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Design and Realization of sensor nodes for dense underwater wireless sensor networks

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Abstract: High cost and high power consumption of underwater acoustic modem have limited the applications and researches of underwater wireless sensor networks (UWSN). This paper presents a node architecture and its low-cost realization to deal with such problems as high cost, high power consumption, large volume, and relative localization in a dense UWSN. Some fundamental functions like short range underwater acoustic communication, relative range measurement, localization among the nodes are realized. And the experimental results show the nodes can meet the basic requirements of the dense UWSN research.

1. INTRODUCTION

In recent years, the research of terrestrial WSN has been improved widely, while less works have been done in underwater domain. The oceans alone cover 70% of our planet and along with rivers and lakes are critical to human being. The application of UWSN has huge potential for monitoring the pollution of river and marine environments.

However, a number of challenges confront us in achieving this goal, such as underwater communication, node disposal and retrial, power supply. In UWSN, underwater acoustic communication replaces electromagnetic communication of terrestrial WSN, as the electromagnetic waves are attenuated strongly under water, especially in salt water. However, the shift from RF to acoustics changes the physics of communication from the speed of light (3×10^8 m/s) to the speed of sound (around 1.5×10^3 m/s)—a difference of five orders of magnitude. Therefore, some limitations of the acoustic signals, such as low speed, long delay, have profound implications on underwater communication and localization. In air, we can use solar energy as the power supply; however, few practical methods can be used underwater except for large capacity batteries, and some low power design method also should be taken out. The expensive commercial acoustic modems with excellent performance and long communication range for sale are far beyond the requirements of the dense UWSN in cost and power consumption.

MIT robot laboratory presents a UWSN platform, which consists of static and mobile underwater sensor nodes. The mobile nodes can locate and hover above the static nodes for data muling, and they can perform network maintenance functions such as deployment, relocation and recovery. The static nodes were installed many sensors, including cameras, water temperature, and pressure. The nodes communication point-to-point using a novel high-speed optical communication system, and they broadcast using an acoustic protocol integrated in the TinyOS stack. As shown in Fig.1, the column one is AUV (Autonomous Underwater Vehicle), and each box is a static node with a docking system (Vasilescu *et al.* 2005).

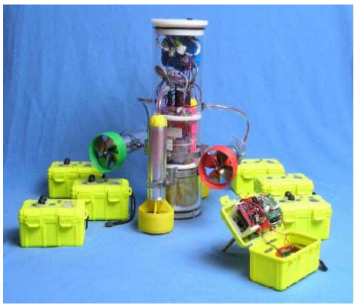

Fig.1 UWSN platform by MIT

ISI (Information Sciences Institute, University of South California), John Heidemann presented a model of dense underwater wireless sensor networks. According to the implementation of MICA 2 which is popular in WSN, the research team designed an underwater acoustic modem, which includes a very low-power and all-analog wakeup tone receiver to trigger the more expensive data receiver, and which can export information about receive signal-strength (RSSI) to support power control and channel quality estimation (Jack Wills *et al.* 2006). The research team also presented a S-MAC protocol (Wei Ye, ec tl, 2004), which was based on 802.11 MAC and improved in power saving. S-MAC adjusts the idle time so as to allot the communication channels automatically, and till now many MAC protocols used in WSN are improved from S-MAC, such as T-MAC (Van Dam T *et al.* 2005).

Compared to high cost, high power consumption and large volume of the on-sale underwater acoustic modems, a low-cost smart UWSN node is presented and implemented in this paper. Section 1 introduces UWSN. And the design of a low-cost smart node is presented in section 2. In section 3, a localization method based on these nodes is given. In section 4, some experiments are carried out and the results are discussed. Then, the conclusion and the future research are given

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2. DESIGN OF A LOW-COST SMART NODE

The low-cost smart node consists of the following components: acoustic communication module, power management module, microcontroller module, sensor interfaces module. The diagram of the node is shown as Fig.2.

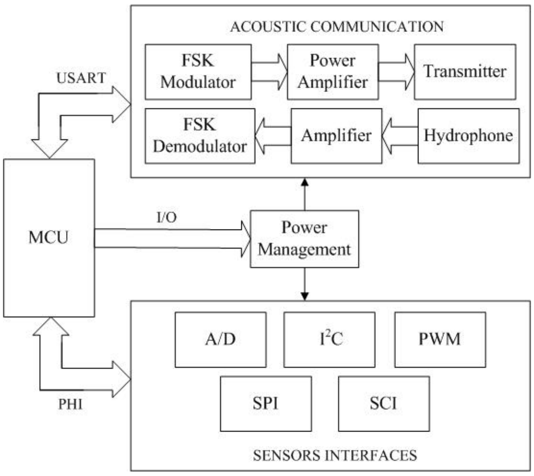

Fig.2 Diagram of the low-cost smart node

2.1 Underwater Acoustic Communication Module

For a dense UWSN, the following characteristics should be provided by the underwater acoustic communication system of a node.

