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Fuzzy Distance Estimation for a Fish Robot

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Abstract

We designed and implemented fish robots for various purposes such as autonomous navigation, maneuverability control, posture balancing and improvement of quick turns in a tank of 120 X 120 X 180cm size. Typically, fish robots have 30-50 X 15-25 X 10-20cm dimensions; length, width and height, respectively. It is essential to have the ability of quick and smooth turning to avoid collision with obstacles or walls of the water pool at a close distance. Infrared distance sensors are used to detect obstacles, magneto-resistive sensors are used to read direction information, and a two-axis accelerometer is mounted to compensate output of direction sensors. Because of the swing action of its head due to the tail fin movement, the outputs of an infrared distance sensor contain a huge amount of noise around true distances. With the information from accelerometers and e-compass, much improved distance data can be obtained by fuzzy logic based estimation. Successful swimming and smooth turns without collision demonstrated the effectiveness of the distance estimation.

Key Words : Fish robot, Fuzzy estimation, Distance sensor, Accelerometers, Direction sensor

1. Introduction

Fish robots have various shapes of real fish and try to imitate the swimming patterns of fish. The fish robot in this paper has three motors for a caudal fin. All three motors in the caudal fin have the same patterns in motion except some phase delay and amplitude. An optimal selection of phase delay makes smooth and natural swimming of the fish robot. The selection of the values depends on the mechanical characteristics. The caudal fin makes periodic swing of its body when a fish robot cruises in a water pool. To change direction, a fish robot uses two different modes. We call these two modes slow turns and quick turns[1]. When a fish robot turns into any direction quickly, the body of a fish robot will be inclined to the left or right side. Furthermore, while a fish robot is swimming, there is a continuous wave of water due to the reflection of water in a small pool.

We use a magneto-resistive sensor to find the direction of a fish robot. This magneto-resistive sensor is very sensitive to inclination. It is necessary to compensate the sensor output to get accurate direction information. Though there are huge amount of noises in distance data due to swing action of a tail fin, the proposed algorithm based on fuzzy logic eliminates them to produce improved data.

The fish robot swims in a confined area of 117 X 80cm which is about the half of the tank. The length of a fish robot is 49cm including a caudal fin. In fact, it is very difficult to swim for a 49cm length fish robot in a small pool considering the turning radius of a fish robot. Therefore the fish robot would meet the walls frequently and it needs an efficient and optimal turning method to make a good trajectory in a small pool. The fish robot demonstrated successful swims for difficult trajectories without collision with walls of the tank.

2. Fish Robots and Sensors

2.1 Fish Robot

Fish-like underwater robots have been designed and developed in our lab. A fish robot for this paper has three servo motors that are used for the caudal fin: for propulsion and horizontal direction control. Two other servo motors are used at pectoral fins, each one at the side for vertical direction control. Two magnetic sensors are installed on a microcontroller card to measure direction information of a fish robot. But these magnetic sensors are very sensitive to the inclination of the sensor. This high sensitivity results in misreading of the sensor data and bad performances in direction control. To solve this problem, a MEMS-type acceleration sensor is installed to measure the posture of the fish robot and to compensate the inclination of the fish robot due to rapid turns and periodic swings[3,4]. All signals are processed based on the MSP430F149 by TI. Also, user commands and sensor data are transmitted between a fish robot and a host notebook PC either by Bluetooth modules of class 1 or by an RF module depending on the operation depth. Figure 1 shows the fish robot and schematics.

2.2 Swim

A real fish turns skillfully using not only its caudal fin but also pectoral or ventral fins. But we assumed a simple structure of the fish robot, which turns only with the swings of the caudal fin. As the caudal fin is used for propulsion and

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turning, the fish robot has a simple structure. In this case, we can think that there are two turning modes, called slow turn and quick turn. A real fish swings its caudal fin to one side slowly or quickly for slow and quick turn during a turning[5].

