Artificial Lateral Line Systems: a Research Review

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Abstract: This paper presents a review of research on artificial lateral line system (ALLS) in recent years. We first sum up the structural characteristics and the sensing principles of fish lateral line system (FLLS) in nature. Several flow sensors based on the proposed bionic principle are described. Using these flow sensors, we introduce some researches that how people structure the ALLS to get the hydrodynamic features in the aquatic environment. Finally, we point out the difficulties in the research on ALLS and look forward its excellent application prospect. Copyright © 2013 IFSA.

Keywords: Sensor, Artificial lateral line system, Flow measurement, Robot.

1. Introduction

It is still a problem to deal with underwater imaging because of the hindrances such as water’s selective absorption of light, the suspended solids on water and light refraction. In addition, there is no light can be used for underwater imaging in dark night or deep sea area, which leads to the part or whole loss of biological vision. Nevertheless, how fish and other underwater creatures can normally live in this environment and accomplish a variety of underwater activities, which attracts much attention from researchers. So the fish lateral line system (FLLS) was found. The FLLS is a unique sense organ of fish and amphibians, helping to detect hydrodynamic information around. FLLS enables fish to accomplish a variety of underwater activities, such as localization of moving prey detection and capture [1-3], detection of stationary objects, obstacles avoiding, schooling [4], rheotaxis [5] and social communication [6-8]. The study of FLLS began in the 17th century when Stenonis [9] did research for subdermal canals along the lateral lines. Thereafter researchers started a detailed study on the nerve constitution and function structure of FLLS [10-12]. For example, the FLLS is comprised of superficial and canal neuromasts, and both of them may contribute to fish-screen detection and avoidance. Also it is shown that fish can detect the direction of flow and face towards the oncoming current [13], which is known as the rheotaxis behaviour.

With the development of robot technology and the continuous advancement of robot intelligent, people begin to pay their attention to underwater technology and underwater robot. The first
biomimetic robotic fish of the world — RoboTuna [13] was manufactured by MIT in 1994. The birth of RoboTuna created a new direction of underwater robotic research, which has an important significance on later robotic fish research. After that, more and more robotic fish with different styles and different functions have been manufactured. However, the early robotic fish can only achieve the swimming mechanism, and can’t sense and monitor the surrounding environment for none of sensors being equipped. Hence, based on the research of fish lateral line system and robot technology, people expect to design a biomimetic artificial lateral line system (ALLS) for robotic fish to sense the surrounding environmental information and make prompt reaction on the hydrodynamic change. But it is not easy to mimic fish to design ALLS. There are many problems, such as information perception, mechanical design, layout, installation, modeling and control. To solve the above problem, the scientific researcher focuses on how to use the lateral line theory to invent artificial lateral line system.

In this paper, we first elaborate the mechanism characteristics and the sensing principle of fish lateral line system in Section 2. And then we introduce the foreign biomimetic researches on flow sensors in Section 3. The flow sensors were invented to sense the flow characteristics, and the flow sensors array was constituted as an ALLS to get the hydrodynamic features in Section 4. These researches have made great breakthroughs, opening up a new path for underwater environment perception. Finally we present the difficulties and problems in the researches of ALLS, and look forward its excellent application prospect.

2. The Structure and Characteristics of the FLLS

Fish is endowed with superior sensory intelligence. FLLS found in fish are sensitive, and it can act in a noisy environment with a wide dynamic range. The biology research of FLLS is the basis of the bionics and the design of ALLS. FLLS is comprised of superficial and canal neuromasts, both of the neuromasts feel the stimulation of water through the sensory nerve cells. Due to the different of location distribution, the morphology and the amount of sensory nerve cells, they have different functions [14].

As shown in Fig. 1 [15], the superficial neuromasts of fish senses the external fluid and responds to the direct-current and low-frequency components of the flow, which is sensitive to displacement and equivalent to the displacement sensor. The basic sensory element of the superficial neuromasts is the hair cell, that is to say, an elongated epithelial cell with a ciliary bundle located at the apical meristem that is consisted of numerous stereocilia and a single eccentrically placed kinocilium. When relative motion occurs between the surface of the water and fish, the hair cells on the surface will incline. It results in the nerve impulses of the neurons under the hair cells: Hair cell is excitatory when the displacement of the hair bundle in the direction of the kinocilium, Hair cell is inhibitory when the displacement in the opposite direction [15]. These nerve impulses are transmitted to the brain nerve center from the nerve endings, and thus the fish feel the flow. Fig. 1 shows the Schematic diagram of a hair cell.