- Low cost. In a dense UWSN, there are hundreds of nodes, and each node has an underwater acoustic modem which is the most expensive component. It is an important reason that current on-sale underwater acoustic modems can not be applied in a dense UWSN widely.
- Low power consumption. Underwater acoustic modem consumes most of the node power. So low power consumption is very important for the design of the node which is only supplied by the batteries.
- Smart design. Some static nodes need to be localized and retrieved by underwater mobile mechanism, for example, UWSN platform made by MIT robot laboratory. So underwater acoustic modem should be small enough to be built into the node.

Underwater acoustic communication system can be implemented in two methods, software or hardware modem. In software modem, signal modulation and demodulation are implemented by microprocessor which must have strong signal processing capacity. In hardware modem, modulation and demodulation are implemented by special integrated circuits, which save the resources of microcontroller and can be implemented in low cost and low power consumption. We select the last one to design the node.

As shown in Fig.2, acoustic communication module consists of transmitting channel and receiving channel. In transmitting channel, communication data signal flows as the following in turn, microcontroller USART Tx, FSK modulating circuit, power amplifier circuit, and transmitter; In receiving channel, communication data signal flows as the following in turn, hydrophone, analog amplifier circuit, FSK demodulating circuit, microcontroller USART Rx.

Underwater acoustic transmitter, whose efficiency determines the communication range and missing rate, is important for node design of a dense UWSN. However, the special underwater acoustic transmitter is too expensive and too large to fit for the applications of UWSN. So the low-cost underwater acoustic transmitter is one difficulty to overcome. Some ideas are proposed to solve such problem, that some terrestrial waterproof transmitter can be applied in shallow water while the carrier frequency decreases to 75% (Vasilescu *et al.* 2005, Jack Wills *et al.* 2006, Li shuyu 2004).

2.2 Power Management Module

The power is consumed mostly on the following options:

- Transmitting in communication. In underwater acoustic communication, the driving voltage of the transmitter need to be amplified so as to transmit longer, which makes this module consume more power.
- Listening in communication. For decreasing chances of missing packets, the receiving channel must stay active in waken status, and much power are wasted in valid listening.
- Sensors. In our node, there is a power output for each sensor interface so as to be apt to install sensors.
- Power conversing efficiency. Some modules need multi powers, such as +5V, +12V, -12V, and it is necessary to converse to them from the battery. Therefore, part of power is consumed in the conversing process.

The methods of decreasing power consumption can be concluded as follows.

- Selecting low power circuits and IC.
- Decreasing the invalid power consumption, such as valid listening.
- Low duty cycle method for some modules

2.3 Sensors interfaces module

As micro-electronics and integrated circuits improved, sensors with various digital interfaces have been appeared. In UWSN, some kinds of sensors are needed to work together for sensing, such as turbidity sensors, temperature sensors, stress sensors, chemical sensors. As a UWSN platform, it is necessary to extend some normal peripheral interfaces, and in our system we extend ADC, SPI, SCI, I^2C, PWM interfaces, which can connect sensors with matched interfaces directly.

2.4 Microcontroller Module

For UWSN, Microcontroller is the core of the node, which must be low-power, high efficiency, and which is responsible for node control schedule generating, senor sampling, communicating between the nodes. Embedded operating system running in MCU determines the main characteristics of the node, such as real-time, power management efficiency, communication efficiency. A compact tiny embedded control system is designed for our node, which fulfills 4 tasks (acoustic communication, power management, memory management, sensor information processing) under the scheduling of the main program.

3. RELATIVE LOCALIZATION AMONG NODES

Localization is one of the important characteristics for UWSN, which confirms each node relative position in local network and is helpful to multi-sensors or multi-nodes cooperation, dynamic network configuration, nodes disposal and retrial.

The realization of relative localization can be summarized as the following process, network coordinates establishing, relative ranging among nodes, coordinates updating of sensing node by sink coordinates and distances information.