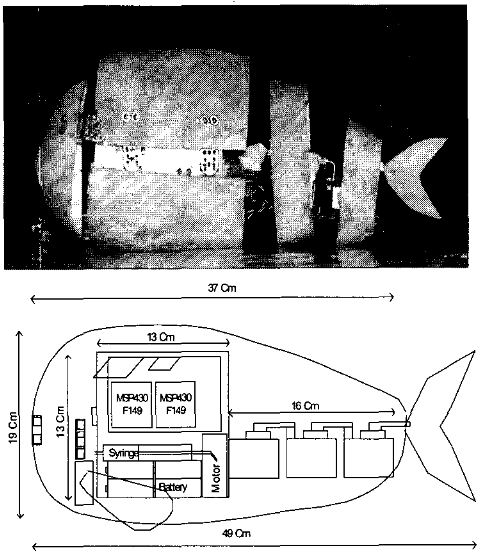


Fig. 1. Fish Robot

Generally, when a fish turns slowly, fish not only swings but turns the caudal fin. But when fish makes a quick turn, it turns the caudal fin to one side quickly without swinging and sustains its caudal fin during the turning motion. We consider these two modes as the most fundamental and important turning modes, because fish robots imitate swimming and turning of real fish. A general swim function is shown in Equation (1).

$$A_i(t) = K_i Am_i \sin(2\pi f t - \theta_i) + \Delta_i(t) \qquad (1)$$

A_i is the angle of the i-th tail motor, K_i is an amplitude factor, Am_i is amplitude, f is frequency of a caudal fin, θ_i is the phase delay of i-th motors, and Δ_i is deflection angle for slow and quick turn. We use 8, 10, and 12 degrees for the maximum amplitudes of angle and 0, $\pi/4$, and $\pi/2$ phase delays for the general swim function, respectively. The swim frequency is 1 Hz.

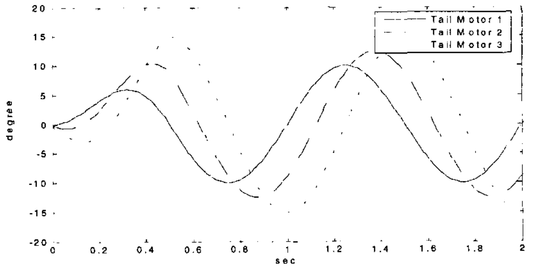


Fig. 2. Angle changes of a tail fin for straight cruise

Generally, deflection angle Δ_i varies smoothly for slow turns, but varies quickly for quick turns. When a fish robot quickly turns its direction, K_i is zero. Figure 2 shows the angles of tail motors in a straight cruise.

2.3 Sensors

A water-proof pressure sensor is used to measure water pressure for depth control. Distance sensors are mounted at the front tip and on each side of the head to measure the distances from obstacles.

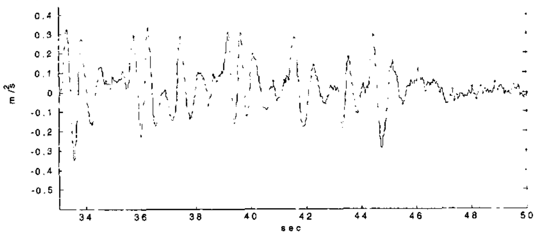
Two magnetic field sensors are aligned parallel to the earth's surface, but rotated by 90 degrees with respect to each other. Philips' magneto-resistive sensors are used to measure weak magnetic fields such as the earth's field. The KMZ51 is a sensor device, which is appropriate to this application, as it comprises one sensitive field sensor in the required configuration in one SO8 package.

A MEMS-type acceleration sensor is installed to measure the posture of the fish robot and to compensate the inclination of the fish robot due to rapid turns and periodic swings. Also it detects acceleration changes such as collisions.

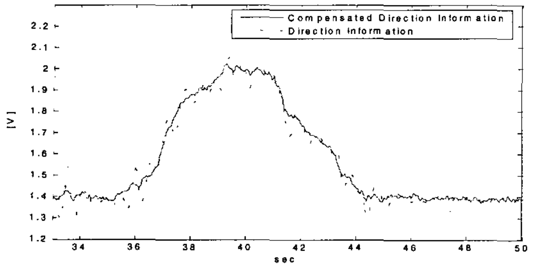
3. Calibration of Direction and Distance Sensors

3.1 Direction Sensors

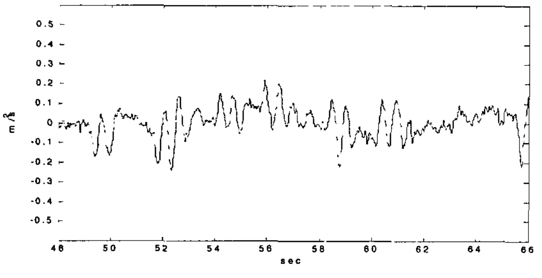
When magnetic field sensors are inclined to any direction, outputs are severely changed. It is necessary to compensate the sensor output due to the periodic swings of the tail motors, rapid turns and perturbation of water. A general two-axis accelerometer ADXL202 by Analog Device is used to compensate the magneto-resistive sensor outputs. One accelerometer is mounted on the head of a fish robot. Two sets of outputs of the acceleration sensor and magneto-resistive sensor, and compensated sensor outputs are shown in Figure 3. When perturbing inclination is slow and small, the magneto-resistive sensor noise is in proportion to the output of an acceleration sensor, and the ratio factor for compensation is obtained experimentally as -0.34 for each axis.



