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Development of Autonomous and Active Monitoring Fish Robots for Water Pollution Using GPS and Ubiquitous Sensor Networks

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Abstract: - We introduce and develop an autonomous monitoring system for water pollution that searches the sources of water pollution and makes measurements of relevant data using a fish robot. Fish robots search actively by themselves and monitor various areas in a real-time mode using GPS receivers, ubiquitous sensor networks and directional sensors. A fish robot has three microcontrollers which provide full functions, for example, motor operations for the sw Localization imming of a fish robot, analog sensor data acquisition including temperature and infrared distance sensors, decoding GPS information, counting the time of sonar in ultrasound sensors and a directional sensor, collecting information of water pollution measurement sensors from Vernier Labpro, and communications. A fish robot swims autonomously in predefined areas and collects the water pollution indexes. Collected information by a fish robot is sent to data collecting nodes by USN motes and Bluetooth, and the data are accessible on the Internet by Ethernet devices.

Key-Words: - Fish Robot, Water Pollution, Autonomous Tracking System, Active monitoring

1 Introduction

Recently, some robotic devices have been developed to investigate and assess aquatic biological systems and their locomotion mechanisms for better performance by the influence of biomimetics [1, 2]. Fish in nature move their bodies to make propulsive power. Also, it is well-known that fish achieve excellent efficiency and maneuverability that has the advantage over conventional propeller based marine vehicles [3, 4].

The conventional methods of water pollution monitoring collect data by sensors attached on fixed posts. More posts are necessary for large areas. Besides, there are many kinds of locations which are dangerous or have limited accessibility. We introduced fish robots in water pollution monitoring tasks to overcome these problems. Fish robots have a fundamental advantage of mobility over the conventional fixed monitoring posts. Since fish robots can swim while collecting pollution measurements, it is possible to track directions that have higher pollutant densities to collect data or water samples at the suspected spots in real time modes. Practically this kind of real time active monitoring method is important in investigation and protection of environmental problems.

In this paper, development of an autonomous active water pollution monitoring in large areas by fish robots is proposed. The basic positional information for navigation is obtained by GPS receivers. The direction data for path planning is calculated using the GPS data. Other than distance sensor data that are necessary to make minor direction changes for obstacle recognition and collision avoidance, the simple GPS data are basic for the autonomous movements of fish robots. In cases when more accurate positional data are necessary, we introduce a sonar localization method using Ubiquitous Sensor Network (USN) for water pollution monitoring fish robots. In experiments, a fish robot has four sonar sensors: one is for the transmitter and receiver of ultrasonic sound and the others are for only receivers of ultrasonic sound. One active sonar sensor is used to find obstacles and avoid them. The others are used to calculate the exact localization information using the ubiquitous sensor network system. Many USN motes are installed at specific points that are uniformly distributed along the boundary of a given area to be monitored.

It is important for fish robots to navigate in a given area uniformly without missing areas or repetitive movements in the same tracks for water pollution monitoring. Thus the navigation problem is quite similar to that of cleaning robots and autonomous lawn mowers. Another related application can be found in the navigation of harvesting tractors for a given large field. Agricultural yield maps[8] which are crop data for given areas provide basic information for better harvest of the following year. Therefore, similar navigation methods can be applied to obtain yield maps by harvesting tractors.

Three microcontrollers are used for a fish robot to reduce calculation loads for the functions of motor operations for swimming, analog sensor data acquisition including temperature and infrared distance sensors, decoding GPS information, counting the time of sonar in ultrasound sensors and directional sensor, collecting information of water pollution measurement sensors from Vernier Labpro, and communications. Collected information from a fish robot is sent to data collecting nodes by USN motes and Bluetooth, and the data are transmitted to a server once per second.

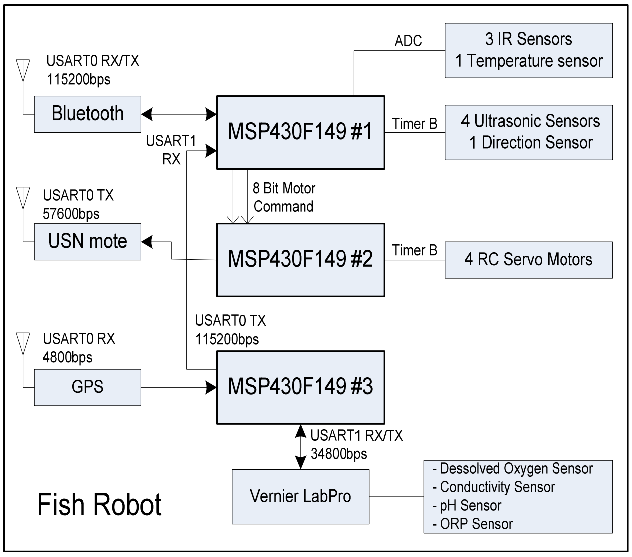
Fish robots with improved functions for autonomous real time water pollution monitoring are described in section 2. The required autonomous localization method is given in section 3. Experiments and the analysis of the active monitoring results are explained in section 4 and the conclusion is given in section 5.

