J. Marine. Sci. Appl. (2008) 7:122-126
DOI: 10.1007/s11804-008-7055-3

Optical fiber based slide tactile sensor for underwater robots

TAN Ding-zhong* (谭定忠), **WANG Qi-ming** (王启明), **SONG Rui-han** (宋瑞晗), **YAO Xin** (姚 昕), **GU Yi-hua** (顾义华)

College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin 150001, China

Abstract: In the underwater environment, many visual sensors don't work, and many sensors which work well for robots working in space or on land can not be used underwater. Therefore, an optical fiber slide tactile sensor was designed based on the inner modulation mechanism of optical fibers. The principles and structure of the sensor are explained in detail. Its static and dynamic characteristics were analyzed theoretically and then simulated. A dynamic characteristic model was built and the simulation made using the GA based neural network. In order to improve sensor response, the recognition model of the sensor was designed based on the 'inverse solution' principle of neural networks, increasing the control precision and the sensitivity of the manipulator.

Keywords: underwater robot; manipulator; tactile sensor; optical fiber
CLC number: TP242.6+1 **Document code:** A **Article ID:** 1671-9433(2008)02-0122-05

1 Introduction

For robots, most of the information is obtained from visual sensors and tactile sensors (including slide tactile sensor). The visibility in the seawater of China is very low except Nanhai. Even in the water of high visibility, the water will be turbid and the visibility will become very low when the robot is working. At present the tactile sensors, especially the slide tactile sensors have become the most important in application[1,2]. Most robot sensors used in space or on the land can not be used in the water, so the flexibility and intelligence of underwater robot are not high compared with the robot working in other environment[3, 4] . The optical fiber sensor technology has advanced greatly since 1977 when American Navy began to carry out the FOSS project[5, 6]. Because optical fiber has many advantages such as anti-electromagnetic, anticorrosive, flame-proof, high-sensitivity, etc., it has been studied by scientists in many countries and been used widely in the fields of measuring magnetism, electricity, sonar, optical, pressure, temperature, speed, etc. In 1980, J. N. Field and J. H. Colc developed the principle of micro-bending optical fiber sensor firstly[7], because of its advantages of simple in structure, cheap, and maneuverability. The micro-bending optical fiber sensor has drawn much attention of people up to now.

2 Design of slide tactile sensor

2.1 The principle, structure, and character of micro-bending optical fiber sensor

Put a multi-mode optical fiber between two teeth which have fixed wavelength. The curve of optical fiber caused by displacement of the deform-tooth causes the coupling between the propagating modes, and the propagating modes in the core of the optical fiber turn into radiating modes, or cause the loss of optical strength when

$$\beta - \beta' = \pm \frac{2\pi}{\Lambda}, \quad (1)$$

where β and β' are propagation constants of the propagating modes, and Λ is the wavelength of deform-tooth.

The propagation constant is defined by Eq.(2)

$$\Delta\beta = \beta_{m+1} - \beta_m = \left(\frac{\alpha}{\alpha+2}\right)^{\frac{1}{2}} \frac{2\sqrt{\Delta}}{a}\left(\frac{m}{M}\right)^{\frac{\alpha-2}{\alpha+2}}, \quad (2)$$

where m is the ordinal number of the modes, M is the total number of these modes, α is the radius of the core, β is the refraction power distribution exponent of the core, and $\Delta\beta$ is the relative refracting power difference between core and cladding.

For the gradient type optical fiber, α=2, so

Received date: 2007-06-06.
***Corresponding author Email:** robot_sensor@126.com

$$\Delta\beta = \frac{(2\Delta)^{\frac{1}{2}}}{a}. \quad (3)$$

Eq.(3) indicates that for the gradient type optical fiber, $\Delta\beta$ has no relation to the ordinal number of the mode. In the space of β, the distance between modes is equal, if one mode turns into another, every mode will turn into the next mode, so as to reach the optimum coupling between modes. For the gradient type of optical fiber, the optimum wavelength of deform-tooth can be calculated from Eqs. (1), (3):

$$\Lambda = \frac{2\pi a}{(2\Delta)^{\frac{1}{2}}}. \quad (4)$$

To design the micro-bending type optical fiber sensor, the following points must be noticed[10, 11]:

1) The power loss caused by micro-bending is in direct proportion to the fourth power of the radius of the core. When the radius of the core increases, the power loss caused by the micro-bending will increase a lot, and the coupling between LED and optical fiber becomes easy for realization too.

