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SYNTHETIC PHYSICAL MODELS FOR ANIMATING UNSTEADY FISH MOTIONS

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Key words: unsteady fish locomotion, artificial life, animation, physical modeling.

ABSTRACT

This paper presents physical models for simulating unsteady fish motions, including bursting, gliding, braking, turning, ascending and descending. A new wave model, the *controllable body wave model*, is developed to undulate the fish body to produce bursting and gliding motions. A *key frame* approach is adopted to realize braking, turning, descending and ascending. In the key frame method, individual motions are decomposed into sequences of key steps. The *gestures* of the fish in these key steps are recorded and regarded as key frames. In the run time, these recorded key frames are sequentially reproduced to generate swimming patterns. In addition to generating swimming patterns, the fish is forced to move along a curve trajectory in each individual motion. The trajectory is sketched by using a cubic Bezier curve so that the motion steering is simplified and the motion path is adaptable.

I. INTRODUCTION

Animating fish motions is important in producing educational materials, computer games and entertainment films. Thus related topics have attracted significant research efforts. Tu [13] applied the *mass spring damper theory* to model the kinematics of fish movement so that various fish swimming patterns were automatically generated. Some other relevant work can be found in Frohlich [2], Gate [3], Liu and Hu [8], Castro *et al*. [1] and Tan *et al*. [11]. Most of these researches focused on mimicking the steady swimming of fish. However, in a natural habitat, fishes rarely swim at uniform speed along straight lines. Instead, unsteady motions, including *turning*, *gliding*, *braking* and *bursting* are more commonly seen. These unsteady movements constitute significant parts of fish behaviors.

In this paper, physical models are presented to imitate unsteady fish motions, including bursting, gliding, braking, turning, ascending and descending. Our models are based on the research results in a number of publications [5-7, 9, 12]. Among these unsteady motions, turning is the most complicated one. Via turning motions, fishes demonstrate their maneuverability and agility to escape from enemies and pursue preys. In conventional fish motion models, turning motions are simulated by using simplified animation methods [13]. To enhance the simulation quality, we apply the theory proposed by Videler [16] and categorize turning motions into three types: the *C-shape*, *S-shape* and *L-shape* turns. These turning motions are then animated by using specialized algorithms so that fish behaviors under different ambient conditions are better reflected.

By modulating sinusoidal waves with square waves, we develop a new wave model, *controllable body wave*, to undulate fish body so that bursting and gliding are vividly produced. Other unsteady motions are realized by using a key frame approach. In the key frame method, we subdivide each unsteady motion into a sequence of key steps. At each key step, the fish demonstrates a specific *gesture*. The gesture is recorded and treated as a key frame of the motion. By sequentially animating the key frames of the motion, the swimming patterns of the fish in the movement are reproduced. Beside generating the swimming patterns, the fish moves along a curve trajectory during the unsteady motion. The shape and curvature of the trajectory is sketched and tuned by a cubic Bezier curve, which can be adjusted by the animator off-line.

The rest of this paper is organized as follows: Section II presents related work on modeling fish swimming. The procedure and structure for controlling the deformation of fish body is described in Section III. Three types of coordinate systems are utilized in our models for representing the scene, producing fish motions and modeling the fish body. These coordinate systems are also presented in Section III. Section IV describes the controllable body wave model as well as the algorithms for creating bursting, braking and gliding. The physical models of turning motions and the method of trajectory sketching are described in Section V. Some experimental results are displayed and discussed in Section VI. We sum up the conclusion of this paper and suggest future work in Section VII.

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II. REALTED WORK

After millions of years of evolution, fishes demonstrate great efficiency, flexibility and maneuverability in swimming and out-perform any man-made underwater vehicles. Studying fish motions is an interesting topic in biomechanics [5-7, 9]. The book written by Videler [16] presents numerous research results and physical models of fish locomotion.

Since the theoretical models for animating fish swimming are either unavailable or hard to realize, some researchers focused their efforts on simulating fish locomotion by using key-frame methods. Yu and Terzopoulus [17] applied a key frame method to speed up the animation. They divided each swimming cycle into a sequence of key frames and stored the mesh of the fish model of each frame at the preprocessing stage. In the animation, these key frames were linearly interpolated to produce the required gestures. Since no physical model had to be solved for the animation, the computation was sped-up. Key frame methods may be too slow to animate fish locomotion in real time if many fishes are present in the scene. Frohlich [2] proposed a Level-of-Detail (LoD) key frame method for simulating fish locomotion. In his method, pyramids of meshes were used to model individual fish gestures. When fishes were farther away from the viewer, their gestures were rendered by using simplified meshes. Fine mesh models were only used to display those fishes which were closer to the viewer.