2 Fish robots

We have constructed several types of fish-shaped underwater robots and improved in their functions in our lab. The robots with various structures and shapes of real fish imitate the way real fish swim. For instance, four servo motors are used at the caudal fin of the robot for propulsion and horizontal direction control. The fish robot in this paper is improved to get positional information from a GPS receiver, to operate between USN motes for sonar localization, and to collect water pollution indexes from Vernier LabPro sensor tips with a conductivity sensor, DO (Dissolved Oxide) sensor, pH sensor, and ORP (Oxidation Reduction Potential) sensor in real-time.

The indexes of water pollution used in the experiments are DO (Dissolved Oxide), pH, Conductivity, and ORP (Oxidation Reduction Potential) in a real-time mode. These four kinds of sensors are important for water pollution indexes. In addition, they are low cost and easy to operate in experiments.

(a) A fish robot



(b) Block diagram of a fish robot

Fig. 1 Underwater Fish-shape robot

A fish robot has three microcontrollers, MSP430f140 by TI, to reduce the load of processing data. The main microcontroller in Figure 1 reads data from several sensors: 1) reading three IR sensors and one temperature sensor through ADC ports, 2) measuring the time of flight of the ultrasound produced by sonar sensors, 3) reading directional sensor to obtain directional information, and 4) communicating with a server using bidirectional Bluetooth modules to send commands or to get various data. The second microcontroller operates four RC servo motors by producing independent PWM signals to generate necessary swim patterns. This microcontroller is also connected to a USN mote for sonar localization to get more precise positional information compared with the GPS-based method in specific and small areas. The third microcontroller receives positional information from the GPS module and communicates with the Vernier LabPro sensor board which has connections with four different sensor tips. All data of a fish robot are gathered in the main microcontroller where proper motor control actions for navigation and commands for sensor data acquisition and communication are produced. The main microcontroller sends the GPS information and pollutant sensor data to a server by Bluetooth modules. The server relays the information on the Internet by Ethernet modules. Therefore, any user can access all information on the Internet whenever the data are required. Figure 2 shows the sensor configuration on a fish robot. All commands for the motor manipulations are transmitted from the first microcontroller to the second microcontroller.

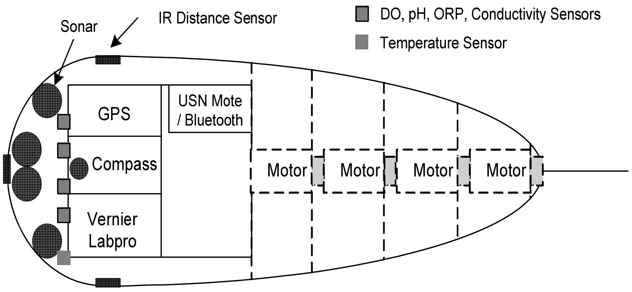


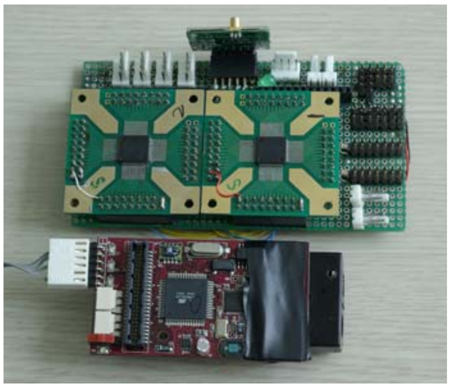
Fig. 2 Sensor configuration on a fish robot

The infrared distance sensors, regardless of obstacle colors, sizes and approaching angles, are generally used to measure distances between a robot and obstacles. Because the detectable ranges of the IR sensors are very short and narrow, while the ranges of sonar sensors are long and wide, two different types of sensors make up for each other. Moreover, when the sizes of obstacles are small or narrow, sonar sensors often miss the detection of obstacles.