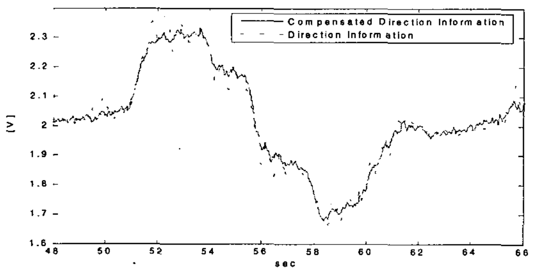
(a) x-axis acceleration



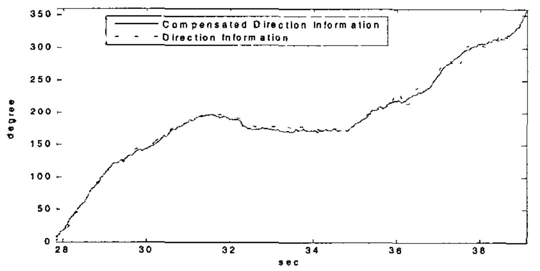
(b) x-axis direction sensor outputs



(c) y-axis acceleration



(d) y-axis direction sensor outputs



(e) Compensated direction sensor output

Fig. 3. Direction sensor outputs when slope is changed

3.2 Distance Sensors

To measure the distance between a robot and an obstacle, it is very common to use the infrared distance sensor regardless of obstacle colors, size and angle. Three infrared distance sensors, GP2D12's, are used to measure the distance between a fish robot and the walls or obstacles. The ranges of sensors are 10-80cm in the air, but the detectable ranges are reduced to about 12-30cm in the water. It is necessary to use a transparent cover to keep the sensor water-proof. Three distance sensors are mounted at the front tip and each side of the head. Measured distance data are used to determine direction changes. Characteristics of infrared distance sensors are shown in Figure 4.

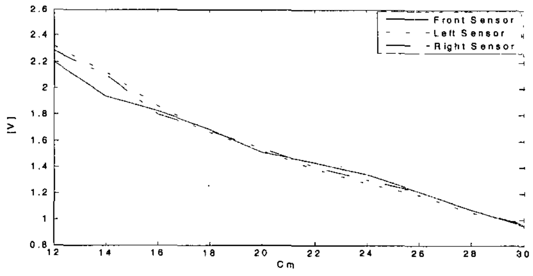


Fig. 4. Distance sensor outputs

4. Distance Estimation

The movement of a caudal fin produces oscillations of the fish robot body. Therefore outputs of the infrared distance sensor change in a swinging pattern, although the real distance does not swing. Figure 5 shows the real distance and various measured distances. When the approaching angle of a fish robot is θ_F and swing angle is $+\alpha$, the fish robot reads longer distance d_{long} for the real distance of d_{real}. Therefore, it is necessary to estimate the exact real distance from the fish robot to an obstacle to find an accurate turning point. A fuzzy distance estimation method is applied to find the exact distance regardless of the swing of its head.

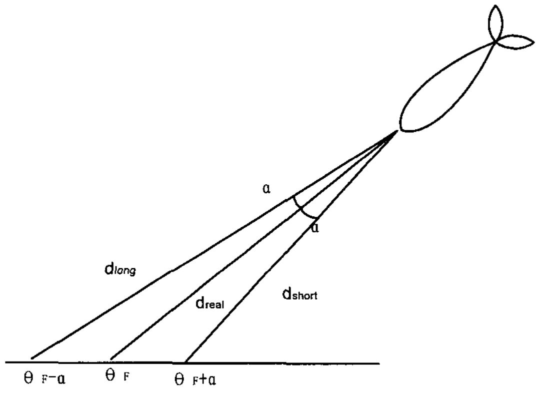


Figure 5. Real distance and perturbed measured distances

4.1 Simple Distance Estimation

The mean value of distance data of one period from the past half to the future half period is defined as a real distance. But in real time operation, it is impossible to use future distance data. Therefore, we use the real distance only to compare the performances of distance estimation methods. We use previous distance data of one swing period to get a simple distance estimation. But this data is mean distance of a half period ago. Thus, a moved distance in the past half period should be added to get a current distance. The sampling time of 20 msec, and swing period of 1 sec are applied for the fish robot.