2) The power loss caused by the micro-bending is in inverse proportion to the second power of the relative refracting power difference between the core and the cladding, that is to say, it is better to decrease the value of numerical aperture, which can increase not only the power loss but also the band width of the optical fiber.

It is demonstrated that the shape of deform-tooth has little relation to the sensitivity of the sensor, but sharp tooth may damage the fiber.

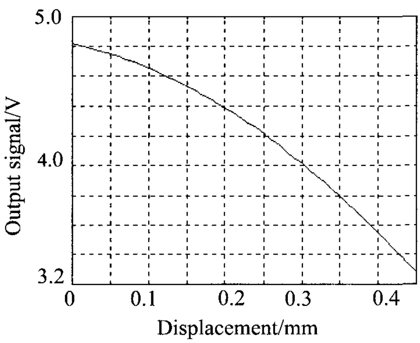


Fig.1 Curve of output signal change with the bending displacement of optical fiber

The static characteristic of micro-bending optical fiber sensor is shown in Fig.1. The relation between the bending displacement and the output signal is calculated as Eq.(5).

$$P = -4.339x^2 - 1.4663x + 4.8464. \quad (5)$$

Eq.(5) is the mathematic model of the micro-bending sensor, and the design for slide tactile sensor will be based on Eq.(5). Derived from Eq.(5), the sensitivity of the micro-bending sensor can be obtained as Eq.(6)

$$\frac{dP}{dx} = -8.678x - 1.4663. \quad (6)$$

It can be seen from Fig.1 and Eq.(6) that the sensitivity is low when the fiber is deformed a little due to deform of the cladding before the core. The little deform only causes very little leak out of the modes.

2.2 The structure and the static character of slide tactile sensor

The output power of optical fiber corresponds with the displacement of the deformation one to one, so in the structure shown in Fig.2, the angle displacement of the roller can be obtained according to the output power, the change of the output power, and the parameter of cam. Mount the structure on the manipulator as shown in Fig.2, the robot can sense the slide tactile, the distance sliding, and the time used.

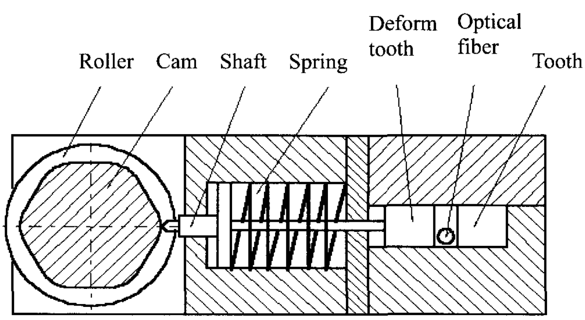


Fig.2 Structure of the slide tactile sensor

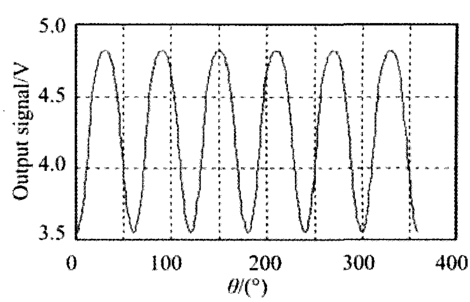


Fig.3 Static character of the slide tactile sensor in theory

The static character of the slide tactile sensor in theory is shown in Fig.3, the value of the sensor's output signal with roller angle displacement in theory is shown in Table 1, and the curve of the sensor's output signal with roller angle displacement in experiment is shown in Fig.4. The error between the experimental and theoretical values of the output signal of the optical fiber's slide tactile sensor is shown in Table 2.

Table 1 Value of the sensor's output signal with roller angle displacement in theory

θ/(°)	Voltage/V	θ/(°)	Voltage/V	θ/(°)	Voltage /V
0	3.5677	20	4.6734	40	4.6734
1	3.5722	21	4.7057	41	4.6332
2	3.5856	22	4.7314	42	4.5839
3	3.6078	23	4.7517	43	4.5239
4	3.6385	24	4.7674	44	4.4512
5	3.6774	25	4.7794	45	4.3721
6	3.7241	26	4.7884	46	4.2913
7	3.7779	27	4.7948	47	4.21
8	3.8383	28	4.7991	48	4.1296
9	3.9045	29	4.8015	49	4.0511
10	3.9758	30	4.8023	50	3.9758
11	4.0511	31	4.8015	51	3.9045
12	4.1296	32	4.7991	52	3.8383
13	4.21	33	4.7948	53	3.7779
14	4.2913	34	4.7884	54	3.7241
15	4.3721	35	4.7794	55	3.6774
16	4.4512	36	4.7674	56	3.6385
17	4.5239	37	4.7517	57	3.6078
18	4.5839	38	4.7314	58	3.5856
19	4.6332	39	4.7507	59	3.5722