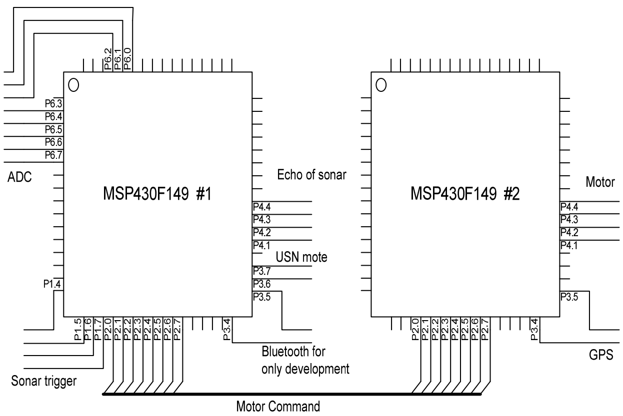
Since obstacle detection and avoidance is the most important function of mobile robots whether they are wheel based or not, lots of previous studies have presented a variety of methods and applications[5-7] for this matter. More detailed specifications of a fish robot are shown in Table 1.

Table 1. Specifications of a fish robot

Item	Specification
Length	78cm
Width	21cm
Height	19cm
Weight	4950g
Length of tail fin	43cm
Maximum angle of tail fin	90°
Minimum rotation radius	42cm
Maximum speed	61cm/sec
Maximum torque of motors	7.4Kg cm at 6V
Angular speed of motors	300°/sec



(a) Microcontroller and peripheral devices



(b) Microcontroller interface circuits

Fig. 3 Microcontroller circuits for a fish robot

Most of the electronic devices including a microcontroller MSP430f149, an electronic compass, and one USN mote, and two battery sets are installed in a 210*150*90mm sized aluminum box with a cover for waterproof. One GPS receiver, three IR sensors, and four ultrasonic sensors with circuits are mounted outside of the box. The microcontroller circuits for a fish robot are shown in Figure 3.

Motor command control words to generate propulsion power and direction changes for fish robots are composed of 8 bits as below.

BIT 7: Operation Control Bit
- 0: Motor stop
- 1: Motor run

BIT 6: Mode Control Bit
- 0: Normal swim
- 1: Quick turn

BIT 5: Direction Control Bit
- 0: Left direction
- 1: right direction

BIT 0 to 4: Direction Information Bits (32 steps)
- Case ‘Normal swim’ – 0° to 31° direction changes
- Case ‘Quick turn’ – 30° to 180° direction changes

The lower flexible body of a fish robot composes a tail fin. The tail fin is made of four servo motors with mechanical connections. Each servo motor is covered with a wrinkle rubber tube and they can move independently.

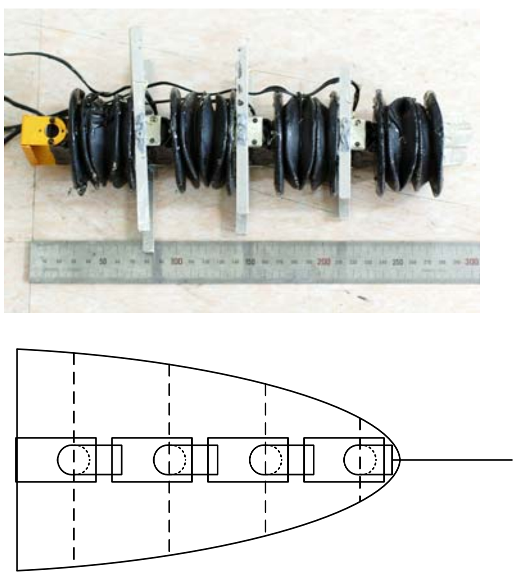


Fig. 4 Lower body and caudal fin of a fish robot

Elaborate movement of four servo motors makes a fish robot swim smoothly and naturally. All control commands of these servo motors are made in a microcontroller MSP430f149. The structure of a lower body and the caudal fin of a fish robot are shown in Figure 4.

3 Autonomous localization

The overall schematic diagram of the proposed dynamic water pollution monitoring system by an autonomous fish robot is described in Figure 5. The position data, which are basic for this monitoring system, are obtained mainly by a GPS receiver on the fish robot. Since water pollution monitoring routines are done without exception in large open areas, the GPS information is the first choice considering cost and easiness.

The **GGA sentence format of the GPS NMEA 0183 format is as follows:

$GGA,hhmmss.ss,llll.ll,a,yyyyy.yy, a,x,xx,x.x,x.x,M,x.x,M,x.x,xxxx*hh**

where each field is separated by a comma. $ represents the beginning of a sentence, **hhmmss.ss** represents hours, minutes and seconds in the coordinated universal time(UTC), **llll.ll** represents latitude coordinates with north or south when **a** is N or S, **yyyyy.yy** represents longitude coordinates with east or west when **a** is E or W, and the remaining **x**’s represent GPS quality indicators that verify stable operations of a receiver. In this paper, only the portions of time, latitude, longitude and GPS quality indicators out of full sentences are used.