Some researchers modeled fish motions by using partial differential equations and applying feasible boundary conditions to simplify the computations. Tan *et al*. [11] solved a coupling system to compute the forces acting on the fish body. In turn, the forces were used to calculate the magnitudes of the fish motion. Castro *et al*. [1] modeled fish bodies and spines by using an elliptic partial differential equation. They introduced some key parameters into their models to control the movements. By carefully setting the parameters, the body undulations of various fishes were produced. Their approaches resembled the theoretic models given in [5, 6, 16], though different formulations were utilized to describe fish motions.

Turning motions comprise a significant portion of unsteady fish locomotion, but only a few papers focused on modeling fish turning motions. Liu and Hu [8] proposed a method for generating C-shape turns for a robotic fish. In the work, the authors used a quadratic curve to model the trajectory of a C-shape turn. The radius of the turn was computed from a physical model at the run time. Four control points were located in the centerline of the fish to bend the fish body during a turn movement. Their method was improved by Hu *et al*. [4] to cope with *cruise-in-turning*, *decent* and *ascent* swimming patterns. These revised models had been successfully implemented in the control system of a robotic fish. Ting [12] used a high-speed camera equipped with laser beams to capture fish motions, including some turning motions. He found that a turning motion could be divided into three stages. At the first stage, the fish deformed its body into a C-shape. Its head and tail were bent toward the direction of turn. At the second stage, the tail moved back and created propulsion to move the fish body. At the third stage, the fish straightened its body and then undulated its body to move forward.

Ting's observations [12] and the research of Hu *et al*. [4] inspire our work. In our physical models, we also decompose a turn into several key stages. However, we expand our work to simulate more unsteady fish motions. Hence gliding, braking, bursting, ascending and descending are included in the proposed physical models. Compared with the published fish motion simulation methods, our work makes the following contributions: (1) We invent the controllable body wave model so that bursting, gliding and cruising behaviors of fishes can be systematically modeled. (2) The scope of fish motion simulation is expanded, including braking, bursting, L-shape turn, S-shape turn and C-shape turn. (3) The proposed physical models are parameterized. Some key parameters are included in the proposed physical models for tuning fish swimming patterns and reflecting intrinsic body characteristics. (4) We utilize Bezier curves to sketch motion trajectories and to simplify the steering of fish motion.

III. THE FISH SKELETON AND COORDINATE SYSTEMS

Two major methods are used to produce the gestures of a virtual life. In the first method, the body surface of the virtual creature is modeled by using a parametric surface. The outer framework of the parametric surface is deformed to produce gestures. In the second method, a skeleton structure is created inside the virtual creature. The skeleton is composed of edges and joints. The edges support the body surface and the joints control the deformation of the body surface. As the animal moves, the edges are rotated and sheared about the joints so that the creature's body is deformed. We adopt the second method to deform the fish body in this work.

1. The Fish Skeleton

The skeleton of a fish model is shown in Fig. 1. It is built to control the deformation of the fish body. At first, the center line of the fish body is computed. Then the fish body is divided into cross-sections. Joints are placed in the intersections of the centerline and the cross-sections. By connecting the joints, the skeleton is created. Two extra joints are added at the base of the pectoral fins to control the motions of the pectoral fins.

In the proposed physical models, we regard the rotational angles of the joints as the parameters of gestures. Assume N joints and K key frames are required in a motion, then K*N angles have to be stored in the preprocessing stage. If extra key frames are needed, linear interpolation is utilized to calculate the intermediate rotational angles between consecutive steps.

2. The Coordinate Systems

Three types of coordinate systems are adopted in the proposed models for defining the scene, animating the fish and

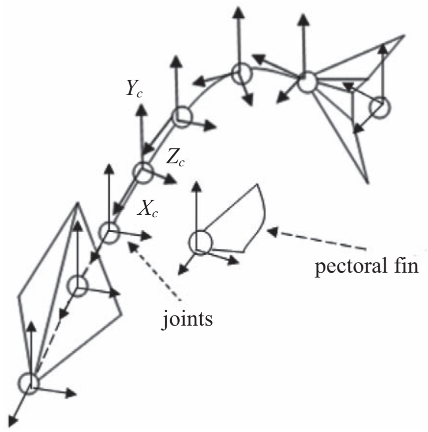

Fig. 1. The fish skeleton and the joint coordinate system.

(a) the body coordinate system (b) the world coordinate system

Fig. 2. The world coordinate system and body coordinate system of fish.

