Calculation Model of Jellyfish for Simulating the Propulsive Motion and the Pulsation of the Tentacles

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Abstract

This paper proposes a method for generating animations of jellyfish with tentacles, and shows the results of the propulsive motion and the pulsation of tentacles. We believe that it is very favorable to simulate jellyfish which move by simple pumping motion not only for generating beautiful animation but also for developing sea-floor exploration robots. We constructed simplified computational model, and this model is straightforward to implement, has a low computational cost and is capable of generating visually plausible results. It is possible to apply changes to various properties of the motion, such as the propagation of pulsations, simply by changing values of Young's modulus and the velocity of flow in the target environment. In addition, by changing the form of the umbrella, or the length of the tentacles and so on, it is possible to simulate various types of jellyfish.

1. Introduction

Jellyfish is one of the most fascinating living thing. They get thrust force almost only by simple pomping movement, however, they took very complex movement and appearance because of their delicate body structure. It is difficult to analyse the jellyfish movement by sensor in water, therefore we believe that it is very important to simulate jellyfish on a computer. However, the simulation of soft-bodied jellyfish with a large number of tentacles using techniques based on precise physical models has been problematic due to the complex interactions between fluids and elastic bodies, and the high cost of the physical computations for handling many thin tentacles in a fluid. In this research a simplified simulation system was constructed specifically for handling jellyfish with many tentacles. This research is very significant not only as new method for generating beautiful animation but also as a presentation of new possibilities of robotics.

2. Related Work

This research uses ideas from elastic body dynamics and fluid dynamics. Various approaches have been adopted as simulation methods for elastic bodies, including [17] using finite difference method, and [7] using finite element methods. [15] use point-based method for representing not only elastic bodies, but also plastic bodies and melting bodies. Comparatively simple methods for expressing deformable objects using mass-spring models have also been developed [4][10]. Coupling elastic bodies and fluids is problematic, and is currently still in the process of development. [1] treats coupling grid-based fluid simulation [5] or tetrahedral fluid simulation [11] with elastic bodies based on FEM. The method of [6] couples rigid bodies and fluids, and applies mass-spring model method to the rigid bodies.

However, the computational cost of these methods is high, and for jellyfish which may have tens or hundreds of tentacles, the simulation time taken by is extreme. A method for simplifying the computational model is thus needed in order to reduce the cost. There are many examples of the use of simple models for expressing the motion of animals which have soft body. Mass-spring models are used for expressing the soft motion of fish [18], snakes and worms [13]. [2] calculated pumping movement of jellyfish in consideration for biologic mechanism of jellyfish [3]. In the research by [16], the annular form of jellyfish umbrellas was utilized, and 3D animations were produced from 2D simulations focused on these umbrellas. However, when generating animations of jellyfish umbrellas, the tentacles are also another important visual element. Jellyfish have tentacles of various lengths and rigidities according to their

ICAT 2008
Dec. 1-3, Yokohama, Japan
ISSN: 1345-1278

type, and this research proposes an animation method which incorporates the expression of these various tentacles.

3. What are Jellyfish? Why Choose Jellyfish?

Jellyfish is a colloquial name for organisms belonging to the phylum Cnidaria, and there are various types at the biological class level, including Hydrozoans, Stauromedusae, Cubozoans, and Scyphozoans. These occupy various living spaces according to their type, inhabiting a wide range from warm waters to cold waters, and shallows to deep sea. The size of their bodies also ranges from those which do not extend beyond a few meters to giants which stretch to tens of meters. Figure 1 shows two representative examples, the Moon Jelly and the Brown Jelly. Jellyfish have very little ability to swim using their own power, and are regarded as being a type of plankton. The greatest motion that jellyfish are capable of performing voluntarily is the expansion and contraction that is due to the muscle known as circular muscle which is running circularly on the edge of the jellyfish umbrella, and the pumping motion observed in many jellyfish is also due to it. The principles of this motion, which is mostly due to expansion and contraction alone are simple, hence jellyfish-like shape may be suitable as sea-floor exploration robots, for example as shown in Figure 2. However, due to the deformable nature of the jellyfish body, the motion of the whole body is extremely complex and fascinating. The physically based simulation of this motion also presents a challenging problem. By computationally modeling the appearance of a jellyfish umbrella and tentacles elegantly pulsating in water it is hoped that new beautiful animations and possibilities of robotics may be demonstrated.