The method based on sonar localization is used when more accurate data than those of GPS are required. Much smaller positional errors are required when fish robots are moving in narrow areas or when they are dealing with collision avoidance of possible obstacles.

Obstacle avoidance for a fish robot is essential for successful performance in water. The fish robot uses three IR sensors for short distance obstacles and a sonar sensor for long range obstacles. A basic set of positional patterns of a fish robot relative to simplified obstacles and the corresponding operations of a fish robot for natural swimming and collision avoidance are described in [7].

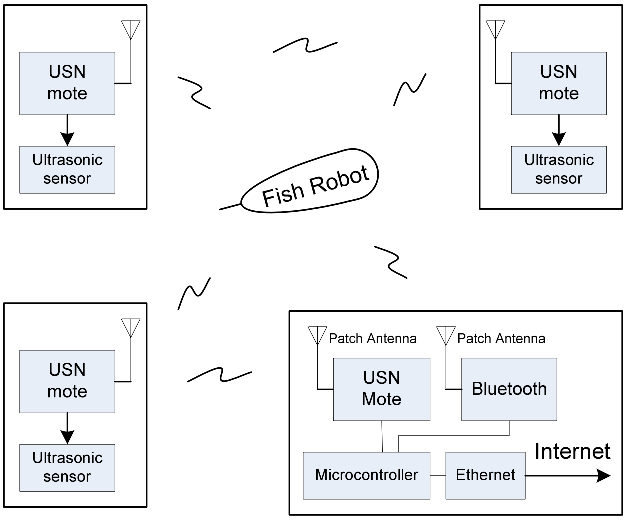


Fig. 5 Water pollution monitoring system

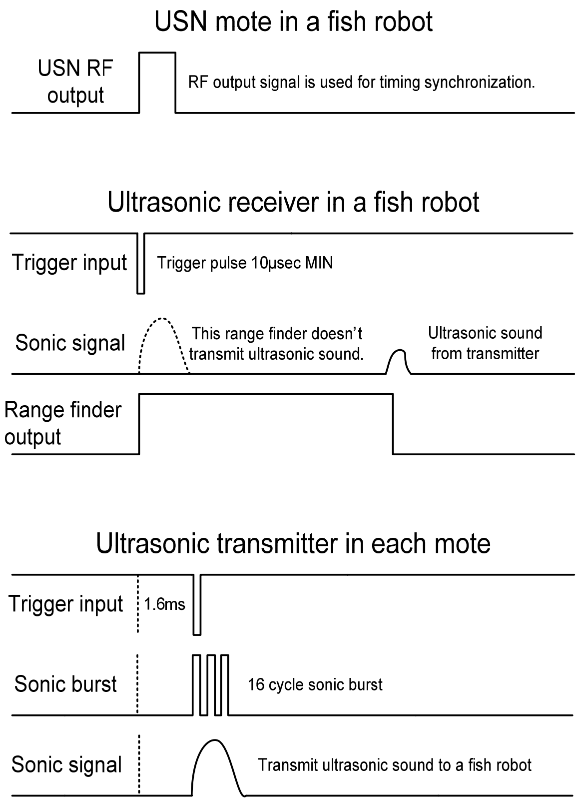


Fig. 6 Operation diagram of ultrasonic sensor systems

The sonar system is composed of one transmitter/receiver and three receivers. The overall system includes several USN motes with the sonar transmitter. One transmitter and receiver set and one receiver are attached in the front of the head. Two receivers are attached in the front sides. This sonar system has two purposes: one is for obstacle detection by reflected echoes from the transmitter/receiver and the other is for localization computation by USN sonar system.

Fig. 7 Sonar sensors

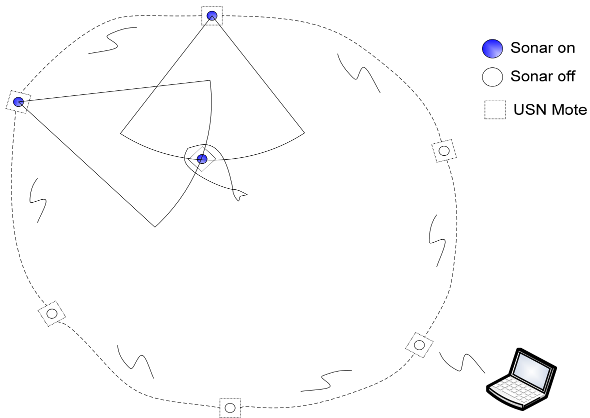


Fig. 8 Detailed localization of a fish robot

The detailed localization method is shown in Figure 8. The fish robot has the exact position information of each mote with a sonar transmitter. Furthermore, a fish robot knows rough position information from the GPS receiver and directional information from an electronic compass. The SiRF Star II serial type GPS receiver is used in our experiments. The robot requests its internal sonar sensor to transmit signals to nearby motes so that it can receive ultrasonic acknowledgement signals from at least two motes. After receiving ultrasonic signals from the two motes, distances from the fish robot to each mote are calculated and then the exact positional information is determined. All data from the fish robot are sent to the server system using USN through a series of motes.