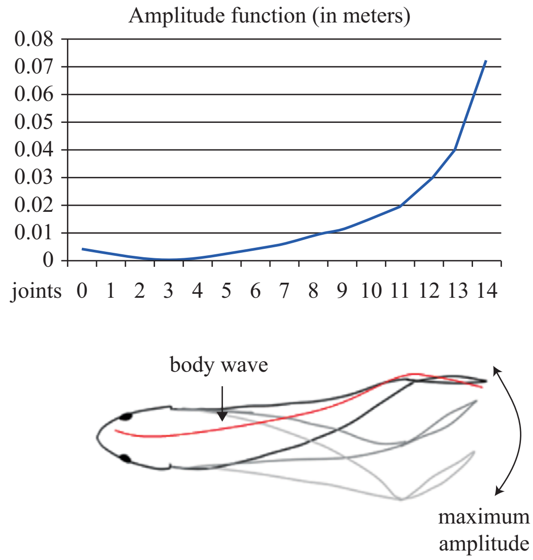

Fig. 3. The amplitude function $A(X_b)$ decides the body wave shape.

deforming the fish body. We use the *world coordinate system* to model the scene. In the world coordinate system, the Y_w axis is directed vertically to the sky and the horizontal space is spanned by the X_w and Z_w axes. In the bounding box of the fish body, the *body coordinate system* is created to specify the geometrical model of the fish body and the positions of the joints. In the body coordinate system, the tip of the fish head is designated as the origin. The X_b axis always points to the coast direction of the fish and the Z_b axis directs to the left side of the fish body. The Y_b axis is the cross-product of the X_b and Z_b axes. The positions of the skeleton joints are specified in the body coordinate system. As the fish swims, the body coordinate system may be shifted and rotated. These two coordinate systems are shown in Fig. 2.

In order to control the rotational angle of each cross-section of the fish body to create a key frame, we establish a local coordinate system at each joint. The local coordinate system is called the *joint coordinate system*. In the joint coordinate system, the Y_c axis points to the dorsal fin, the Z_c axis orients to the left side of the fish body, and the X_c axis is perpendicular to the cross-section centered at the joint. The joint coordinate systems in a fish skeleton are displayed in Fig. 1. As the fish undulates its body, the X_c and Z_c axes of the joints are rotated about the Y_c axes of the joints such that the cross-sections and the fish body are deformed in each stroke.

IV. LINEAR UNSTEADY MOTIONS

We divide unsteady fish motions into two groups. The first group is composed of unsteady movements carried out along straight trajectories, including bursting, braking and gliding. The second group contains unsteady motions performed along curve trajectories, including turning, descending and ascending. The physical models of the movements of the first group are presented in this section while the algorithms for animating the rest unsteady movements are described in the next section.

1. The Body Wave Theory

We adopt *the body wave theory* presented by Videler [16] to model the steady swimming of fish. According to his theory, a fish undulates its body to produce a body wave travelling backward and triggers an anti-force pushing the fish forward. We assume that the body wave is a sinusoidal wave defined in the body coordinate system. By regarding the Z_b coordinate as a function of the X_b coordinate and time variable t, the body wave equation is expressed as follows:

$$Z_b(X_b, t) = A(X_b)\sin\left(\left(\frac{2\pi}{\lambda}\right)(X_b - v*t)\right), \tag{1}$$

where $A(.)$ denotes the amplitude of body wave at the joints and λ and v represents the wavelength and speed of the body wave respectively.

In the body wave model, the amplitude $A(.)$ is a function of X_b. Therefore the body wave amplitude varies over the fish body. An example is shown in Fig. 3 to illustrate the body wave model. The body wave amplitudes at the joints are depicted by a curve in the upper part and the resultant body wave is displayed in the lower part. The fish tail possesses the maximum amplitude and the undulation magnitude is maximized at the fish tail. The minimum amplitude is located at the fish neck. As the fish swims, its neck moves almost

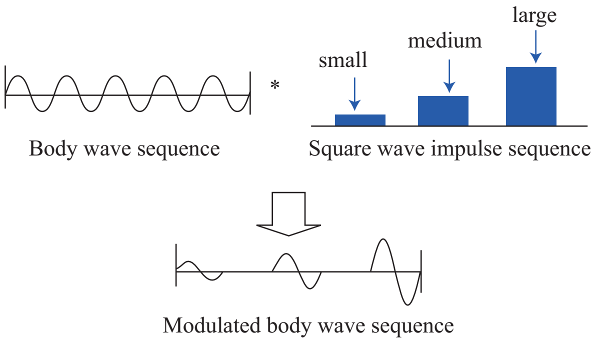

Fig. 4. Generating controllable body waves, top-left: normal body waves, top-right: square waves with varying amplitudes, bottom: the controllable body waves.

straightforward. The amplitude at the fish head is small. Therefore, the fish head slightly swings when the fish swims.