Table 2 Error between the experimental and theoretical values of the output signal of the optical fiber's slide tactile sensor

θ/(°)	Error/V	θ/(°)	Error/V
0	-0.0166	30	-0.0152
3	0.0145	33	-0.0125
6	-0.03	36	0.0159
9	-0.0374	39	0.0128
12	-0.0262	42	-0.0133
15	-0.0371	45	0.0134
18	0.0188	48	-0.0198
21	0.0154	51	0.0143
24	0.0257	54	-0.0292
27	0.0195	57	0.0129

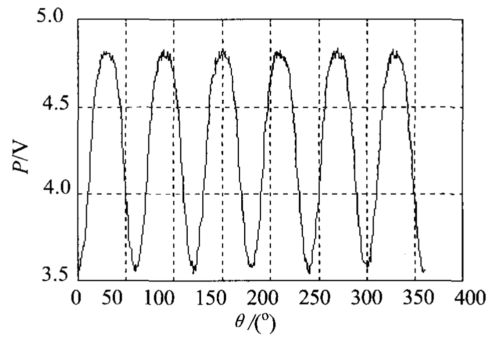
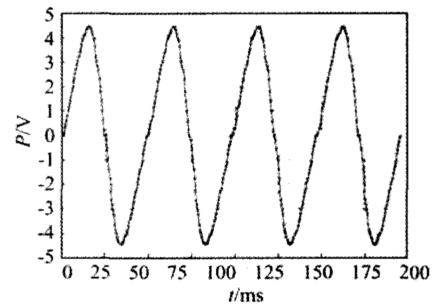
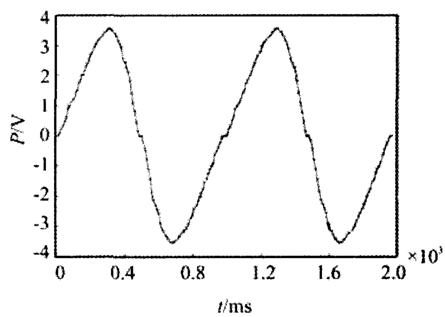


Fig.4 Curve of the sensor's output signal with roller angle displacement in experiment

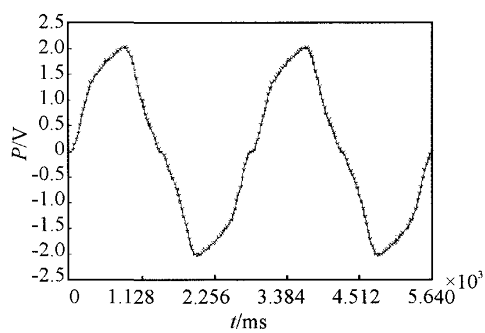
3 Ddynamic model and inverse solution model based on neural network



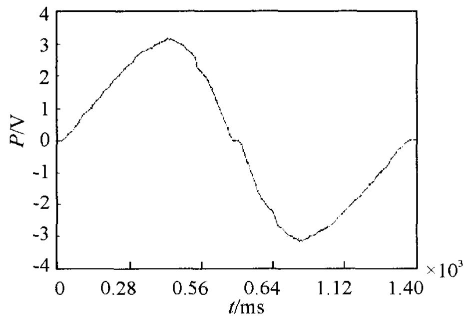
(a) Output signal of the sensor when the object's slide speed is 0.16 m/s



(b) Output signal of the sensor when the object's slide speed is 8 mm/s



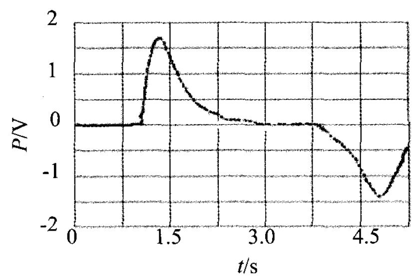
(c) Output signal of the sensor when the object's slide speed is 2.60 mm/s