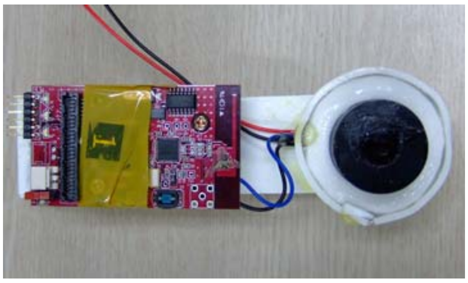


Fig. 9 Mote with Sonar for localization

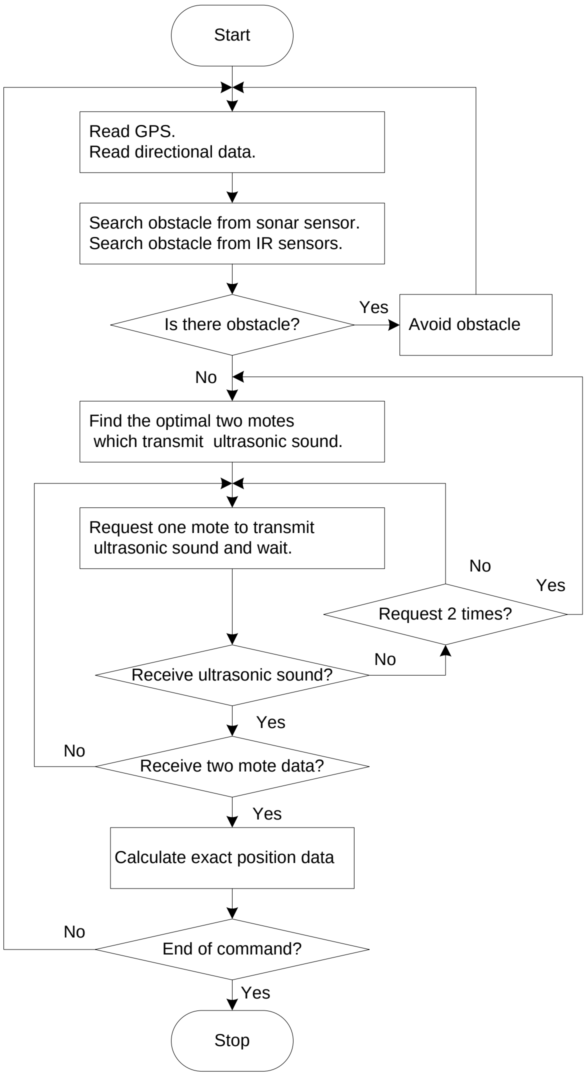


Fig. 10 Flow chart for localization procedures

Information which is obtained from the two sonar sensors is enough to calculate the exact positional information, because a fish robot swims near the surface of the water and knows GPS information. A mote with a sonar sensor which transmits ultrasonic sound is shown in Figure 9. We use Zigbex by Hanback Electronics (www.hanback.com) for Ubiquitous Sensor Networks.

The localization flow chart is shown in Figure 10. After a fish robot reads GPS and directional data, it must search obstacles using the sonar sensor and IR sensors. When it detects obstacles, a fish robot changes its path to avoid obstacles [6, 9]. When there is no obstacle, it finds the two optimal motes which transmit ultrasonic sound for localization from the GPS data and directional data. First, a fish robot requests one mote to transmit ultrasonic sound, and wait until it receives the sound. After receiving the sound, it requests the other mote to transmit the sound. Unless it receives the ultrasonic sound in one second, a fish robot makes a request again. When it doesn't receive ultrasonic sound two times successively from the same mote, it must find another mote to get the signal.

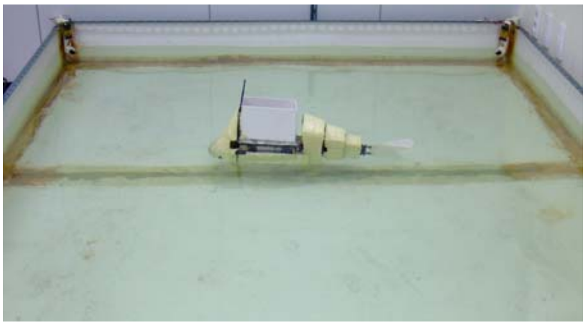
The microcontroller operates the timer immediately after transferring the command string to request transmission of sonar system until a fish robot receives an acknowledgement sound. We consider both the processing time of 11 characters at the baud rate 57,600 bps and time for transferring commands in a microcontroller to calculate the distance. The processing time after transmitting the command is about 1.9msec.