Figure 1. Photographs of jellyfish. Left: the 'Moon Jelly' (*Aurelia aurita*), right: the 'Brown Jelly' (*Chrysaora melanaster*).

4. Algorithm

The relationship between the jellyfish umbrella and fluid is easy to understand because the umbrella has comparatively unsubtle shape, but the relationship between a lot of numbers of tentacles and fluid is very confusing. For efficiency, we assumed the thrust motion is controlled only by the umbrella and the tentacles just follows to the umbrella, and we used different comuputing model for the umbrella and the tentacles, respectively.

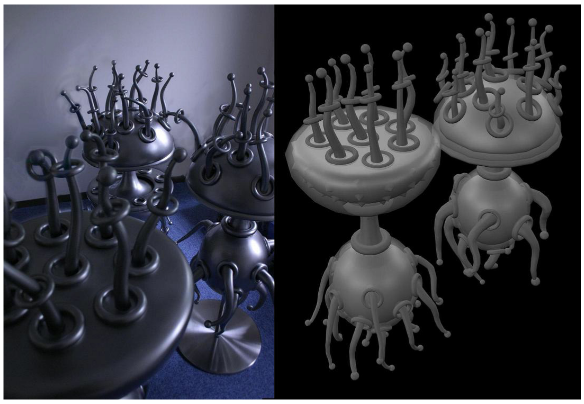

Figure 2. Sculptures of design proposals of jellyfish-shaped robots (left) and the computer generated image (right).

4.1. Tentacles

4.1.1 Modeling of Tentacles

Tentacles can be assumed as rod-shaped elastic bodies. Physical simulation by solving the elastic body equations of motion is possible, but when there are a large number of tentacles the computational cost is high, and considering the interactions with a fluid in addition is extremely problematic. This research thus uses a one-dimensional tentacle model with particles connected in the simple manner shown in Figure 3 (right). Also, assuming that pliableness is the most important when animating tentacles because the stretching and retraction of tentacles can hardly be seen when observing actual jellyfish, we suggest the elastic rod computational model which is focused on bending. During calculations, by constraining the distance between particles to remain constant, stretching forces are ignored, and a simple computational model based on Ewing's experimental apparatus for measuring Young's modulus [19] is used which considers bending stiffness of rod-shaped elastic bodies. This method takes very small computational cost, is easy to program, and users can easily adjust pliableness.

When the rod sags in the manner shown in Figure 4 (left), the descent of the midpoint, h, is expressed by Equation (1). I is the cross-sectional 2-dimensional moment. In the case of a cylinder with diameter d, I is given by Equation (2). Figure 4 (right) shows this Ewing's apparatus converted into a computational model of a tentacle. In this model the range of the particles, diameter d(=distance between particles), is regarded as a cylinder of diameter d. Particle i and its two contiguously adjacent particles $i-1$ and $i+1$ are taken as elastic rods riding on a Ewing's apparatus. If we regard inversely the fact that when a force P is applied at midpoint descent of h as shown in Figure 4 (left), then when

ICAT 2008
Dec. 1-3, Yokohama, Japan
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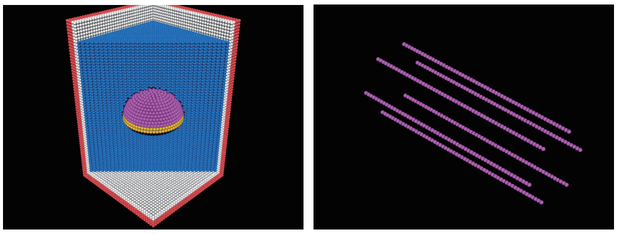

Figure 3. Left: umbrella model, right: tentacle model. A 1D model calculated in 3D space is used for the tentacles. A model with particles connected by springs is used for the umbrella, and calculated within a particle method fluid.