After producing a body wave, the fish accelerates its speed to u. If the fish body is highly streamlined, the magnitude of u is approximately equal to 70% of v. In Videler [16], the body wave parameters and the ratio of u to v of numerous fishes are listed. We use these data to model the swimming speeds of fishes in this work.

2. Gliding and Bursting

In conventional fish locomotion models [13, 17], a fish swims forward by continuously undulating its body. But, in reality, a fish seldom performs such kind of movement, since the energy consumption is high. Instead, the fish usually generates one body wave to accelerate its swimming speed and then glides until the resistance of water reduces its swimming speed below a threshold. Therefore the fish can swim for a longer distance by consuming less energy. This periodic swimming style is called *gliding*. In some circumstances, the fish has to undulate its body vehemently to achieve a high speed movement in a short period of time. For examples, it wants to escape from an enemy or it is trying to catch a prey. Related theoretical studies and observations were reported in [5-7, 9]. This kind of locomotion is called *bursting*. The physical models for producing gliding, bursting and braking are presented in the following paragraphs.

1) The Controllable Body Wave Model

To mimic the bursting and gliding behaviors, we introduce a new physical model for generating body waves. Assume $I(t)$ is a square wave signal with varying amplitudes, as shown in the top-right part of Fig. 4. By modulating normal body waves with the square waves, we create a *controllable body* wave sequence by using the following equation:

$$Z_b^{'}(X_b, t) = Z_b(X_b, t) * I(t), \tag{2}$$

where Z_b is defined in Eq. (1). A sequence of controllable body waves are shown at the bottom of Fig. 4.

2) Bursting

To generate a bursting movement, we enlarge the magnitude of $I(t)$ at the crucial step and reduce the magnitude of $I(t)$ to its normal level at the following steps. Thus the fish undulates its body vehemently at the crucial step to accelerate its speed but produces normal body waves to move forward hereafter.

3) Gliding

Using the controllable body wave model, we can also establish a gliding locomotion model. At first, the fish generates a body wave and accelerate its speed to $u(t)$. Then the magnitude of the square wave is reduced to zero so that no body wave is generated in the following cycles. As the fish moves forward, the surrounding water produces a resistance force to slow down its speed. When $u(t)$ is lower than a predefined threshold, the magnitude of the square wave at that moment is increased to the normal level and the fish undulates its body to generate a new body wave to move forward.

In modelling bursting and gliding, the anti-force of has to be calculated at each time step. Based on the physical model for computing the water resistance against a ship body [14, 15], the deceleration by water is estimated by

$$a(t) = b^* |u(t)|^2, \tag{3}$$

where b is a constant, called the *deceleration coefficient* in this work. At the next step, the fish's speed is reduced by:

$$u(t + \Delta t) = u(t) - \Delta t * a(t). \tag{4}$$

The deceleration coefficient b is a shape-dependent parameter. If the fish body shape is streamlined, the deceleration coefficient is small and the coefficient value is set to 0.2~0.3. If the fish body shape is blunt, the deceleration coefficient is large and the coefficient value is increased to 0.7~0.8. We utilize this coefficient to model gliding behaviors of different fishes.

3. Braking

To perform braking, the fish relies on the anti-force caused by water to decelerate its speed to zero. To maximize the anti-force, the fish deforms its body into a curve and expand its pectoral fins. In our model, we realize braking locomotion by combining the key frame procedure and the physical model of gliding. At the first step, the fish stops generating body waves and prepares for braking. Then it bends its body and expands the pectoral fins at the second step. As the fish glides with the deformed body, the resistance coefficient b is increased to 0.8~1.0 and the fish's speed is quickly decreased. At the final step, the fish fully stops. The key frames of these steps are shown in Fig. 5.

V. TURNING MOTIONS

A fish can perform three types of turn, the S-shape,

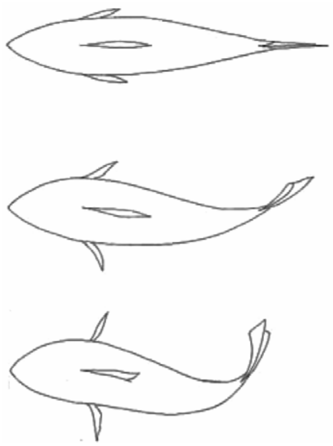

Fig. 5. Three key steps for realizing a braking motion, top: preparing to brake, middle: bending the fish body, bottom: being fully stopped.

