to the correspondent template.

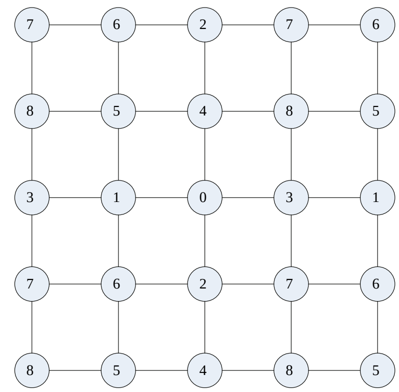


Fig.5 The considered 4-Connectivity network

The time slot set is represented as $S = \{S_0, S_1, \cdots, S_8\}$. The time slot of an un-assigned node's 1-hop neighbor node is $H_1(S_i)$, the time slot of an un-assigned node's 2-hop neighbor node is $H_2(S_i)$, and $S_i \subset S$. An un-assigned node can determinate its own time slot based on the assigned time slots of its 1-hop and 2-hop neighbor nodes. The rules for the node time slot assignment is given in Table. 2.

Table 2. Templates for time slot assignment

Time slots of 1-hop and 2-hop neighbor nodes	Time slot assignment
$H_1(S_1) \cap (H_2(S_3) \cup H_2(S_5) \cup H_2(S_6))$ OR $H_1(S_2) \cap (H_2(S_4) \cup H_2(S_6) \cup H_2(S_7))$ OR $H_1(S_3) \cap (H_2(S_1) \cup H_2(S_7) \cup H_2(S_8))$ OR $H_1(S_4) \cap (H_2(S_2) \cup H_2(S_5) \cup H_2(S_8))$	S_0
$H_1(S_0) \cap (H_2(S_2) \cup H_2(S_3) \cup H_2(S_4))$ OR $H_1(S_3) \cap (H_2(S_0) \cup H_2(S_7) \cup H_2(S_8))$ OR $H_1(S_5) \cap (H_2(S_4) \cup H_2(S_6) \cup H_2(S_8))$ OR $H_1(S_6) \cap (H_2(S_2) \cup H_2(S_5) \cup H_2(S_7))$	S_1
$H_1(S_0) \cap (H_2(S_1) \cup H_2(S_3) \cup H_2(S_4))$ OR $H_1(S_4) \cap (H_2(S_0) \cup H_2(S_5) \cup H_2(S_8))$ OR $H_1(S_6) \cap (H_2(S_1) \cup H_2(S_5) \cup H_2(S_7))$ OR $H_1(S_7) \cap (H_2(S_3) \cup H_2(S_6) \cup H_2(S_8))$	S_2
$H_1(S_0) \cap (H_2(S_1) \cup H_2(S_2) \cup H_2(S_4))$ OR $H_1(S_1) \cap (H_2(S_0) \cup H_2(S_5) \cup H_2(S_6))$ OR $H_1(S_7) \cap (H_2(S_2) \cup H_2(S_6) \cup H_2(S_8))$ OR $H_1(S_8) \cap (H_2(S_4) \cup H_2(S_5) \cup H_2(S_7))$	S_3
$H_1(S_0) \cap (H_2(S_1) \cup H_2(S_2) \cup H_2(S_3))$ OR $H_1(S_2) \cap (H_2(S_0) \cup H_2(S_6) \cup H_2(S_7))$ OR $H_1(S_5) \cap (H_2(S_1) \cup H_2(S_6) \cup H_2(S_8))$ OR $H_1(S_8) \cap (H_2(S_3) \cup H_2(S_5) \cup H_2(S_7))$	S_4
$H_1(S_1) \cap (H_2(S_0) \cup H_2(S_3) \cup H_2(S_6))$ OR $H_1(S_4) \cap (H_2(S_0) \cup H_2(S_2) \cup H_2(S_8))$ OR $H_1(S_6) \cap (H_2(S_1) \cup H_2(S_2) \cup H_2(S_7))$ OR	S_5

$H_1(S_8)\cap(H_2(S_3)\cup H_2(S_4)\cup H_2(S_7))$	
$H_1(S_1)\cap(H_2(S_0)\cup H_2(S_3)\cup H_2(S_5))$ OR $H_1(S_2)\cap(H_2(S_0)\cup H_2(S_4)\cup H_2(S_7))$ OR $H_1(S_5)\cap(H_2(S_1)\cup H_2(S_4)\cup H_2(S_8))$ OR $H_1(S_7)\cap(H_2(S_2)\cup H_2(S_3)\cup H_2(S_8))$	S_6
$H_1(S_2)\cap(H_2(S_0)\cup H_2(S_4)\cup H_2(S_6))$ OR $H_1(S_3)\cap(H_2(S_0)\cup H_2(S_1)\cup H_2(S_8))$ OR $H_1(S_6)\cap(H_2(S_1)\cup H_2(S_2)\cup H_2(S_5))$ OR $H_1(S_8)\cap(H_2(S_3)\cup H_2(S_4)\cup H_2(S_5))$	S_7
$H_1(S_3)\cap(H_2(S_0)\cup H_2(S_1)\cup H_2(S_7))$ OR $H_1(S_4)\cap(H_2(S_0)\cup H_2(S_2)\cup H_2(S_5))$ OR $H_1(S_5)\cap(H_2(S_1)\cup H_2(S_4)\cup H_2(S_6))$ OR $H_1(S_7)\cap(H_2(S_2)\cup H_2(S_3)\cup H_2(S_6))$	S_8