The robot requests its internal sonar sensor to transmit signals to nearby motes so that it can receive ultrasonic acknowledgement signals from at least two motes. After receiving ultrasonic signals from the two motes, distances from the fish robot to each mote and the exact positional information of itself are calculated.

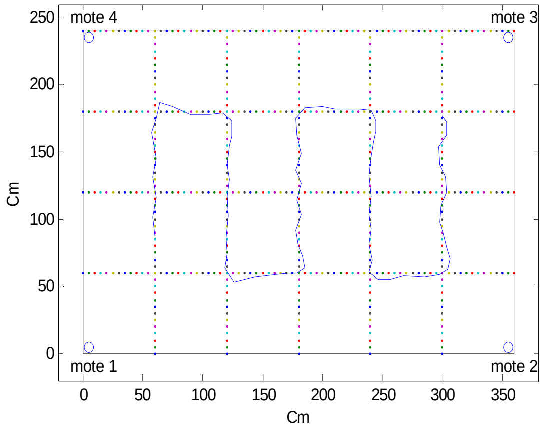
4 Autonomous monitoring

A virtual grid of 40cm*40cm over the pool which has the dimension of 3.6*2.4*0.35m is arranged. The objective of this experiment is to check the performance of the sonar localization method.

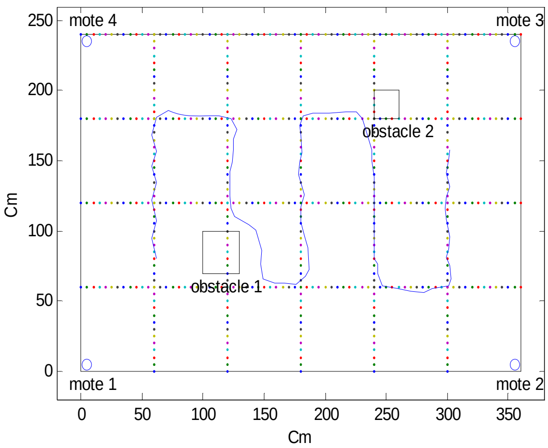
It is very difficult for a fish robot to know the exact positional information in water or in the air. Furthermore, there is no small and cheap localization system available underwater except big or extremely expensive devices. In this experiment, we implemented more precise localization system using USN with sonar sensors. Figure 11 shows a fish robot operating inside a pool and the results of passage. One fish robot with a USN mote and sonar sensors swims in the pool, where there are four USN motes with a sonar sensor attached to each mote. The GPS data is not used in this experiment because of the small sizes of the pool. The mean value of absolute position errors in Figure 11 is 2.3cm and the standard deviation is 1.6cm.



(a) Fish robot in a pool



(b) Tracks of 60cm apart with four USN motes



(c) In case of (b) with two obstacles

Fig. 11 Tracks of a fish robot in a pool

(a) Monitoring fish robot

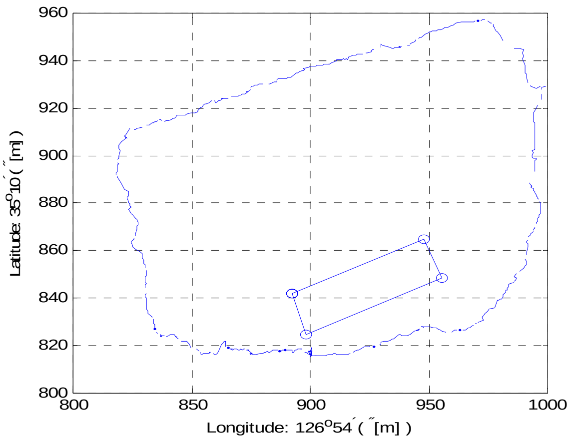
(b) A large pond on campus

(c) A reservoir near campus

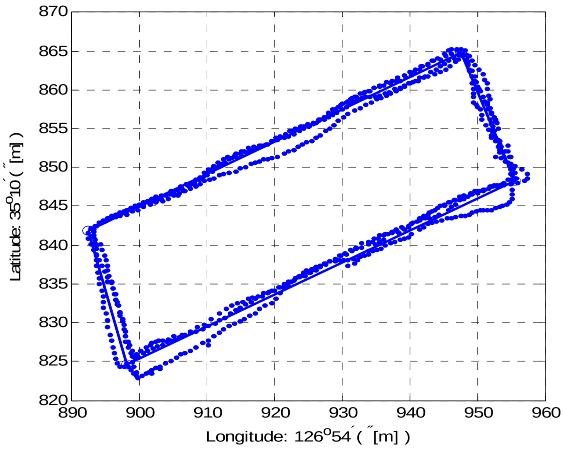
Fig. 12 Test beds for pollution monitoring

Figure 12 shows a monitoring fish robot and two test beds, one large pond on campus and one reservoir near campus.