3.1 Network Coordinates Establishing

In our UWSN, there are two kinds of static nodes, sink nodes and sensing nodes. Sink nodes can communicate with terrestrial sever by electromagnetic and also can broadcast with sensing nodes by underwater acoustic communication, which establish the network coordinates. Sensing nodes employ acoustic communication delay to measure the distance with sink nodes, and then updating their coordinates in local network.

3.2 Relative Range Measurement

The range measurement among the nodes is necessary for the network's geographic distribution and nodes localization. And the range between nodes which are able to communicate each other can be calculated by the flight time and travelling speed of acoustic signal. The ranging process will be described as follows.

Step 1: Node 1 transmits measurement command to Node 2, and it marks the time T_1 when transmitting is over.

Step 2: Node 2 reply Node 1 immediately after it receives the measurement command from Node 1.

Step 3: Node 1 stops timer and marks the time T2 when it receives the response from Node 2.

Step 4: The range between Node 1 and Node 2 can be calculated according to the equation (1),

$$R = V \times (T_2 - T_1 - T)/2 \qquad (1)$$

Where R is the distance between node 1 and node 2; T_1, T_2 are the start time and the end time of node 1 timer separately; V is the travelling speed of underwater acoustic signals; T denotes the time which node 2 takes to process communication data and reply.

3.3 Localization Method

As discussed above, sink nodes are the datum marks, which establish the 3-D coordinates for UWSN. And sensing nodes which localize themselves through sink nodes are used for sensing environment. When sensing nodes are put into water, they first find the sink nodes, then calculate their positions based on the sink nodes, and update their 3-D coordinates. The localization process is described below in detail.

Step 1. Sink nodes disposing. Sink nodes are put into water at appointed positions, which are not in a plane.

Step 2. Coordinates are built based on these sink nodes.

Step 3. Sensing nodes disposing and ranging with neighbour sink nodes. For disposing sensing nodes, it must be sure that sensing nodes can communicate with 4 sink nodes at least so as to confirm their positions. The ranging method has been discussed in section 3.2.

Step 4. Sensing nodes updating their own coordinates based on the measured distances and the sink nodes coordinates. Assuming a sensing node and its four neighbour sink nodes are denoted as N (x, y, z), A(x_1, y_1, z_1), B(x_2, y_2, z_2), C(x_3, y_3, z_3), D(x_4, y_4, z_4), and the distances between N and A, B, C, D are denoted as d1, d2, d3, d4 respectively. The coordinates system is shown as Fig.3.

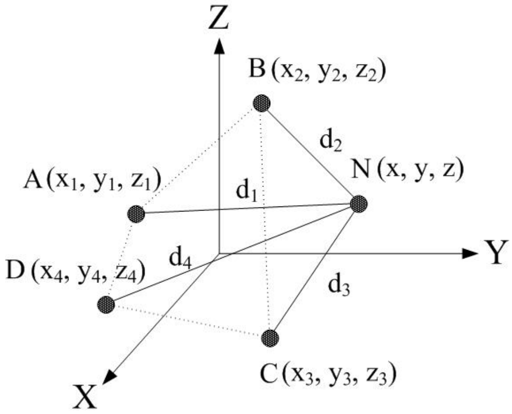

Fig.3 3-D coordinates with sink nodes and estimated node

According to fig.3, the following expressions can be derived

$$\begin{aligned} d_1^2 &= (x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 \\ d_2^2 &= (x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 \\ d_3^2 &= (x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 \\ d_4^2 &= (x-x_4)^2 + (y-y_4)^2 + (z-z_4)^2 \end{aligned} \qquad (2)$$

With the condition of A, B, C, D not in a plane, the above Equations will have unique solutions, which are expressed below.

$$\begin{pmatrix}x\\y\\z\end{pmatrix}=\frac{1}{2}\times\begin{pmatrix}x_2-x_1 & y_2-y_1 & z_2-z_1\\ x_3-x_1 & y_3-y_1 & z_3-z_1\\ x_4-x_1 & y_4-y_1 & z_4-z_1\end{pmatrix}^{-1} \tag{3}$$

$$\times\begin{pmatrix} d_1^2-d_2^2-[(x_1^2-x_2^2)+(y_1^2-y_2^2)+(z_1^2-z_2^2)]\\ d_1^2-d_3^2-[(x_1^2-x_3^2)+(y_1^2-y_3^2)+(z_1^2-z_3^2)]\\ d_1^2-d_4^2-[(x_1^2-x_4^2)+(y_1^2-y_4^2)+(z_1^2-z_4^2)]\end{pmatrix}$$

Taking the coordinates of A, B, C, D and the distances information into the above expressions, and the coordinates of N will be derived.