The algorithm for time slot assignment is simple and easy to implement on a low-cost underwater sensor node to improve the network communication efficiency. The algorithm also has to be studied further for different situations.

DISTANCE MEASUREMENT FOR SENSOR NODES

Localization is an important problem for the underwater sensor networks. And geographic information of sensing data and routing of sensor networks are related closely to the nodes' localization information. The range-based localization algorithms are better than those range-free localization algorithms. But the range-based algorithms need the distance information between sensor nodes. So the distance measurement based on the acoustic communication is proposed. The basic idea is from TWTT (Two Way Travel Time) which is a method without requirements of time synchronization between two nodes. One node sends a ranging signal to another one and waits for the respond signal, the other one will reply a respond signal immediately at the time that it has received the ranging signal, so the two ways travel time can be used to estimate the distance between two nodes. But the underwater nodes can not reply the ranging signal immediately because of noise and traducer characteristics. So the TWTT has to be modified to fit the underwater nodes' requirements. The nodes received the ranging signals wait for a given period and then reply to the nodes sent the ranging signals. And the distance between two nodes is calculated according to the following Equation.

$$D = V \times \frac{(t_r - t_s) - t_p}{2} \tag{3}$$

Where D is the distance between two nodes; V is the propagating velocity of the acoustic signal; t_r is the time when the node starts to send the ranging signal; t_s is the time when the node has received the ranging signal reply; t_p is a given period that a node waits from the time that it has received the ranging signal to the time that it starts to reply the ranging signal.

In order to reduce the time consumption in distance measure process, the ranging process is improved based on the TDMA protocol. One node sends the ranging signal to its 1-hop neighbor nodes in its own time slot. Its 1-hop neighbor nodes listen in the communication channel. And each neighbor node starts its internal timer when it has received the ranging signal. When a neighbor node's time slot arrives according to its internal timer, it sends a reply to the node sent the ranging signal. The node sent the ranging signal listens to the channel, and separately records the times that it receives its neighbor nodes' replies. The distance between the node and its neighbor nodes can be calculated according to Eq.3. The parameter t_p in Eq.3 is decided by the time period between the time slot of the node sent ranging signal and the time slot of its neighbor node.

The above ranging process can be distributed. Different nodes can start the process synchronistically and most of the distance information among the underwater sensor network can be obtained within several TDMA time frames. And the ranging method can work harmoniously with TDMA-based network. Such localization algorithms as MDS may be used for estimating node positions.

PROTOTYPE SYSTEM AND EXPERIMENTS

A prototype system of dense underwater sensor network is developed based on the proposed algorithms. Management software is designed for users to access the underwater network through the remote server. And experiments are carried out to validate the prototype system.

Prototype System

As shown in Fig.6, the developed prototype system includes 8 underwater sensor nodes. One of them works as sink node, which has both acoustic transducer and radio transceiver. Other underwater sensor nodes only have acoustic transducer. The 8 underwater sensor nodes must be deployed at a horizontal plane. The acoustic transducers of the nodes are not omni-direction and the communication range is limited. The communication links among nodes may be lost when the nodes are not on the horizontal plane. The sink node relays the sensing data to a laptop and commands to underwater sensor nodes. Management software runs on the laptop.

Fig.6 A prototype system with 8 nodes

Management software

Management software, UWSN Platform, is designed for managing the underwater sensor network. The basic modules shown in Fig.7 include user interface, communication module, data process module, and data storage module. Communication module is designed for data exchange between remote server and sink node. Data process module is designed for processing the information of network topology, distance between the nodes and sensing data from the nodes. Data storage module is designed for storing all the necessary information. User interface is designed for displaying the network topology, node state and sensing information, setting necessary network parameters.

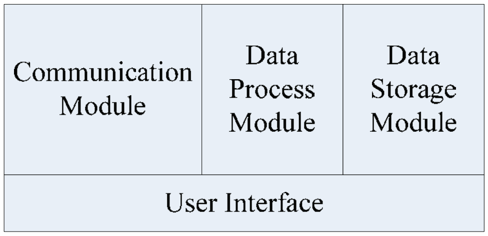


Fig.7 Software architecture for UWSN platform

Experimental Results

The experiments carried out in an area of a canal to validate the basic functions of the prototype system. The experimental area is 20m length, 10 m width, 0.8m ~ 1m depth. 6 underwater sensor nodes are networked to build the underwater sensor network. One of the nodes is equipped with temperature sensor, and one of the nodes is equipped with temperature sensor and pressure sensor.