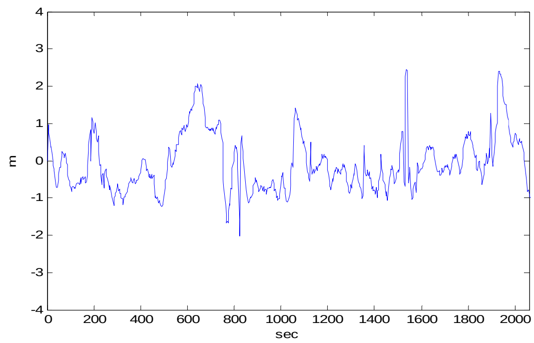
The conventional methods of water pollution monitoring collect data by sensors attached on fixed posts. The proposed method, however, relies on fish robots that have a fundamental advantage of mobility over the conventional fixed monitoring posts. Since fish robots can swim anywhere while collecting pollution measurements, it is possible to track directions that have higher pollutant densities in real time modes. Practically this kind of real time dynamic monitoring method is very important in the investigation and protection of environmental problems.



(a) GPS map of a pond on campus



(b) Tracks of GPS data



(c) Errors of received GPS data

Fig. 13 Trajectory of a fish robot

Since the ideal paths of a monitoring robot are required to be uniform without missing areas or repetitive movements in the same tracks for given areas, the navigation problem is quite similar to that of cleaning robots and autonomous lawn mowers. Another similar application can be found in the navigation of harvesting tractors for given large fields. Agricultural yield maps[8] which are crop data for given areas provide basic information for better harvest of the following years. Similar navigation methods can be applied to obtain yield maps by harvesting tractors.

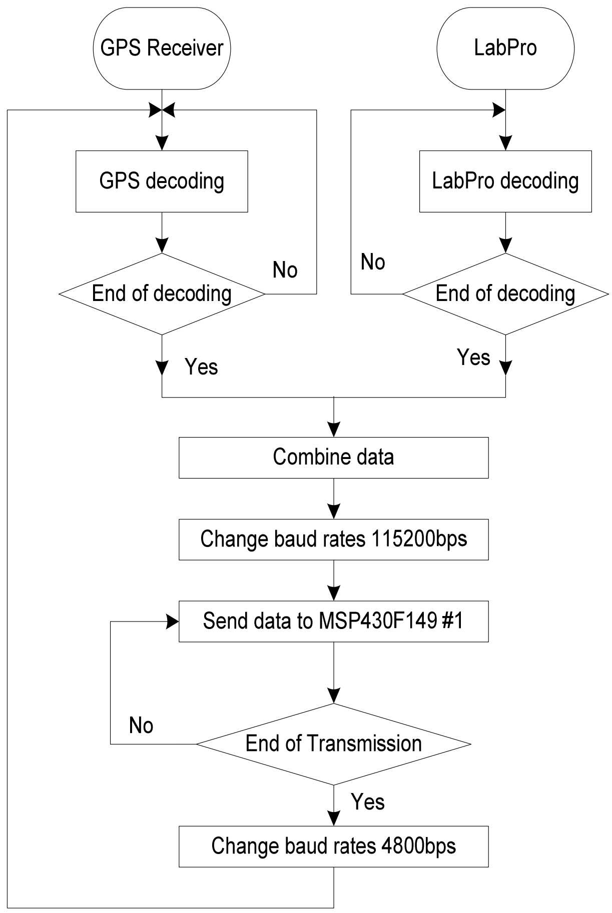


Fig. 14 Flow structure of decoding and interface of GPS and sensor data

A rectangular region is chosen at a pond on campus for a test bed of GPS data as shown in Figure 13(a). The effectiveness of the GPS data for large areas such as pollution monitoring is tested by the repetitive tracking of the same route. Figure 13(b) shows the three tracks that are made of the GPS data received by the monitoring robot. The maximum positional error is about 5 meters between different circulations and the standard deviation of the positional errors is 0.83 m.