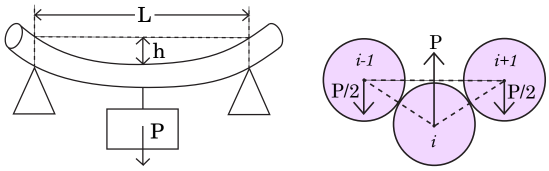

Figure 4. Ewing's experimental apparatus (left) and the computational model (right).

a midpoint descent of h occurs a force of P in the direction opposing bending is calculated as being applied at the midpoint. When E is set to an arbitrary value, I is obtained from Equation (2), and h and H are measured from the simulation process, then the value of P may be obtained from Equation (1). Also, from the balancing of forces occurring in Ewing's apparatus, at the fulcrum (the triangular stand in the diagram) the forces in the opposite direction to that of P are each a half of P, so in the model, for particles $i-1$ and $i+1$, a force of only half P is applied in the opposite direction to P.

Table 1 shows the Young's modulus for a variety of materials. In this research the values of the Young's modulus for jellyfish tentacles were chosen to be smaller than that of gelatin, $E = 0.24$[MPa].

$$h = \frac{PL^3}{48EI} \tag{1}$$

$$I = \frac{\pi d^4}{64} \tag{2}$$

4.1.2 Coupling of Tentacles and Fluids

Performing calculations for a water-filled tank in order to calculate the mutual interactions with the fluid is difficult, and since calculations are also performed for fluid at a distance which hardly contributes to the tentacles the efficiency is poor. Therefore, the speed of only the fluid flowing around the tentacles was assumed arbitrarily, and a computational model approximating the drag force was constructed. When calculating the drag due to a fluid experienced by a cylinder the orientation and rotational moment of the cylinder must be considered, and complicated calculations are necessary. Here, the tentacle is given as a model composed of connected particles so the drag force is approximated by calculating the mutual interactions occurring between the particles and the fluid at each point. This method calculates the drag between a sphere and the fluid. Since a sphere is symmetrical about a point its orientation and rotation may be ignored and the drag force may be straightforwardly calculated from the flow rate of the fluid surrounding the sphere. The drag force F_{fluid} experienced by a sphere moving through a fluid with a relative velocity of u_r is obtained as follows. When the particle distribution is d, the Reynold's number Re_p for the particle motion in the fluid is defined according to Equation (3). Also, the drag coefficient C_R may be formulated according to Equation (4). Using these values, the drag due to viscosity experienced by a body moving relative to a fluid, F_{fluid}, may be expressed as shown in Equation (5). This equation is a product of the drag coefficient C_R, the kinetic energy of the fluid, and the projected area of the sphere. Figure 5 shows an animation of an elastic rod waved in a computational space which assumes a uniform flow.

Further description about the elastic bar simulation method is shown in [9], which shows that the macroscopic physical properties of the simulated elastic bar are maintaind, and that it is suitable method as elastic bar simulation.

$$Re_p \equiv \frac{\boldsymbol{u_r} d\rho}{\mu} \tag{3}$$

$$C_R = \begin{cases} 24/Re_p & (Re_p < 1), \\ \left(0.55 + 4.8/\sqrt{Re_p}\right)^2 & (1 < Re_p < 10^4). \end{cases} \tag{4}$$

$$F_{fluid} = C_R \left(\frac{\rho_f \boldsymbol{u}^2}{2}\right)\left(\frac{\pi d^2}{4}\right) \tag{5}$$