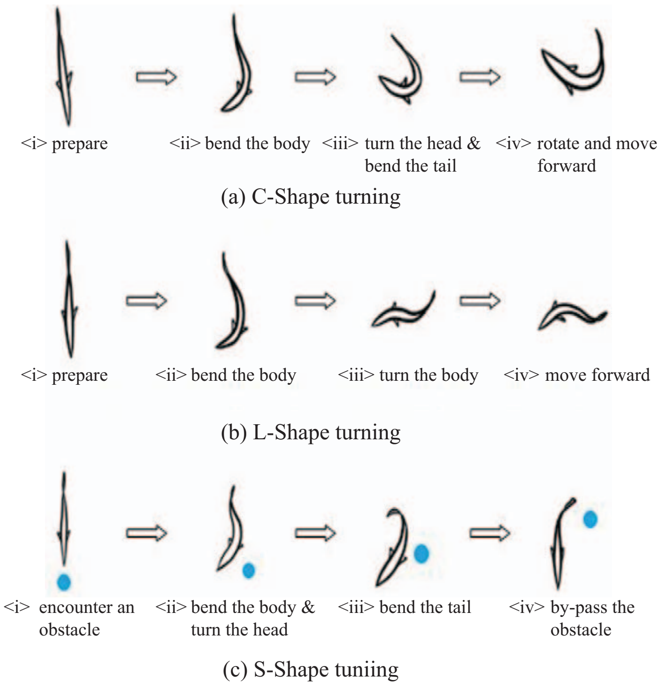

Fig. 6. Key frames of the C-shape, L-shape and S-shape turning motions of fish.

C-shape and the L-shape turns [16]. In this section, we present physical models for animating these turning motions. Ascending and descending motions are also treated as turns. However, ascending and descending are regarded as pitches of a mass point. The algorithms for generating ascending and descending are described in this section too.

1. Key Turning Motion Frames

To model a turning motion, we decompose the progression of the turn into a series of key steps. The fish's gestures at these steps are analyzed in advance. The rotational angles of the joints for creating these gestures are computed and stored in the geometrical model of the fish. In the run time, the gestures are reproduced by using these information to deform the fish body.

Key frames of the three turns are presented in Fig. 6. In the part (a) of Fig. 6, the four key frames of the C-shape turn are shown. In the first frame, the fish prepares to turn. The fish body keeps straight. In the second frame, the fish bends its body and rotates its head toward the new coast direction. In the third frame, the fish tail is bent toward the new coast direction. Then the fish rotates its body along the turning trajectory and reduces the bending angle of the tail gradually until it completes the turn, as shown in the fourth frame.

In the part (b) of Fig. 6, the key frames of the L-shape turn are depicted. To start an L-shape turn, the fish bends its body and turns its head toward the new coast direction. In the meantime, it undulates its tail slightly to acquire the propelling force. In the third frame, the fish rotates its body toward the new coast direction and undulates its body quickly to move forward.

Fishes use S-shape turns to bypass obstacles. They do not change their coast directions after carrying out S-shape turns. Four key frames of an S-shape turn are shown in the part (c) of Fig. 6. In the first frame, the fish detects the obstacle and prepares to bypass the object. The obstacle is represented by using a blue circle. Then the fish's head turns to one side to avoid colliding with the obstacle, as shown in the second frame. Its tail bends to the same side and recovers quickly to produce the propelling force in the third frame. In the fourth frame, the fish undulates its body slightly and moves forward to complete the turn.

2. Turning Trajectories

We use a cubic Bezier curve to model the path of a turn. The Bezier curve is defined by using four *control points*. Its definition can be expressed by:

$$r(t) = \sum_{i=0}^{3} B_{i,3}(t) P_i, \tag{5}$$

$$B_{i,3}(t) = C\binom{3}{i} t^i (1-t)^{3-i}, \tag{6}$$

where $\mathbf{r}(t)$ is the trajectory, $\mathbf{P_i}$ are the control points and $B_{i,3}$ are the Bernstein polynomials of degree 3. The shape, orientation and curvature of the curve can be altered by adjusting the positions of the control points.

