INTERACTION BETWEEN WATER AND DYNAMIC SOFT BODIES

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Abstract: The water animation by moving soft bodies, changing their shapes, is the subject of the present work. The mechanism of movement transformation from a body to a liquid is elaborated on the basis of Lattice-Boltzmann method of fluid modeling. The use of boundary conditions, destined to perform this transformation visually realistic and computationally quite inexpensive, is one of the main innovations of our approach. The model is applied to the jellyfish propulsion water.

1 INTRODUCTION

The subject of this work is a physically based modeling of a liquid animation caused by a soft dynamic body movement. In computer graphics, physical based models have an important advantage compared to empiric ones. They make the scene evolve automatically and do not require the user intervention for each animation step. Once the relations and laws of interaction among objects and/or medium are given, the correctly produced system automatically simulates the behavior of the whole scene. This gives essential increasing of computational time. Recent physically based models (Guendelman, Selle, Losasso, Fedkiw, 2005), (Muller, Solenthaler, Keiser, Gross, 2005) are developed in order to maximally reduce the calculation time and to present visual plausibility, keeping the details of a real world animation.

The model presented in this paper proposes a quite simple way of transforming body motion to liquid motion. The special, easy to apply boundary conditions are elaborated in application to the Lattice Boltzmann method for this purpose. The model is applied to underwater scenes with swimming jellyfish. The simulations of jellyfish movement and its interaction with particles in water and with algae are performed.

The paper is composed as follows. In the second part, the liquid animation models are discussed. The third part is devoted to the transformation of soft body movement to surrounding water and consequently to neighboring objects. In this part, we can find the main innovation of this work: the boundary conditions for moving soft bodies. The fourth part presents the results obtained by this method. The last section concerns conclusions and future work.

2 ANIMATION OF LIQUIDS

In this section we give a brief review of liquid modeling. There are the fluid dynamics methods, simplified to satisfy the needs of computer graphics.

Computational fluid dynamics proposes a variety of tools for fluid motion modeling, but it demands special skills and resists external control. In addition, it is very time consuming. In order to be applied in computer graphics, simplified physically based approaches were intensively developed during recent years. To introduce first branch, one can refer to (Foster, Metaxas, 1996), (Stam, 1999), (Foster, Fedkiw, R., 2001). Visual fidelity is the main goal of these models. These methods solve the Navier-Stokes equations on a discrete voxel grid that causes decreasing the time step or refinement of a grid when the boundary geometry is complex.

There are several problems already considered in this branch of liquid modeling; the models were essentially improved compared to the first ones. In (Genevaux, Habibi, Dischler, 2003) the fluid-solid interaction was explored; the method is based mainly on the definition of a coupling force between

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the solids and the fluid. In (Guendelman, Selle, Losasso, Fedkiw, 2005) the method for water - cloth interaction, well suiting also to water - air and solid - fluid interface, is given. The rigid body - fluid interplay is presented by a Rigid-Fluid method in (Carlson, Mucha, Turk, 2004).

Recently, the Smoothed Particle Hydrodynamics method was presented in application to fluid - fluid interaction, water pouring into a glass and interaction of fluid with deformable solids (Muller, Solenthaler, Keiser, Gross, 2005), (Muller, Charypar, Gross, 2003), (Muller, Schrim, Teschner, Heidelberger, Gross, 2004).

The other direction in flow simulation is the Lattice-Boltzmann method (LBM) (Chen, Doolean, 1998), (Wei Li, Zhe Fan, Xiaoming Wei, Arie Kaufman, 2003). It gives a microscopic representation of a fluid as a set of microscopic particles. The method is derived from the Boltzmann equation from the kinetic theory of gases. Almost all Lattice-Boltzmann equations simulate compressible fluids with some finite sound speed c_s. However the computed solutions are expected to converge to incompressible limit, when the liquid speed $|\vec{u}|$ is sufficiently small compared to the sound speed c_s (Mach number $M_a = |\vec{u}|/c_s \to 0$).