Canal neuromasts situated in subdermal canals along the lateral lines is equivalent to the pressure gradient sensor. It usually open to the environment through a series of small pores, respond to the high-frequency components, react proportionally to the net acceleration and is sensitive to pressure gradient. The subdermal canals are filled with mucous, which through a number of pores communicate with the outside water environment [16]. The schematic diagram of a superficial neuromast is show in Fig. 2. When there is a velocity gradient between adjacent pores, a pressure difference is generated. At the same time, the pressure difference generated promotes the mucous moving, which causes the canal neuromasts excitatory. These nerve impulses are transmitted to the brain nerve center from the nerve endings, and thus the fish feel the pressure gradient. Moreover, the canal neuromasts also can feel the oscillation of the underwater object in still or running water.

Based on the biological functions and feature of the lateral line system, the researchers begin to design and develop the ALLS, and variety of micro-flow sensor is designed to sense the action of water. The sensing system of ALLS is based on the sensors to detect the water motion. Two kinds of sensors used to form the basic sensing element of ALLS are haircell sensor and pressure sensor. The haircell sensor mimics the theory of the superficial neuromast to sense the direction and displacement of the flow. And the pressure sensor mimics the theory of the canal neuromast to sense the pressure gradient of the flow. The multiple sensors arrays constitute ALLS to mimic the fish lateral line system.
3. The Characterization and Situation of Hair Cell Sensor

Fish can feel the flow by the neuromasts’ excitatory, and then transmit the excitatory by electric current, which is a biological processes integrating mechanical and electric effect together. While most sensors share a common mechanical transfer functions: they turn force/displacement signals into electronic pulses. Combined with fish superficial neuromasts sensing characteristics, researchers design numerous flow sensors to sense the flow. Here we post the situation about the research of these sensors.

Most haircell sensor consists of an inplane silicon cantilever beam with a vertical artificial cilium attached at the distal, show as Fig. 3. Doped silicon strain gauges are located at the base of the cantilever. When the relative motion occurs between the flow and the cilium, an impact force generates along the direction of the flow, which creates a bending moment on the cilium. And then the torque introduces a longitudinal strain that can be detected by the piezoresistors at the base. So it feels the flow. The history of peoples’ using sensors is not long, but the developing of sensors is very fast and all kinds of sensors are used it almost everywhere, including underwater.

Yoshihiro Ozaki reported an air flow sensor which is modeled on windreceptor hairs of insects, shown as Fig. 4. It detects low velocity air flow by measuring the force on a sensory hair [17]. Two different appearance designs of mechanical structures were composed of cantilevers and strain gauges.

Tests were made to perform the characterization and a flow rate sensitivity of 2 mm/s had been demonstrated. The sensors above are based on biological inspiration and have the characteristics of small size and high precision. In addition, they have the ability of flow sensing, which can obtain the information of the velocity and the direction of the flow. While using for underwater, the most important thing we should concern about is water proof. Small size of the sensor makes it more difficult to do the water-tightness well. Moreover, the flow changed with fast frequency, there is a higher requirement that the respond of the sensors should be fast, to meet the real time information collection.
4. ALLS for Underwater Sensing

ALLS provides a new way of perception to sense the flow characteristic, making the underwater robot owns perception capability so that they can sense like fish. Recent years, more and more researches about ALLS are proposed for location and hydrodynamic study. Y. C. Yang [20] developed an ALLS by using biomimetic neuromasts sensor array to test localization capability. In his research, biomimetic neuromasts sensors were constituted an ALLS wrapped around a cylinder in Fig. 7. A cylinder was employed to imitate the fish body with outer diameter 89 mm. 15 biomimetic neuromasts sensors were wrapped around the cylinder, among which 9 were along the axis with linear spacing of 30 mm, and others were along the cross section with angular spacing of 30°. Tests were made in a pool with water. A dipole source was employed as a vibration. In the course of the dipole source underwater approaching the cylinder, the vibration features were sensed by the ALLS. A beamforming algorithm was used for processing data. The result showed the capability of his ALLS for location. In his researches, the localization capability of the ALLS was employed to examine by a dipole source, even a natural tail-flicking crayfish. And the probable position can be located. While in his system, there was a deviation as large as 27 mm in some orientation and the real time capability was not very well with a response time of 10 s. It can be improved so that is more effective maybe.