In Fig. 7, three Bezier curves are shown to demonstrate the adjustment for the trajectories of turns. In the part (a), the trajectory of a C-shape turn is displayed. The distance between the control points $\mathbf{P_0}$ and $\mathbf{P_1}$ is small such that the fish will turn its head to the new direction within a few steps. The edge, decided by $\mathbf{P_2}$ and $\mathbf{P_3}$, is relatively long. Hence the path become a straight line when the turning motion is completed. The turning angle is equal to the angle between the first

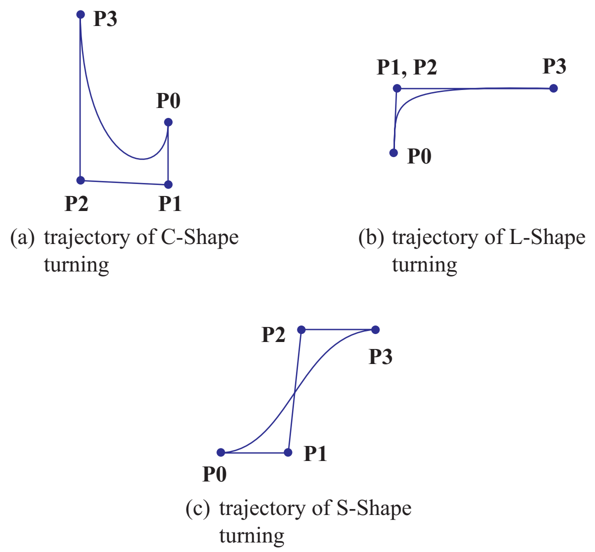

Fig. 7. The trajectories of the C-shape, L-shape and S-shape turns.

edge < $\mathbf{P_0}$, $\mathbf{P_1}$ > and the 3rd edge < $\mathbf{P_2}$, $\mathbf{P_3}$ >. The curvature of the path is decided by the turning angle and the length of the edge < $\mathbf{P_1}$, $\mathbf{P_2}$ >. For a flexible fish, for example an eel, the turning angle can be near 180 degrees and the length of the 2nd edge will be short.

In the part (b) of Fig. 7, the path of an L-shape turn is displayed. To model the trajectory of an L-shape turn, the three control points $\mathbf{P_1}$, $\mathbf{P_2}$ and $\mathbf{P_3}$ should be co-linear. In this example, $\mathbf{P_1}$ and $\mathbf{P_2}$ share the same position such that the turning angle is almost 90 degrees. However, for modeling a smooth L-shape turn, the distance between $\mathbf{P_1}$ and $\mathbf{P_2}$ would be similar to the distance between $\mathbf{P_0}$ and $\mathbf{P_1}$.

In the part (c) of this figure, the trajectory of an S-shape turn is shown. The control polygon of the Bezier curve resembles the English character **N** such that the coast direction of the fish is preserved after it completes the turn. The curvature of the trajectory is decided by the angles at $\mathbf{P_1}$ and $\mathbf{P_2}$. If these two angles are small, the turn would be sharp.

3. Steering Turning Motions

Beside demonstrating key gestures and moving along the trajectory, the fish must adjust its coast direction and orient its body in a turning motion. The steering mechanism can be explained by using Fig. 8. At the initial stage, the fish performs the following actions:

1) The fish head is bent toward the new coast direction.
2) If the turning is a C-shape or L-shape turn, the fish tail is bent to the new coast direction, too.

Then the fish starts to turn. Assume that **r**(t) and **T**(t) are the trajectory and tangent of trajectory, the fish performs the following actions:

1) The tip of the fish body is moved along **r**(t).

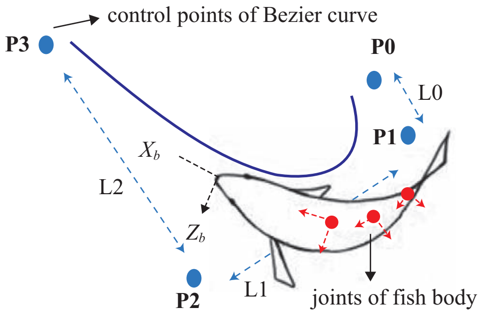

Fig. 8. Orientation of the fish body in a turning motion.

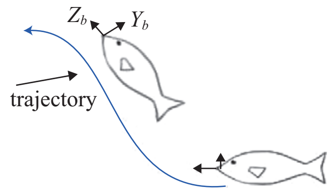

Fig. 9. Trajectory and orientation of the ascending motion.

2) The fish rotates so that the X_b axis of the body coordinate system is parallel to **T**(t).

The tangent vector **T**(t) is computed by:

$$T(t) = \sum_{i=0}^{2} Q_i B_{i,2}(t),$$

$$Q_i = 3(P_{i+1} - P_i),\ i = 0, 1, 2, \tag{7}$$

where $B_{i,2}$ are the quadratic Bernstein polynomial. At the 3rd stage, the fish completes the turning motion and undulates its body to move forward in the new coast direction.