Let us consider the principles of LBM. The liquid is represented by a finite regular grid and by a set of a packet distribution values $\{f_{qi}\}$ for each cell of a grid. Each packet distribution value f_{qi} corresponds to the velocity direction vector $\vec{e}_{qi}$ shooting from a node to its neighbor. A pair $(f_{qi}, \vec{e}_{qi})$ indicates how many particles f_{qi} in the cell have the velocity direction $\vec{e}_{qi}$.

It is supposed that there always exists a local equilibrium particle distribution f_{qi}^{eq} dependent only on the density ρ, and on the local fluid velocity $\vec{v}$. The LBM updates the packet distribution values at each cell based on two rules:

collision: $f_{qi}^{new}(X,t) - f_{qi}(X,t) = \Omega_{qi}$ (1)

propagation: $f_{qi}(X+\vec{e}_{qi}, t+1) = f_{qi}^{new}(X,t)$ (2)

where X is the coordinate in R^3, and Ω_{qi} is the general collision operator. Since the components of $\vec{e}_{qi}$ can only be chosen from {-1, 0, 1}, the propagation is local.

Collision describes the redistribution of packets at each local node. Propagation means the packet distributions move to the nearest neighbor along the velocity direction.

The density and velocity are calculated for each cell from the packet distributions as follows (Wei Li, Zhe Fan, Xiaoming Wei, Arie Kaufman, 2003):

$$\rho = \sum_{qi} f_{qi}, \qquad \vec{v} = \frac{1}{\rho}\sum_{qi} f_{qi}\vec{e}_{qi}.$$

Mass and momentum are conserved locally. Then, the collision step (with commonly used BGK collision term (Bhatnagar, Gross, Krook, 1954)) is:

$$f_{qi}^{new}(\rho,\vec{v}) - f_{qi}(X,t) = -\frac{1}{\tau}\left(f_{qi}(X,t) - f_{qi}^{eq}(\rho,\vec{v})\right),$$

where τ is a relaxation time (timescale for which every variable relaxes towards equilibrium), which determines the viscosity of the flow, f_{qi}^{eq} is the local equilibrium distribution function.

A great advantage of this method is that it supports dynamic boundary conditions. For more details see (Chen, Doolean, 1998), (Wei Li, Zhe Fan, Xiaoming Wei, Arie Kaufman, 2003).

There exist the following usual models with a rest particle for 3D space (see Fig.1): D3Q15 (fifteen velocities), D3Q19 (nineteen velocities), D3Q27 (twenty seven velocities) (Renwei Mei, Wei Shyy, Dazhi Yu, Li-Shi Luo, 2002). A minor variation of those models is to remove the rest particles from the discrete velocity set; the resulting models are known as the D3Q14, D3Q18, and D3Q26 models, respectively. The LBM with a rest particle generally have better computational stability.

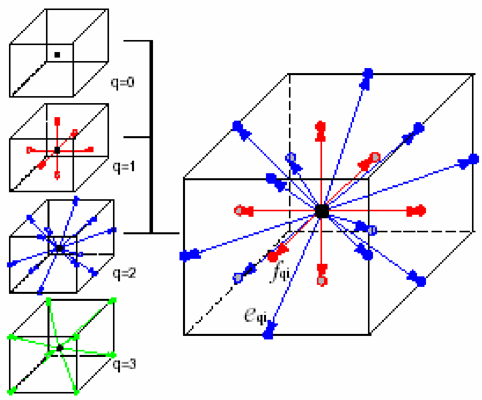

Figure 1: 3D lattice geometry. On the left side there are presented the four sub-lattices that are defined in a 3D lattice. On the right side is the combination of sub-lattices 0, 1, and 2 (19 packets) (Wei Li, Zhe Fan, Xiaoming Wei, Arie Kaufman, 2003).