4.1.3 Interpolating Tentacles

Depending on the type of jellyfish the number of tentacles may be an extremely large number in excess of a hundred. In this case, the method of simulating a certain number of tentacles and using the results to interpolate further tentacles may be considered. Taking together the fact that tentacles pulsate in accordance with the flow, and the fact that the flow varies in a spatially continuous manner, it may be supposed that the motions of a given tentacle and its adjacent tentacles describe similar trajectories. It was therefore thought that when two tentacles are located in positions which are not too widely separated, if another tentacle

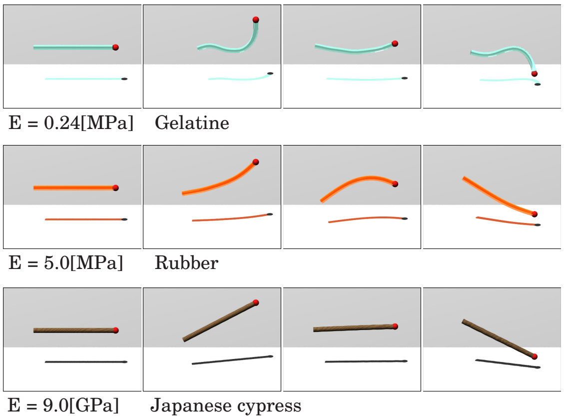

Figure 5. Animation of many kinds of rod. Assuming a uniform flow of 0.3[m/s] (from right to left in each figure), the tip of the elastic rod (the red ball) is compelled to oscillate. Experiments were conducted with various materials by changing the Young's modulus.

is taken as existing between them, then its form can be obtained by morphing between the original two. In this way, it is possible to freely increase the number of tentacles by performing interpolations between tentacles after conducting simulation, therefore the simulation of a vast number of tentacles is unnecessary. Cosine interpolation, rather than linear interpolation was used in order to produce smooth interpolations.

4.2. Umbrella

4.2.1 Modeling the Umbrella

Types like the Brown Jelly (Figure 1 right) can move relatively quickly, and posses umbrellas with a rigidity capable of withstanding these speeds. For this reason, the shape of the umbrella does not change greatly, and it can be animated manually having enough reality. However, for types such as the Moon Jelly (Figure 1 left) the propulsive power of pumping is weak, and the umbrella pulsates in the fluid while moving gently. In such cases the umbrella is modeled computationally and simulated due to the difficulty of constructing it manually.

The umbrella is expressed as a set of particles, and the interparticle distance is about the same as the interparticle distance of fluid, l_0. a model is adopted which uses springs to connect the particles within a influence radius r_e in the initial position. We set the influence radius $r_e = 2.4l_0$. Empirically, the range from $r_e = 2.0l_0$ to $4.0l_0$ is suitable. The spring force experienced by mass point i, F_i is expressed in Equation (6) by means of Hooke's law. j is the index of a neighboring particle, k is the spring constant, $\boldsymbol{r}_{ij} = \boldsymbol{r}_i - \boldsymbol{r}_j$, and $|\boldsymbol{r_0}_{ij}|$ is the initial distance between particle i and j.

$$F_i = -\sum_j k(|\boldsymbol{r}_{ij}| - |\boldsymbol{r_0}_{ij}|)\frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|} \tag{6}$$

4.2.2 Coupling of Umbrella and Fluids

A particle method known as the Moving Particle Semi-implicit (MPS) method is used to simulate the fluid around the umbrella [12]. The MPS method is one of the techniques known as a particle method which expresses a fluid as a set of particles, and was developed for the numerical computation of incompressible fluids. It is a meshless Lagrangian solution method, and calculates incompressible flow using a semi-implicit algorithm. The governing equations for the fluid are the continuity equation (7) and the Navier-Stokes equation (8). By way of representative particle methods, there is also the Smoothed Particle Hydrodynamics (SPH) method [14]. It is essentially the same solution method as MPS though how to use the kernel is a little different. The computational cost of particle methods is dominated by the high cost of searching for proximal particles, but techniques for acceleration using GPUs have also been developed [8].