4. Ascending and Descending

The sea bed is not a flat surface. Therefore, ascending and descending are common fish locomotion. Ascending and descending are completed in 3 stages. At the first stage, the fish rotates about the Z_b axis of the body coordinate system. Then, the fish undulates its body and moves along the trajectory until reaching the extreme point of the trajectory at the second stage. At the final stage, the fish rotates its body again so that the fish body is parallel to the horizontal space. The trajectory and orientation of the fish are shown in Fig. 9. The trajectory of the ascending and descending movement is defined by using the cubic Bezier curve for producing the trajectory of S-shape turn.

VI. EXPERIMENTAL RESULTS

To verify the fidelity of our physical models, we create an artificial fish model and simulate the unsteady motions of this fish. The fish's skeleton composes of 17 joints. Fifteen joints

Table 1. The parameters of the artificial fish.

Fish type	Rainbow trout
Fish length	105 mm
Body wave length	93.45 mm
Body wave speed (v)	378 mm/sec.
Ratio of u/v	0.7

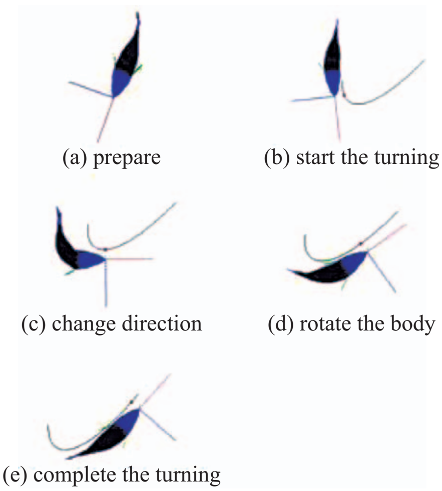

Fig. 10. Five snapshots of the C-shape turn.

reside in the center line of the fish body and the other joints are located at the bases of the pectoral fins. The detail data of this fish are depicted in Table 1. The artificial fish is a rainbow trout. It is 105 mm in length. Its body wave length λ is equal to 93.45 mm. The amplitude function $A(.)$ is illustrated in Fig. 3. This fish can generate rapid body waves. The speed of body wave of this fish is 378 mm per second. The fish body is streamlined, thus the ratio of the swimming speed u to the body wave speed v is 0.7.

1. Turning Motion Simulation

Since the turning motions are the most complicated motions, only the results of simulating the turning motions are presented and discussed in this section.

In the first test, a C-shape turn is produced. Five snapshots of the motion are displayed in Fig. 10. At step (a), the fish undulates its tail to gain momentum for the turn. At step (c), the fish bend its body into a C-shape. Then it moves along the trajectory. Its tail is gradually recovered from the bending , as shown at step (d). At the end, it undulates its tail to swim forward in the new coast direction.

When the fish encounters a wall or a big rock, it has to turn its coast direction by 90 degrees to change the coast direction. The gestures of the fish in an L-shape turn are shown in Fig. 11. At step (b), the fish undulates its tail to produce the propelling force. At step (c), the fish bends its body into an L-shape. At step (d), the fish turns along the trajectory and the fish tail gradually recovers from the bending. The fish finishes the L-shape turn at step (e) and keeps swimming forward.

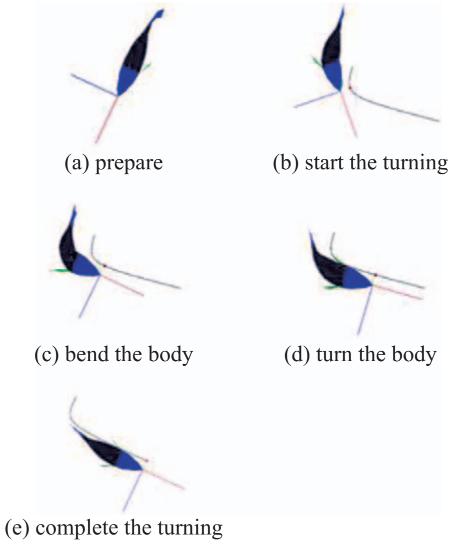

Fig. 11. Five snapshots of the L-shape turn.

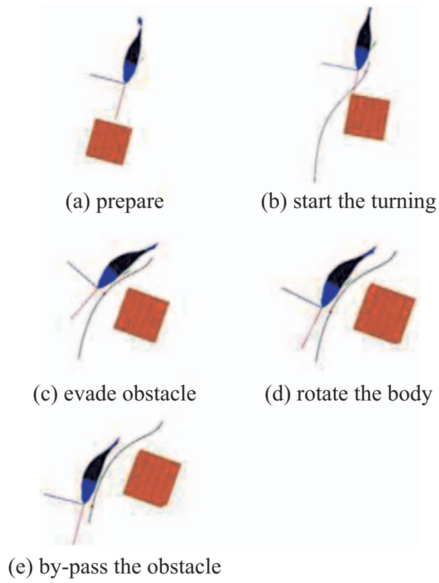

Fig. 12. Five snapshots of the S-shape turn.