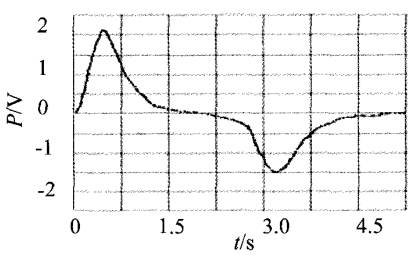
(d) Output signal of the sensor when the object's slide speed is 5.3 mm/s

Fig.5 Output signal of the sensor when the object slides at different speeds

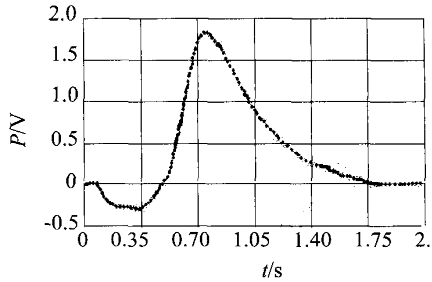
The strength type optical fiber sensor is disturbed by environment, drift and noise as other sensors. Nowadays, in order to obtain high precision and stability, the most common method is to put up a reference channel to compensate the error caused by disturbance, but it is not easy to realize it in practical engineering. Slide tactile is dynamic signal, so the sensor element and the signal process circuit are coupled by electric capacity, which can not only eliminate the error caused by low-frequency noise such as cross sensitivity, draft, etc., but also increase the sensor's sensitivity. The dynamic character of the slide tactile sensor shown in Fig.5 is the output signal of the sensor when the object slides at different speeds. The output signal of the sensor when grasping different objects is shown in Fig.6.



(a) Output signal of the sensor when the object's mass is 1 kg, grasping force is 9.8 N



(b) Output signal of the sensor when the object's mass is 1.75kg, grasping force is 19.6 N



(c) Output signal of the sensor when the object's mass is 4 kg, grasping force is 68.6 N

Fig.6 Output signal of the sensor when grasping different objects

Drive the object sliding with fixed speed on the surface of the manipulator on which the slide tactile sensor is mounted, the output character of the sensor at this sliding speed is obtained; drive the object sliding with different speeds, the output character at different sliding speeds is obtained. Because of the nonlinear parts, the sensor is a nonlinear system, and its dynamic character model can't be built by classical theory. Neural network is a new intelligent theory which is widely used in the fields of information process, automatic control, optimum seeking, failure examine, system recognition etc., it has advantages in solving problems of nonlinear, undetermined and undefined systems. The most commonly used neural network is BP network, and BP algorithm is one of the gradient decline algorithms. The seeking direction of the two kinds of substitution in neighbor is perpendicularly crossing, that is to say, the substitution of gradient decline algorithm always changes its direction when drawing close to the minimum value, so the converging speed is low. Because of its nonlinear optimum seeking, usually the minimum value, its sought is only partial, not wholly. GA (Genetic Algorithm) has the advantages such as optimum seeking on the whole, processing the information with high speed, automatic adaptability, and automatically acquiring knowledge etc., and can solve the above two problems. In this paper, the dynamic character model of the sensor is built by a four-layer neural network of $N_{2,4,2,1}$, the two input variables are angle of roller (θ) and sliding speed, the output is the output signal of the sensor according to the input. the 'inverse solution' model is built by a four-layer neural network of $N_{2,16,6,1}$, the two input variables are two sampling points in the vicinity in fixed sampling cycle, and the output is the sliding speed determined by the input. Fig.7 is the structure of BP neural network's inverse model.

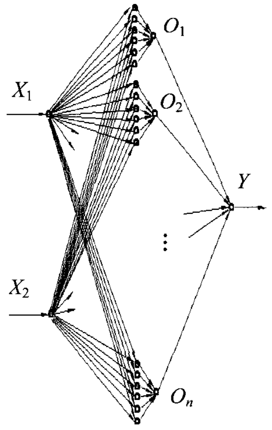


Fig.7 Structure of BP neural network's inverse model

4 Conclusions

The optical fiber's slide tactile sensor is simple in structure, cheap, reliable, and maneuverable. It can be used in the robot working underwater, and in space or on the land as well. It is mounted on the underwater working hydraulic manipulator in the lab nowadays because of its special signal processing circuit and intelligent algorithm, and the control precision and sensitivity of the manipulator are therefore increased.

References

[1] LIU Ruifu, SHI Jinshan. Optical fiber sensor with application[M]. Beijing: Mechanical Industry Press, 1987: 110-113.