The umbrella particles are influenced by the fluid force as follows; the spring force of the umbrella particles is calculated at the explicit stage of the algorithm of MPS method, and at the other steges the umbrella particles are calculated as fluid particles and deformed in the same manner as fluid. Some losses of physical strictness may be observed when the umbrella expands and contracts because of calculations of incompressiblity, but the influence does not appear obviously if the number of umbrella particles is enough less than the number of fluid particles, and the contraction of the circular muscle is not too high (see on the section 4.2.3). We used 57240 particles for fluid and 1113 particles for umbrella.

$$\frac{D\rho}{Dt} = 0 \tag{7}$$

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\boldsymbol{u} + \boldsymbol{g} \tag{8}$$

4.2.3 Movement by Muscle

The contraction of the circular muscle was modeled. When the umbrella is modeled and calculated, the springs connecting the particles at the edges of the umbrella (the yellow particles in the diagram on the left in Figure 3) repeatedly contract in the jetting phase, and loosen in the relaxation phase. When the springs contract, the spring constant is also increased. In this research, the spring contraction ratio was set to 0.40, and the spring constant was set to $k = 20.0$[N/m]. The spring constant in the jetting phase was scaled by a factor of 50.

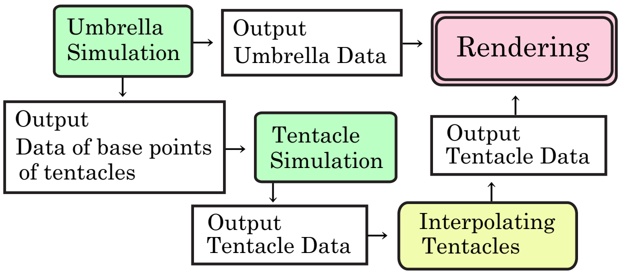

Figure 6. Workflow: at first the umbrella data are generated, and next the tentacle data are generated, then finally these data are combined and the images are rendered.

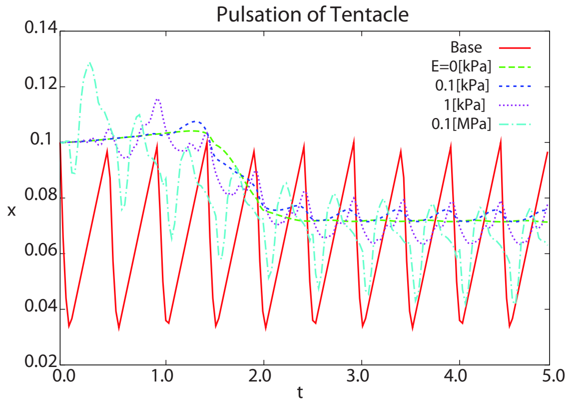

Figure 7. Pulsation of tentacles : Wave propagations when Young's modulus is changed. Red line in this figure represents the movement of the base point of the tentacle which was oscillated forcibly, and another lines represent the movement of the tip point of the tentacle.

4.2.4 Connection Between Umbrella and Tentacles

The base points of the tentacles on the edge of the umbrella were fixed in advance, and the coordinate and velocity data for these points was stored during simulation of the umbrella. The base points were compelled to oscillate using this data for the root coordinates of the tentacles. The complete workflow is shown in Figure 6.

5. Results

We examined two types of animated jellyfish. POV-Ray was used for rendering (http://www.povray.org/).