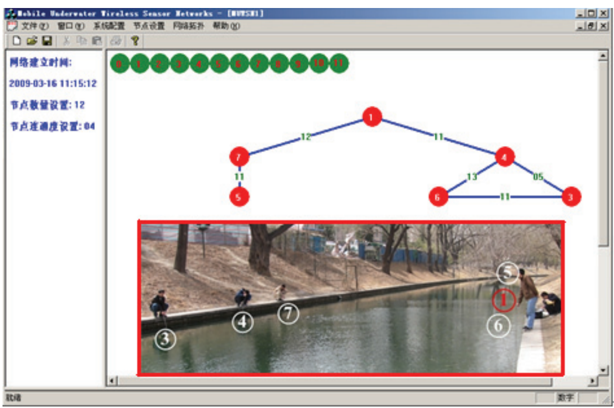


Fig.8 Topology of underwater sensor network

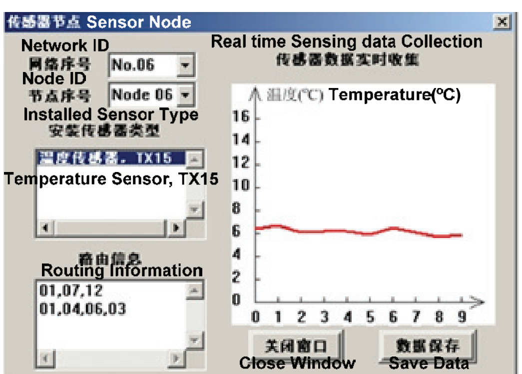


Fig.9 Collected sensing data and node states

In Fig.8, the photo of experimental scene is overlapped on the user interface. The circles represent the underwater sensor nodes and the lines represent the connectivity between the sensor nodes. The number on the circle is the node ID. The number on the line is the distance between two nodes.

In Fig.9, the underwater sensor node information is shown in the window. Because of the unstable acoustic links, the network topology may be changed. The network ID is the times of rebuilding the underwater network. The node ID is the node's identification number. Installed sensor type represents the sensor installed on the current node. Routing information shows the routing information of the network. The collection of real time sensing data is shown in a graph. And the temperature data are plotted with respect to the sample times.

CONCLUSIONS

In this paper, a prototype system of dense underwater sensor network is introduced. The underwater sensor node design is given. The networking methods for node discovery, time synchronization and time slot assignment are proposed. Distance measurement for node localization is also introduced. And the system management software is developed and experiments are carried out. Experimental results show the prototype system can fulfill some basic functions of underwater sensor networks. And the research is still ongoing to integrate mobile wireless sensor nodes with the prototype system.

ACKNOWLEDGEMENTS

The work is supported by NSFC (Grants No. 60635010 and No. 60725309) and 863 programme (Grants No. 2007AA041502, and No. 2008AA040207).

REFERENCES

Akyildiz, I F, Pompili, D, Melodia, T (2005). "Underwater Acoustic Sensor Network: Research Challenges," *Ad Hoc Networks*, Vol 3, No 3, pp 257-279

Asakawa, K, Mikada, H, Kawaguchi, K, Shirasaki, Y, Kojima J, Muramatsu J, Horiuchi Y, and members of ARENA (2004). "ARENA : A New Scientific Cable-network for Real-time and Long-term Underwater Observation," *14th (2004) Int Offshore and Polar Eng Conf*, Toulon, France, ISOPE, pp 363–370.

Dunbabin, M, Corke, P, Vasilescu, I, Rus, D (2006). "Data Muling over Underwater Wireless Sensor Networks Using An Autonomous Underwater Vehicle," *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, Orlando, Florida, USA, pp 2091-2098.

Lu, C, Wang, S, Tan, M (2008). "Design and Realization of Sensor Nodes for Dense Underwater Wireless Sensor Networks," *Proceedings of the 17th World Congress of the International Federation of Automatic Control*, Seoul, Korea, pp 12819-12824.

Partan, J, Kurose, J, Levine, BN (2006). "A Survey of Practical Issues in Underwater Networks," *Proceedings of WUWNet`06*, Los Angeles, USA, pp 17-24.

Vasilescu, I, Kotay, K, Rus, D, Dunbabin, M, Corke P (2005). "Data Collection, Storage, and Retrieval with an Underwater Sensor Network," *ACM SenSys 2005*, San Diego, California, USA, pp 154~165

Wang, S, Tan, M (2005). "Research on Architecture for Reconfigurable Underwater Sensor Networks," *IEEE conference on Networking, Sensing and Control*, Tucson, Arizona, USA, pp 831 – 834