Procedures to get a simple estimation:

1. Calculate the mean value of distance data(Dm) for past one swing period.
2. Calculate the mean value of past ten samples at current(Dc) and past(Dp) one swing period ago.
3. Calculate the distance change for one swing period. Let Op=(Dc-Dp)/2
4. The simple distance estimation Oc is Dm+Op.

Figure 7 shows measured distance data and estimated distance data for various approaching angles. But we can see noticeably big oscillation in the simple distance estimation. Therefore, a fuzzy estimation method is introduced to reduce this oscillation using direction data as well as distance data.

4.2 Fuzzy Distance Estimation

A TSK fuzzy inference method is applied to produce a fuzzy distance estimation using distance data and direction data as well. As the fish robot swings its caudal fin, the body of the fish robot swings. When the swing angle is inward, the measured distance gets shorter. When the swing angle is outward, the distance becomes longer. Figure 6 shows measured distance and direction data. We propose a simple routine to estimate the real distance without swinging.

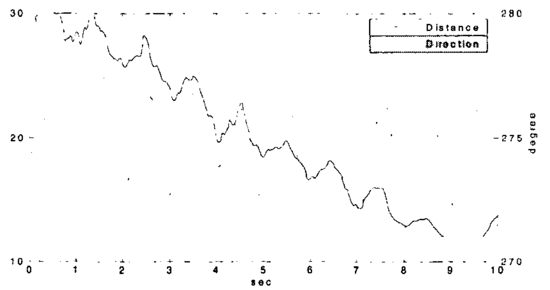


Figure 6. Measured distance and direction information

Procedures to get a fuzzy estimation:

1. Calculate the mean value of distance data(Dm) for past one swing period.
2. Calculate the mean value of past ten samples at current(Dc) and past(Dp) one swing period ago.
3. Calculate the distance change for half swing period. Let Op=(Dc-Dp)/2
4. Calculate a compensation factor Oc using direction data which is calculated by a simple fuzzy logic system as shown below.

We use distance data Dm, change of distance for half swing Op, and Direction information D for input variables. As a training routine for Sugeno-type fuzzy inference, ANFISEDIT of Matlab is used for optimization.

The i-th fuzzy rule R^i is given by

$R^i : IF\ x_1(t)\ is\ M_1^i$ and ... and $x_k(t)\ is\ M_k^i$, Then z is c

$x_k(t)$: premise variables,

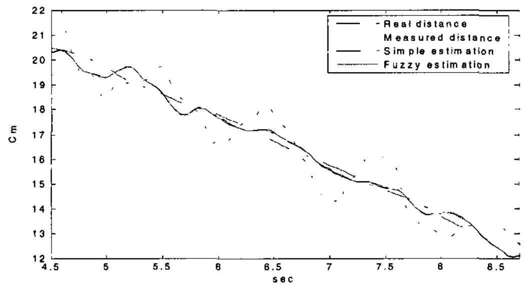
M_k^i : fuzzy sets, i = 1, ..,. 2, I, k = 1, 2, ..., K

I : number of fuzzy rules,

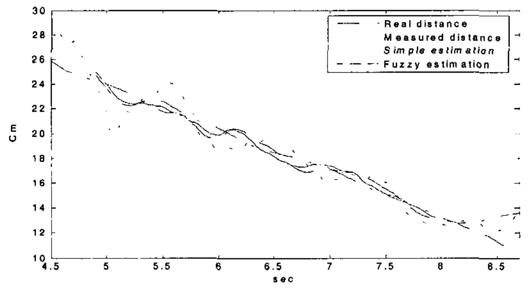
K : number of fuzzy inputs,

c^i : singleton value of fuzzy output

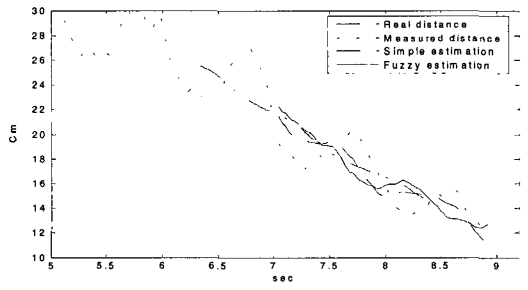
$$z = \frac{\sum_{i=1}^{I}\prod_{k=1}^{K} M_k^i(x_i(t))c^i}{\sum_{i=1}^{I}\prod_{k=1}^{K} M_k^i(x_i(t))} \tag{2}$$