Case 1. Rigid umbrella and long tentacles. An animation was created using the Brown Jelly shown in Figure 1 (right) as a reference. The umbrella was animated manually because the shape of umbrella does not deform greatly (see on the section 4.2.1), therefore only tentacles are simulated. The interparticle distance in the tentacles was 0.01[m], and each tentacle was connected with 60 particles. Six tentacles were computed. The drag force was computed assuming immersion in a flow in the direction of the tentacle. With the speed of the flow of surrounding fluids fixed at $v = 0.3$[m] with small random noise, experiments were performed with the Young's modulus of the tentacles, E, set to various values. The random noise is added only for animating asymmetric movement, and the value is pretty smaller than the value of v. Figure 7 compares coordinate values projected onto the x axis of the root and tip of a single tentacle. Examining this figure reveals that the higher the Young's modulus, the easier it is for the oscillation compelled at the base to propagate to the tip. Also, Figure 8 shows a comparison of various flow rates for the surrounding fluid, with a Young's modulus of $E = 0.1$[kPa]. It can be seen then when v is large, the propagation of oscillations becomes large. Also, by comparing the case when $v = 0.0$ with the case when $v > 0.0$, it can be seen that the coordinate value of the tip converges towards the range of the root's oscillation according to the influence of the surrounding fluid. As a consequence, the shape occurring in the jetting phase shown in Figure 9 and the shapes occurring in the relaxation phase tend toward those of an actual jellyfish. Figure 9 shows an animation made with the number of tentacles increased by a factor of 10 using interpolation.

Case 2. Soft umbrella and short tentacles. An animation was created using the Moon Jelly shown in Figure 1 (left) as a reference. The umbrella was modeled with a radius of 2.0[m], and simulation was performed within fluid particles based on the MPS method. The interparticle distance in the tentacles was 0.03[m], and each tentacle was connected with 20 particles. Ten tentacles were computed. The Young's modulus of the tentacles was $E = 0.24$[MPa]. The drag force was computed assuming immersion in a fluid for which the speed of flow in the direction of the tentacles was uniformly $v = 1.0$[m/s] with small random noise. This type of jellyfish has short tentacles which are extremely numerous. In Figure 10 the number of tentacles is scaled by a factor of 30 using interpolation, and 300 tentacles are rendered. The thrust movement of the umbrella is shown in Figure 11. Because we neglected the gravity force assuming the buoyancy force and the gravity force are completely the same in this simulation, we could conclude that the umbrella got thrust force by pumping movement, while phase shift occured between contraction and propulsion of the umbrella.

Figure 12 and Figure 13 shows the example of animated jellyfish.

6. Conclusion and Future Work

We modeled jellyfish with tentacles and simulated the movement. Using the calculation model, we succeded in making artistic animation of jellyfish and representing jet propulsion of the umbrella and wave propagation of tentacles in a computer. The contributions of this method are as

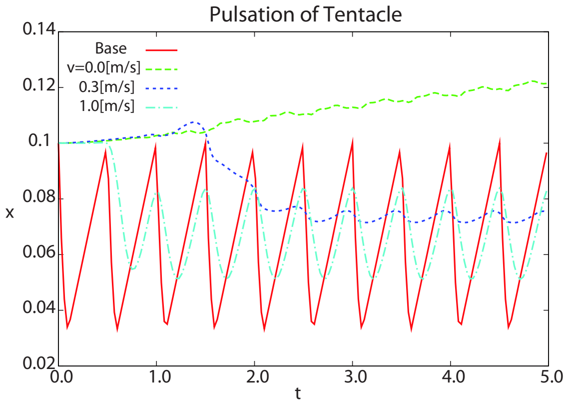

Figure 8. Pulsation of tentacles : Wave propagations when flow velocity is changed.

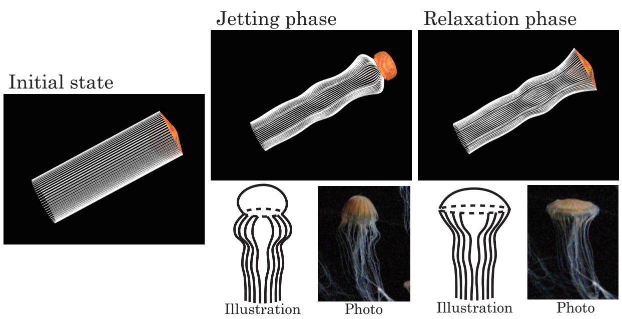

Figure 9. Comparison of shapes occurring in the jetting phase and relaxation phase. $E = 0.1[kPa]$.