4. EXPERIMENTS AND DISCUSSION

The node we implemented is shown in Fig.4.

Fig.4 Picture of the node

According to fig.4, the implementation of each module will be discussed in detail as follows.

XR2206 and XR2211 are used as FSK modulator and demodulator, and the carrier frequency can be adjusted from 10KHz to 300KHz for matching different transmitters. Power amplifier is the driver between FSK modulator and transmitter, and the factor of the power amplifier can be adjusted by a variable resistor so as to keep trade-off between communication range and multi-channel interferes. XR2211 has inner AGC (Automatic Gain Control) circuit and can modulate signals from 3mV to 3V, which helps to increase communication reliability.

On the basis of a series of transmitter experiments, the results and analysis show that T/R40 can work well in shallow water when working at 32KHz.

The realization of power management consists of the schedule generation of power enables and working status, the design of high efficiency power suppliers. Two 3.7V Li batteries in series are chosen as the node power supply. In the power circuit design, some high efficiency voltage regulators with enable functions are used to provide +5V voltage and each power enable is controlled by the microcontroller. In acoustic transmitting module, a DC-DC module is used to generate +12V and -12V voltages for driving the transmitter to increase the acoustic signal strength.

ATMega128 is chosen as the microcontroller of the node, which is a high performance and low power MCU with abundant peripheral interfaces, such as SPI, SCI, ADC.

According to the above design, all the components of the node are inexpensive, which totally cost about 49$ (listed in detail in table.1), while the normal commercial underwater modem costs more than 20,000$, which can transmit 1.5km.

Table.1 Cost list of each item

Item	Cost ($)
Electronic components	30
Transducers	4
Packaging (waterproof casing and underwater connectors)	15
Total	49

The effective communicating range of the node is about 30m, which will be discussed in section 4.1.1. For the research of a dense UWSN, the low-cost smart modes would be organized to build a suitable experimental platform for monitoring the underwater environments.

There are 4 statuses for the node, including transmitting status, listening status, sensing status, idle status. Power consumption of each status is listed in table.2. The sensing power consumption is blank because it is related to the selected working sensors installed on the node.

Table 2 Power consumption list

Status	Power consumed (mW)
Transmitting	516
Listening	300
Sensing	-----
Idle	55

Some experiments on the node have been done recently, including underwater acoustic communication performance, ranging precision, relative localization.

4.1 Acoustic Communication Experiments

There are 3 important characteristics for acoustic communication, which are effective range, missing rate, baud rate. For finding the best compounding among them, we did some experiments on these characteristics in Zizhuyuan lake of Beijing.

According to some outdoor experiments in the lake, we concluded that 256bps baud rate is fit for our UWSN in 30m with the missing rate less than 20%. The results of missing rate along with the range are listed in table 3.

Table 3 Effective communicating range and missing rate

Range (m)	Transmitting Packets	Receiving Packets	Missing Rate
1.2	100	100	0%
2.4	100	99	1%
3.2	100	96	4%
4.8	100	93	7%
7.2	100	95	5%
9.6	100	94	6%
14.4	100	91	9%
21.6	100	88	12%
32	100	82	18%

From the above table, we can see that the maxim communicating range can reach 30 m, which can satisfy the research of UWSN well.

4.2 Relative localization experiments

Just for examining localization method, there are not too many differences between underwater environment and air environment. Therefore, we did some localization experiments in air.

4.2.1 Distance measurement experiment

According to the ranging method discussed in section 3.2, we did some experiments in air. The ranging results are listed in table.4.

Table 4 Ranging experiments in air

Distance (cm)	Estimate Distance(cm)	Error Percentage
0.5	0.48	4%
1.0	1.01	1%
1.5	1.46	3%
2.0	1.94	3%
2.5	2.41	4%
3.0	3.08	3%
3.5	3.70	6%
4.0	4.19	5%
4.5	4.65	3%

What make distance errors can be concluded as the following with respect to the node design and experiment method.

- Phase errors from demodulating. SNR (Signal to Noise Rate) of receiving signal determines the phase locked time, which directly effects the ranging timer.
- Experiment environment influence. For example, some underwater roadblocks can reflect the acoustic signal, which will bring multi-channel interferes for ranging nodes.
- Acoustic travelling speed estimated error. Acoustic speed is related with many characteristics of environment. And we used 340m/s to estimate the distance.