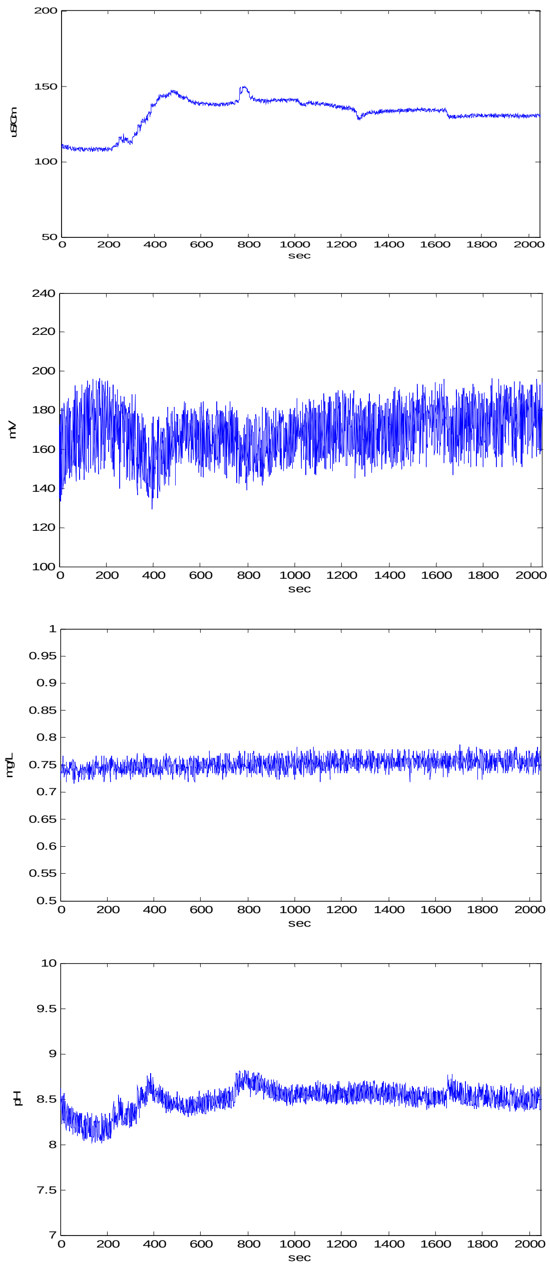


Fig. 15 Measurements of Vernier LabPro sensors (Conductivity, ORP, DO and pH, respectively)

The microcontroller receives positional data from the GPS module and communicates with the Vernier LabPro sensor board which has connections with four different sensor tips. The whole process for decoding and interface of GPS and sensor data is shown in Fig. 14.

The microcontroller decodes data portion for time, latitude, longitude, and GPS quality indicator from GPS data sentences, and receives and decodes sensor information from Vernier LabPro. The GPS module has a very low data transmission speed of 4,800bps and LabPro has 34,800bps baud rates. After the third microcontroller gathers all information from the GPS receiver and LabPro, the microcontroller changes the baud rates to 115,200bps and sends all information to the main microcontroller. Then it changes the rates to 4,800bps back to receive the next GPS and sensor data.

A fish robot collects the water pollution indexes while swimming autonomously in predefined areas or in remote controlled modes. Collected information by a fish robot is sent to data collecting nodes by USN motes and Bluetooth, and the data are accessible on the Internet by Ethernet devices.

The most important indexes of water pollution are BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand). But it takes much time to get the exact values of these indexes. Instead of these two indexes, we can get other indexes for water pollution, for example, DO (Dissolved Oxide), pH, Conductivity, and ORP (Oxidation Reduction Potential) in a real-time mode. These four kinds of sensors are important for water pollution indexes. In addition, they are low cost and easy to operate in experiments.

Figure 15 shows a typical example of measured water pollution indexes by a fish robot monitoring system at a given area. A Vernier LabPro sensor board on a fish robot with conductivity, ORP, DO and pH sensors are used for the measurements as described in Fig. 1(b).

5 Conclusions

Development of an autonomous and active water pollution monitoring system that searches the sources of water pollution and makes measurements of relevant data using a fish robot is presented. A fish robot searches and monitors various areas using GPS receivers, USN and detection sensors. Several functions including motor operations for the swimming of a fish robot, detection sensor data acquisition, decoding GPS information, counting the time of sonar, collecting information of water pollution measurement sensors from Vernier Labpro, and transmission of data to a server are managed by a control board on a robot. Collected information by a fish robot is sent to data collecting nodes by USN motes and Bluetooth, and the data are accessible ubiquitously on the Internet by Ethernet devices.

Fish robots have a fundamental advantage of mobility over the conventional fixed monitoring posts. Since fish robots can swim while collecting pollution measurements, it is possible to track directions that have higher pollutant densities in real time modes. Practically the real time active monitoring method is very important in the investigation and protection of environmental problems.

Acknowledgements
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