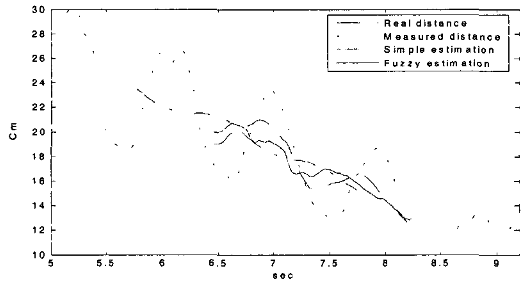
(a) 60°



(b) 50°



(c) 40°



(d) 30°

Figure 7. Measured and estimated distances for various angles

Table 1. RMSE of estimated distances

RMSE degrees	Measured distance	Distance Estimation	Fuzzy Estimation
60°	0.8944	0.4363	0.4289
50°	1.2746	0.9332	0.4064
40°	2.1872	0.8016	0.5927
30°	3.3642	1.4647	0.6980

5. Control Performance of a Fish Robot

Quick and slow turns of the fish robot are used to change the direction to avoid collision. When the angle to be changed is small, the fish robot turns slowly. But when the angle is large, it turns quickly. It is necessary to determine new functions for slow and quick turns to control the direction of the fish robot. A slow turn is performed by increasing or decreasing $\Delta_i(t)$ smoothly in Equation (1). A quick turn is performed by Equation (3). Suitable selections of AM, T_q, T_w and T_r produce a good performance. AM is maximum amplitude, T_q is the first half swing time, T_w is a waiting time to keep angle change and T_r is return time for the end of the quick turn. Generally T_q is very short and T_r is very long. AM and T_w depend on the changes of the angle. To make a control problem simple, we fix T_q and T_r. And we change AM and T_w to control the direction of the fish robot. When the fish robot turns left or right quickly, all swing components have zeros. All tail motors have the same angle in a quick turn mode. Therefore, it can be represented as

$$A_i(t)=\begin{cases} AMsin(\frac{\pi t}{2T_q}) & ,t\leq T_q \\ AM & ,T_q\leq t\leq T_w \\ AM\frac{t-T_r}{T_w-T_r} & ,T_w\leq t\leq T_r \end{cases} \quad (3)$$

But the waves of water caused by rapid movements of the fish robot in a small pool would disturb the direction control. It is very difficult to get optimal coefficients for good performances. We got fundamental data for direction control of the fish robot for various angle changes in a static condition. The data in a static condition are used to select amplitude AM. Figure 8 shows fundamental data and direction control performances in respect of various direction changes. The first figure shows angle changes for each second, when the maximum amplitude varies in 10 to 35 degrees. The others show control results. The dotted line is reference, continuous line is the measured direction, and dashed line represents the motor angles.