In the present work the D3Q15 model is taken, the simplest model for 3D space, in our case it suits well due to the smoothness of the movement and the simplicity of the scene objects:

$$e_i = \begin{cases} (0,0,0) & i=0, \quad rest \;\; particle \\ (\pm1,0,0), \;\; (0,\pm1,0), \;\; (0,0,\pm1) & i=1,...,6 \quad group \;\; I \\ (\pm1,\pm1,\pm1) & i=7,...,14 \quad group \;\; II \end{cases}$$

3 TRANSFORMATION OF BODY MOVEMENT TO A LIQUID MOVEMENT

The movement of the dynamic body, once properly transferred, animates the liquid and neighboring soft bodies, the passive and the active ones. An example is the swimming jellyfish, which can transfer the motion to other jellyfishes and algae surrounding it.

Let us suppose that the parameters of dynamic body surface, such as coordinates and velocities of the control points, are known at each time step. The most important part in a water animation by a body is the interaction, where the movement of a dynamic surface should be properly transferred to the lattice cells. Here we are restricted to one-way transformation of movement, which means that the body is not influenced by a liquid but acts as a motor of a motion. The full interaction, the reciprocal influence of the body and the liquid complicates the problem.

The transformation of the movement is done with assigning local surface velocities to the boundary lattice cells touching the jellyfish surface and their subsequent influence on the other cells. At the starting point at time $t = 0$ the uniform equilibrium distribution with velocity $u = 0$ and constant water density is assigned to all lattice cells.

The coordinate of a unit cell is a vector, formed by the minimal integer numbers of cell points coordinates. So, the point (-5.3, 2.6, 0.1) belongs to the cell with coordinates (-6, 2, 0).

Further, we consider the swimming jellyfish as an example. The movement of the jellyfish suits to our aim of deforming body – liquid interaction simulation. The movement consists of contraction and relaxation of the bell forming the body, so the jellyfish opens and closes its bell.

Now we have to explain briefly the model of jellyfish body and its animation model made here. The jellyfish is presented as a NURBS surface with axial symmetry (see Fig. 2). For the deformation a dynamic particle system is used; the particles are shown in the figure with points. The particle system is a set of unit-masses, where the forces are applied. The particles are placed in 96 CVs, the control points, which control the shape of the surface.

For a better implementation of the deformation system in the present model, the particles were placed in CVs and then the shape of the surface was modified. Particles positions at the low part of jellyfish do not correspond to CV positions, but still keep connection; the particle translations are applied to corresponding CVs.

Jellyfish contractions are simulated by 10 axisymmetric mass-spring systems. Each spring acts accordingly to its rigidity, a length at rest, and weights of the particles at the ends. At the beginning the springs are supposed to be stretched, that gives a contraction. At the relaxation phase, the springs are supposed to be compressed. For simplicity, the properties of the springs are changed at certain time points during scene evaluation in order to alternate contractions and relaxations.

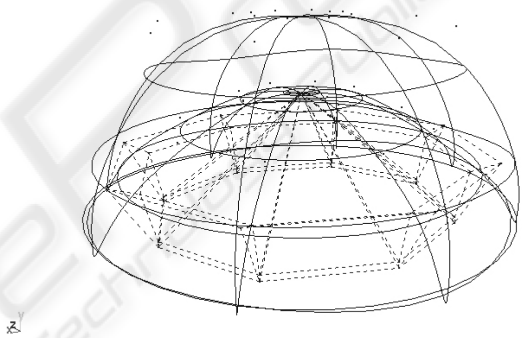

Figure 2: Jellyfish model with particle system and mass-spring system.

As we know the coordinates of the control points of the body, these 3D coordinates determine the corresponding boundary cells; the velocities of the control points allow the calculation of the packet distributions for LBM. They can be taken as the equilibrium distributions with the local surface velocity and a constant water density for all cells, as the water is a non-compressible liquid. Linear interpolation is applied to calculate coordinates and velocities of the cells in between the control points.

The lattice is finite and the boundary conditions are to be set for the boundaries of the lattice, as well as for the boundaries of the body.

3.1 Boundary Conditions on the Lattice Border

Boundary conditions in the LBM may take several forms (Wei Li, Zhe Fan, Xiaoming Wei, Arie Kaufman, 2003). The conditions that can be applied to the border of the lattice include periodic boundary and outflow boundary. For periodic boundary, the outgoing distributions wrap around and re-enter the lattice from the other side. For outflow boundary, distributions propagating outside the lattice are simply discarded. However, boundary cells also have some distributions propagating inwards from fictitious cells just outside the boundary.