[2] XU Lina. Neural network control[M]. Harbin: Harbin Institute of Technology Press, 1999: 88-124.

[3] UMETANI Yoji. A review on advanced robotics[J]. Proceedings of International Symposium on Advanced Robot Technology, 1991, 3(1): 12-15.

[4] WEISBIN C B, BURKS B L, EINSTEIN J R. HERMIES-III: A step toward autonomous mobility, manipulation and perception[C]// Proceedings of the NASA Conference on Space Telerobotics. Pasadena, CA. 1989: 233-245.

[5] BATTAZZ G. Hierarchical architecture for robotics experiments with multiple sensors[C]// Proc of IEEE 5th ICAR. Arlington, Virginia, 2004: 43-48.

[6] NUNES U, FAIA P, ARAUJO R. Development and control issues in contact and proximity sensing for a robotic system[C]// USA Proc of IEEE International Workshop on Intelligent Robots and Systems. Cambridge, USA, 1991: 1357-1362.

[7] TREVELYAN J. *Simplifying* robotics: a challenge for research[J]. Robotics and Autonomous Systems, 1997, (9): 207-220.

[8] SILV C W, de. Intelligent control of robotic systems with application in industrial processes[J]. Robotics Autonomous System, 1997(17): 221-237.

[9] UOLD E. An overview of fiber-optic sensor[J]. Rev Sci Instrum, 1995, 166(8): 4015-4030.

[10] WANG Anbo, MILLER M S. Slip-spectrum intensity based optical fiber sensor for measurement of micro-displacement[J]. Strain and Pressure Applied Optical, 1996, 155(3): 2595-2601.

[11] LE Wei, LIAO Yanbiao, ZHANG Zhipeng. Guided wave optical sensors: Theory and technique[M]. Beijing: Sciences Press, 1998(in Chinese).

TAN Ding-zhong was born in 1970. He is a professor at Harbin Engineering University. His current research interest is robot technology.

Optical fiber based slide tactile sensor for underwater robots

作者： TAN Ding-zhong， WANG Qi-ming， SONG Rui-han， YAO Xin， GU Yi-hua
作者单位： College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin 150001, China
刊名： 船舶与海洋工程学报
英文刊名： JOURNAL OF MARINE SCIENCE AND APPLICATION
年，卷(期)： 2008，7(2)

参考文献(11条)

1. LIU Ruifu.SHI Jinshan Optical fiber sensor with application 1987

2. XU Lina Neural network control 1999

3. UMETANI Yoji A review on advanced robotics 1991(01)

4. WEISBIN C B.BURKS B L.EINSTEIN J R HERMIES-III:A step toward autonomous mobility,manipulation and perception 1989

5. BATTAZZ G Hierarchical architecture for robotics experiments with multiple sensors 2004

6. NUNES U.FAIA P.ARAUJO R Development and control issues in contact and proximity sensing for a robotic system 1991

7. TREVELYAN J Simplifying robotics:a challenge for research 1997(09)

8. SILV C W,de Intelligent control of robotic systems with application in industrial processes 1997(17)

9. UOLD E An overview of fiber-optic sensor 1995(08)

10. WANG Anbo.MILLER M S Slip-spectrum intensity based optical fiber sensor for measurement of micro-displacement 1996(03)

11. LE Wei.LIAO Yanbiao.ZHANG Zhipeng Guided wave optical sensors:Theory and technique 1998

相似文献(10条)

by means of controlling the position of the counterweight using the optimal servo system. In addition trajectory control of the manipulator can be carried out by using DCC which regards the reaction force due to the movement of the counterweight as a disturbance.

4.外文会议 Norimitsu Sakagami.Manabu Inoue.Takeshi Yoshizaki.Sadao Kawamura Analysis of Dynamics for An Underwater Robot Manipulators

In the water, the additional forces and moments called added mass, hydrodynamic damping and buoyancy act on the manipulator in addition to mechanical dynamics. It is generally difficult to estimate the dynamics of manipulator in the water, because these forces and moments have complicated behaviour. First, we classify situation of hydrodynamic damping. Next, under assumptions we try to analyze the dynamics of a manimpuletor in the water.