Figure 10. Animation of a giant jellyfish. Left: initial shape, center: jetting phase, right: relaxation phase. $E = 0.24[MPa]$.

follows: we can estimate the rigidity of the tentacles from actual values for the Young's modulus more logically than existing method such as the mass-spring model, and we can program the computational model of the umbrella and the tentacles easily because it is a simple particle-based model.

In this paper, we have compared only the shape of the simulated tentacles with the shape of actual tentacles, however, we have not conducted comparison experiment between the simulated movement and the movement of actual jellyfish or robots in water. Further validations may be necessary when we apply this simulation method to robotics as a future work. Moreover, our model deal with the umbrella and the tentacles separately due to computational efficiency, hence it could be another future work to calculate the influence not only from the umbrella to the tentacles but also from the tentacles to the umbrella for verifying the effect of the tentacles on swimming ability of jellyfish.

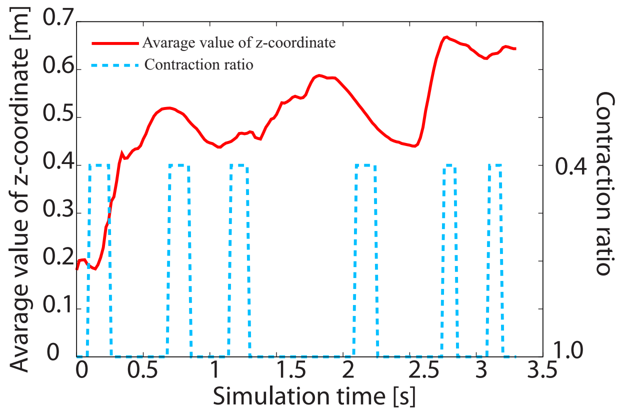

Figure 11. Thrust movement of the umbrella. The red line shows the z-coordinate average value of the umbrella particles and the blue dash line shows contraction ratio of the radious of the umbrella.

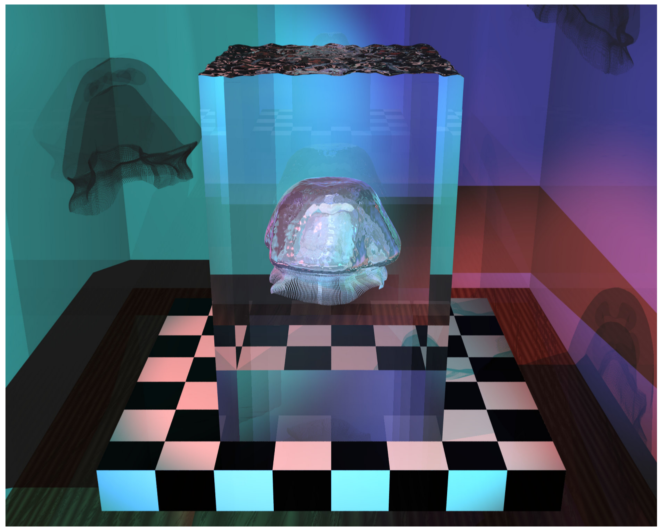

Figure 12. A room with a jellyfish in a water tank. The water is simulated by particle method when umbrella simulation. The jellyfish is exposed to light from three directions and the shadows are projected on the wall. $E = 0.1[kPa]$.

Acknowledgement

We would like to thank CREST of JST (Japan Science and Technology) for supporting our research. Also, we would like to thank Professor Seiichi Koshizuka, The University of Tokyo, for providing the source code of MPS method.

Figure 13. School of purple jellyfish. Long oral arms are animated by the same method as tentacles. $E = 5.0$*[MPa]*.

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ICAT 2008
Dec. 1-3, Yokohama, Japan
ISSN: 1345-1278