The progression of an S-shape turn is depicted in Fig. 12. An obstacle is put in the scene. The obstacle is a cube. The fish swims toward the obstacle at step (a) and makes an S-shape turn to avoid colliding with the obstacle. At step (b), the fish turns its head to avoid the obstacle. Then the fish swims along the trajectory by undulating its tail, as shown in the images of steps (c) and (d). Once bypassing the obstacle, the fish moves forward in the original coast direction. The snapshot is displayed in the last image.

2. Computational Cost Analysis

In order to verify the usability of the proposed physical models in real time fish motion animation, a sequence of complicated tests were conducted. We created an artificial

Table 2. Speed of fish locomotion animation.

Hardware	Frame rates
AMD Phenom II CPU, 3 GHz. NVIDIA GeForce GTX 460 GPU. DDR3 4 gigabyte main memory.	50 fishes + 10 obstacles. Frame rate: 57 ~ 59 fps.
	100 fishes + 11 obstacles. Frame rate: 20 fps.

Table 3. Profile of the animation costs.

Procedure	Cost profile (in %)
Physics models	1.5 %
Collision detection	63.4 %
Rendering	33.4 %
Others	1.7 %

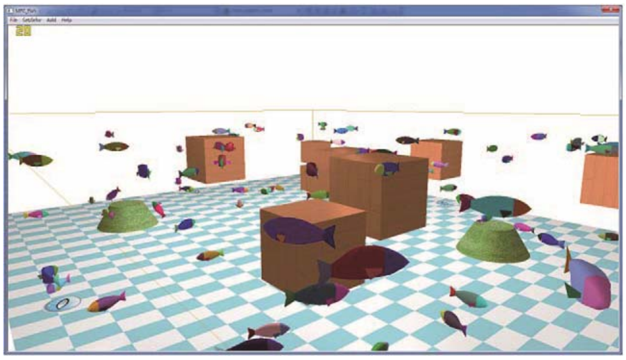

Fig. 13. A water tank containing 11 obstacles and 100 fishes.

water tank containing some obstacles and fishes. These fishes have to detect collision, select feasible motions and steer motions automatically. A snapshot of the simulation is shown in Fig. 13.

At first, we built 10 obstacles in the water tank where 50 fishes were released. The frame rate was 57~59 frame-per-second (fps). Then we added an extra obstacle and release another 50 fishes into the water tank. The frame rate was dropped to 20 fps. The frame rate and the key specification of the embedded computer system are shown in Table 2.

The profile of the computing costs is depicted in Table 3. As the results show, the costs for computing the proposed physical models are merely 1.5% of the total cost. The most expensive procedure is the collision detection. More than 63% of the computing efforts are consumed by this procedure. The rendering process displays the scene and the graphical user interface. The system spends 33.4% of the costs in the rendering process. The profile verifies that the proposed physical models are efficient and practical for real time fish motion animation.

VII. CONCLUSION & FUTURE WORK

This paper proposes physical models for simulating unsteady fish motions. We create a skeleton inside the fish body to control the deformation of the fish body. Each unsteady motion is decomposed into a series of key steps. The gestures of the fish in these key steps are generated by undulating the skeleton to reveal the swimming patterns. The trajectories of turning, descending and ascending motions are generated by using cubic Bezier curves. In each motion, the fish is guided to move along the trajectory and demonstrates the key gestures. Test results verify that the proposed physical models are efficient and capable of producing various fish motions in real time. Our physical models expand the scope of fish motion simulation. They can be used to create artificial fishes for gaming and educational applications.

Recently, some researchers have proposed Artificial Intelligent (AI) models for controlling fish motions. Tu [13] proposed intelligence models for fish motions. Stephen *et al*. [10] also presented an improved knowledge model for controlling fish behaviors. These AI models are based on the finite state machine model. Each individual action is controlled by a *crisp* rule, which might produce unnatural behaviors. A more flexible AI model should be developed to control the behavior of a fish. We propose to use the *fuzzy logic theory* to construct the *brain* of fish. In the AI model, each event is represented by using a fuzzy variable. Multiple fuzzy variables are grouped into fuzzy expressions by using fuzzy logic operators to reflect compound events detected in the environment. The rules of action are evaluated by using these fuzzy expressions so that the fish's behaviors are more realistic and flexible.

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