5.外文会议 Kawamura. S..Sakagami. N. Analysis on dynamics of underwater robot manipulators based on iterative learning control and time-scale transformation

A new method to analyze the dynamics of underwater robot manipulators is proposed in this paper. In the proposed method, hydrodynamic terms such as added mass, drag and buoyancy in dynamics of underwater robots are obtained by iterative learning control and time-scale transformation. The advantage of the proposed method is not to use parameter estimation of the dynamics. In this paper, we explain that the proposed method can be applied to hardware design, motion control and motion planning of underwater robots. Moreover, the experimental results using a 1-DOF and a 3-DOF manipulator demonstrate the effectiveness of the proposed method.

6.外文期刊 Lee M..Choi HS. A robust neural controller for underwater robot manipulators

This paper presents a robust control scheme using a multilayer neural network with the error backpropagation learning algorithm. The multilayer neural network acts as a compensator of the conventional sliding mode controller to improve the control performance when initial assumptions of uncertainty bounds of system parameters are not valid. The proposed controller is applied to control a robot manipulator operating under the sea which has large uncertainties such as the buoyancy, the drag force, wave effects, currents, and the added mass/moment of inertia. Computer simulation results show that the proposed control scheme gives an effective path way to cope with those unexpected large uncertainties. [References: 23]

7.外文会议 Shojiro Ishibashi.Masanori Ito.Etsuro Shimizu Autonomous Motion Planning for a Manipulator Equipped on AUV in a Workspace Divided into Cubes

In this paper, an approach for the autonomous motion planning for an underwater manipulator is proposed. An aim of this approach is to decide tip positions of the manipulator and manipulator's postures in the water. Therefore this approach is composed of the tip position planning and the posture planning. And in order to execute each planning, a workspace of a manipulator is divided into cubes. In the tip position planning, a cube is selected as an objective tip position from among twenty-six cubes in the workspace. And in the posture planning, manipulator's postures are evaluated using the positional relation between the manipulator and obstacle domains defined by some cubes, so that a secure manipulator's posture to avoid obstacle is decided. And owing to executing each planning repetitively, the whole manipulator's motion is planned. In this paper, the validity of the proposed approach is shown in experimental results.

8.外文会议 Shojiro Ishibashi.Masanori Ito.Etsuro Shimizu Autonomous Motion Planning for a Manipulator Equipped on AUV in a Workspace Divided into Cubes

In this paper, an approach for the autonomous motion planning for an underwater manipulator is proposed. An aim of this approach is to decide tip positions of the manipulator and manipulator's postures in the water. Therefore this approach is composed of the tip position planning and the posture planning. And in order to execute each planning, a workspace of a manipulator is divided into cubes. In the tip position planning, a cube is selected as an objective tip position from among twenty-six cubes in the workspace. And in the posture planning, manipulator's postures are evaluated using the positional relation between the manipulator and obstacle domains defined by some cubes, so that a secure manipulator's posture to avoid obstacle is decided. And owing to executing each planning repetitively, the whole manipulator's motion is planned. In this paper, the validity of the proposed approach is shown in experimental results.

9.外文会议 Ping Zhang.Tanaka. K..Shimizu. E..Ito. M. A teleoperating system for underwater manipulator with virtual model aid

This paper explores the use of virtual reality technology to help visualize the remote environment and control the remote underwater robot indirectly. Also an online parameter prediction system is developed to cope with the time delay. The paper consists of two parts: (I) the development of improved virtual model based teleoperating system, and (II) an investigation into the feasibility of the predictor performance. The experimental system is an Internet-based teleoperating system for an underwater 7-axis manipulator. The task of this project is a time-limited task. That is to retrieve and catch a moving target in the water through the tele-operating system.

10.外文会议 Norimitsu Sakagami.Manabu Inoue.Sadao Kawamura Theoretical and Experimental Studies on Iterative Learning Control for Underwater Robots

On underwater robot manipulators, high speed and high precision are basic requirements in order to improve efficiency of operations. To satisfy these requirements, feedforward control inputs are crucial. For making feedforward inputs, one method is to estimate all parameters of the robot dynamics including hydrodynamic terms such as added-mass, drag force, and buoyancy. However, the parameter estimation of hydrodynamic coefficients is not suitable for forming the feedforward control inputs of underwater robot manipulators because it is difficult to model and estimate the hydrodynamic terms. To overcome such a difficulty, we apply iterative learning control to underwater robots. In this paper, we theoretically and experimentally investigate the performance of iterative learning control for underwater robot manipulators. The effectiveness of iterative learning control is demonstrated through several experimental results.