4.2.2 Localization method experiment

An experiment was designed to examine the relative localization method presented in section 3.3. Indoor experiment scene is shown in fig.5. Sink nodes are denoted as A, B, C, D, and the estimated node is denoted as N. The corresponding 3-D coordinates system is shown in fig.6.

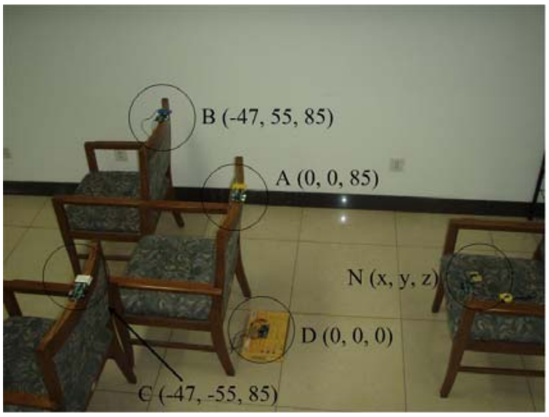

Fig.5 Indoor localization scene

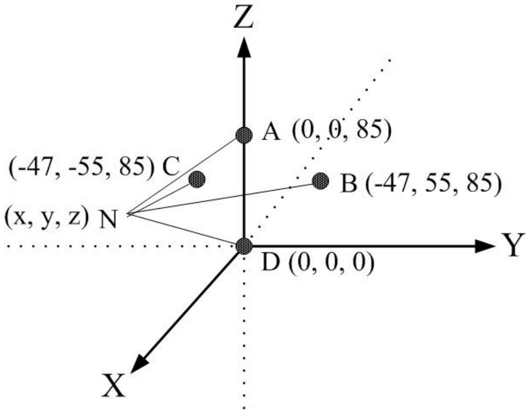

Fig.6 Indoor localization 3-D Coordinates

Step.1 Localizing sink nodes (A, B, C, D) at appointed stations with the condition that the estimated node N can communicate with them simultaneously, just as shown in fig.5, and the corresponding 3-D coordinates system is shown in fig.6. The 3-D coordinates of sink nodes are set respectively as A (0, 0, 85), B (-47, 55, 85), C (-47, -55, 85), D (0, 0, 0).

Step.2 Node N ranging with sink nodes (A, B, C, D). The estimated distances are listed in table.5.

Table 5 Ranging results with sink nodes (cm)

No.	N-A	N-B	N-C	N-D
1	101	162	153	103
2	103	158	155	103
3	101	155	156	105
4	105	155	158	101
5	99	157	154	105

Step.3 Calculating coordinates of N. Taking the estimated distances and sink nodes coordinates into equations 3, we can get the coordinates of N, which are listed in talbe.6.

Table 6 Coordinates results in 3-D coordinates (cm)

No.	X	Y	Z
1	99.9	-12.8	44.9
2	92.0	-4.3	42.5
3	93.0	1.4	47.3
4	87.6	4.3	37.7
5	97.3	-4.2	49.7

Estimated coordinates can be obtained from averaging (x, y, z) coordinates separately listed in table.6, and comparing results with real coordinates are shown in table.7.

Table 7 Comparing between real coordinates and estimated coordinates (cm)

	X	Y	Z
Real Coordinates	94	0	43
Estimated Coordinates	94	-3.12	44.4

In table 7, there are some errors for coordinates, and the reasons can be concluded as follows.

- Accumulative errors from the equation 3. In the deriving process from equations 2 to equations 3, there are some rounding errors, and after such errors are accumulated, it will affect the result largely.
- Original measuring error, such as ranging error, sink coordinates error. When the reference sink coordinates remains little errors, the result will be affected largely.

How to decrease the accumulative error has been done much in the research of GPS positioning systems, and some technologies of increasing localizing precision may be modified and employed for the underwater localization.

5. CONCLUSIONS

In this paper, a low-cost underwater sensor node with acoustic communication is designed and realized for the dense UWSN research. In order to reduce the cost and power consumption of a node in a dense UWSN, hardware modulation and demodulation are selected and used in the architecture of an underwater sensor node. And the range measurement, relative localization based on acoustic communication are given, which do help the further research in UWSN. The sensor nodes are realized and several experiments based on these nodes are carried out. The experimental results show the nodes are capable to meet the basic requirements of UWSN research. In the future work, the efficiency of ranging should be improved, and some UWSN link layer and network layer protocols should be done more research based on the node.

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