Xiaobo Tan [21] proposed an ALLS consisting of arrays of the inherent sensing capability of ionic polymermetal composites (IPMC) using for the localization of a dipole source. The ALLS equipment is shown as Fig. 8. A prototype comprising six millimeter-scale IPMC sensors, is constructed, with a body length of 10 cm. With a maximum localization
error of 0.3 cm, the IPMC-based lateral line can localize the dipole source 1-2 body lengths away. Differing from existing studies mostly focused on the localization of a fixed underwater vibrating sphere, his later research examined the problem of tracking a moving dipole source using an ALLS [22]. It is an efficient method for his research to localize the dipole source with a high precision. However the equipment is just composed by a sample aligned sensors array, it is more biomimetic that adjust the distribution of sensors array to the positions of neuromasts on the fish skin surface along the fish lateral line. In addition, the equipment in the research only senses the flow passively for its stationary position. More improvements should be made to apply this system in engineering.

Paolo Fiorini presented the equipment shown as Fig.9 that took local measurements using a rigid body with laterally distributed parallel pressure sensor arrays to study uniform flows and Karman vortex streets [23]. The difference between uniform flows and Karman vortex streets can be discriminated and the hydrodynamic features, such as vortex shedding frequency, vortex travelling speed and downstream distance between vortices and the wavelength, can be computed. In his experiment, an ALLS was consisted of 20 pressure sensors which were linearly distributed parallel along the two sides of a platform. The sensors were not interconnected and every sensor had a separate compartment with a corresponding hole. The experiments were carried out in a flow channel and the flow direction was parallel to the axis of the platform. In his research the several hydrodynamic features were took measure in different scenarios. It is significant to do such a work and is a big breakthrough of study method in underwater flow measurement. Nevertheless, to get these hydrodynamic features, prohibitively many sensors pressure sensors were required in his equipment, increasing the costs. And more sensors produced large amounts of data, increasing the difficulty of data processing. Also the hydrodynamic features got by his equipment can be used for underwater robot control, which is an application in engineering.

In the meantime, it is amazing to hear that Maarja Kruusmaa did researches on an ALLS formed by pressure sensors array using in an underwater vehicles for detecting hydrodynamic regimens and for controlling the robot’s motion with respect to the flow [24]. The robot fish in Fig. 10 contains the pressure sensors array in head. It is the first time to use ALLS in robotic fish to sense the hydrodynamic features. By the information obtained from ALLS, a PID controller was designed to the robotic fish to implement station holding in a steady stream and in the wake of a bluff object. The swimming performance was evaluated in holding station experiment, with a standard deviation that the downstream position is 40.5 mm and that of the lateral position is 12.7 mm. This is a significant breakthrough in the using of ALLS. Also, more advanced progress should be made so that the robot can sense like fish.

5. The Problem to Be Solved about ALLS

To sum up, though a significant progress has been made in the design of the sensor and the formation of the lateral line system, there is a big gap between
ALLS and fish lateral line system, and the stability, accuracy of the ALLS need to be further guaranteed. To design a more powerful ALLS, realize the flow sensing function of robotic fish, there are some problems to be overcome.

1) The distribution of ALLS is along the axis of the cylinder. There is not much theoretical support to distribute like that. During the long evolutionary history, the creature gains a precise body structure, and the distribution of superficial neuromasts locates in a perfect position for hydrodynamic features sensing. The distribution of ALLS should be based on bionics principles so that can take advantage of biological adaptation to the environment.

2) The ALLS mentioned is not complete mimic the fish lateral line. The ALLS sense surrounding hydrodynamic features like the use of superficial neuromasts of fish, which realize only a part of the function of fish lateral line. More powerful ALLS need to be designed including superficial neuromasts sensing and canal neuromasts sensing to obtain the displacement information and pressure gradient information.

3) Multi-sensor information fusion is an intensive research topic in the field of mobile robot. So enormous the quantity of the data obtained by the multi-sensor of ALLS that we need to propose an effective algorithm to process data. So the ALLS does its work for abstracting the useful information to control the robot.

In addition to these problems, some technical problems still exist in ALLS, such as information collection and transmission, sensor waterproofing, power supply and so on. The particularity of the work environment also caused some problems on material of the ALLS. How to solve these problems, improving stability and reliability of ALLS, is a key point of the development of ALLS.

6. Conclusions

To sum up, the ALLS has been more common. With the continuous development of material science, bionics, control theory, mechanical design and manufacture, low-cost and low-power computer, the ALLS will develop steadily and fast, and its perception ability will be more and more powerful. By applying the ALLS to the underwater robot, the underwater robot will develop toward a higher autonomization and intelligentization, and have a similar perception ability of a real fish, which is beneficial to the military, rescue, navigation, and environmental monitoring. It is sure that the ALLS will have broader development and application prospect in the near future.

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