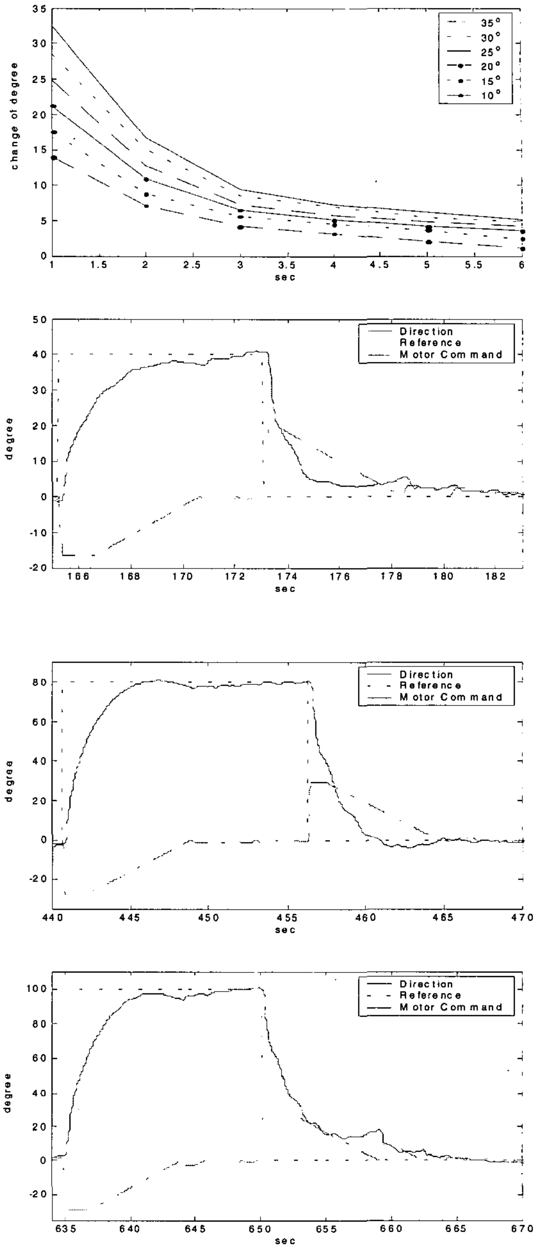


Fig. 8. A basic data set for direction control and the results of typical angles

When the error is greater than 10 degrees, the fish robot turns quickly. When the error direction is less than 10 degrees, the fish robot turns slowly and swings its tail fin periodically. Therefore, the operation of tail motors produces periodic swing of its head. It is difficult to reduce the swing of the body, because the swing of the fin makes propulsion power. The first image of Figure 9 is the trajectory of the fish robot head showing oscillations, the second is the trajectory of a center of its body, the third is the detailed trajectory of head in a quick turn mode at a corner, and the forth is the angle control result measured using a direction sensor.

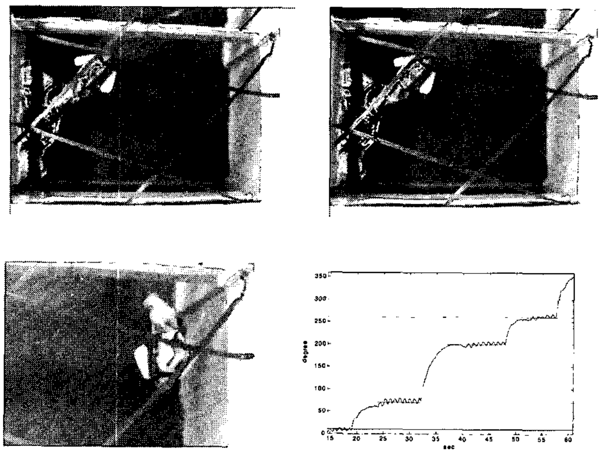


Fig. 9. Trajectory images and angle control of a fish robot

6. Conclusions

It is essential for a fish robot to have the ability of quick and smooth turning to avoid collision with obstacles or walls of a water tank at a close distance. Infrared distance sensors are used to detect obstacles, magneto-resistive sensors are used to read direction information, and a two-axis accelerometer is mounted to compensate output of direction sensors. We proposed a fuzzy inference method to produce a distance estimation using distance and direction data as well in a fish robot when severe swinging noises present. With the information of accelerometers and e-compass, much improved distance data can be obtained by fuzzy logic based estimation. Successful swimming and smooth turns without collision demonstrated the effectiveness of the distance estimation.

Acknowledgments

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References

1. Sfakiotakis, M., Lane, D. M., and Davies, J. C., “Review of fish swimming modes for aquatic locomotion,” *IEEE Journal of Oceanic Engineering*, Vol. 24, No. 2, pp. 237-252, 1999.
2. Yang, E., Ikeda, T., and Mita, T., "Nonlinear Tracking Control of a Nonholonomic Fish Robot in Chained Form," *SICE Annual Conference*, Hukui University, Japan, pp. 1260-1265, 2003.
3. Seung Y. Na, Daejung Shin, Jin Y. Kim, and Su-Il Choi, "Collision Recognition and Direction Changes Using Fuzzy Logic for Small Scale Fish Robots by Acceleration Sensor Data," *FSKD 2005, LNAI 3614*, pp. 329-338, 2005.
4. Daejung Shin, Seung Y. Na, C. H. Na, and C. D. Kee, "Robust Dynamic Weight Measurement Using Acceleration Data.," GSPx2004, Santa Clara, 2004.
5. Junzhi Yu, Min Tan, Shuo Wang, and Erkui Chen, "Development of a Biomimetic Robotic Fish and Its Control Algorithm," *IEEE Trans. on Systems, Man, and Cybernetics – Part B: Cybernetics*, vol. 34, no. 4, pp. 1798-1810, 2004.

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