3.2 Boundary Conditions on the Body

Now let us consider obstacle boundaries, which should be set for objects inside the lattice. The "no-slip" boundary condition requires that the tangential component of the fluid velocity along the boundary be zero. The simple implementation is a bounce-back rule. The outgoing distribution, facing the boundary, re-enters the lattice at the same cell, but associated with the opposite velocity.

In (Wei Li, Zhe Fan, Xiaoming Wei, Arie Kaufman, 2003) improved boundary conditions are applied to complex geometries and moving boundaries. They are represented as a complex function including neighbor cell distributions, velocity of the local surface, proportional distances to the cell nodes (coordinate points) and surrounding water velocities.

In the present work the moving boundaries are treated in different manner. The main purpose of proposed boundaries is to transfer the movement from object to water independently of surrounding water velocities. This is the main distinction of our method. The boundary cells are, in some way, the fictitious cells. They affect the other lattice cells, but are not affected by other cells. The properties of these cells depend totally on the local surface velocity. The velocity distributions in these cells are set to the equilibrium values. The aim is to transfer the object-in-water motion properly and in a simple manner. The method proposed, uses the bounce-back rule in combination with the interaction with the fictitious boundary cells.

The lattice cells are separated in three groups, see Fig.3. The first one (group A) is the group of body inner cells. Inner cells mean the cells, which stay inside the body as well as all of its neighbors. These cells are passive and the distributions for them are not calculated, they keep zero.

The second group (group B) includes water cells. These are the cells, which are the cells of water as well as all of its neighbors. The velocities of these cells are calculated according to the standard procedure in two steps: collision and streaming.

The third group (group C) is the boundary and pre-boundary cells. This group is the most important and is again divided into three groups:

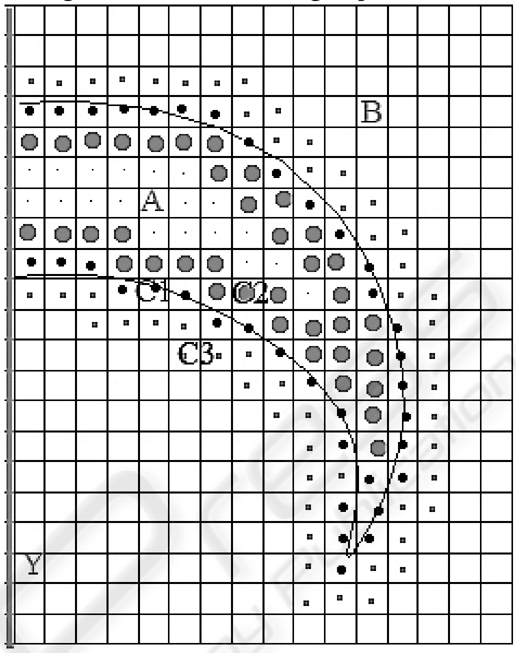

Figure 3: Groups of lattice cells: A are the inner cells, B are the water cells, C1, C2, C3 are the boundary cells.

1. boundary cells (group C1)
2. inner cells of the body which have at least one boundary cell as a neighbor (group C2)
3. water cells which have at least one boundary cell as a neighbor (group C3).

Further, we will discuss group C and its under-groups. The cells of the first group, C1, get the distributions $f_{qi}^{eq}(\rho,\vec{v}_{loc})$ depending on local surface velocity. The remaining two groups are responsible for proper transferring of the movement.

Let us consider group C2, the inner cells. Since we use linear interpolation to find the water cells intersecting with body surface in between the control points of dynamic system, it is important to find all the cells having exchanges with the outside cells. They are all inner cells having, at least, one C1 neighbor. In the present model their distributions are set as average distributions of surrounding boundary cells C1 (inner cells A are not taken into account).

The pre-boundary cells of group C3 get the incoming distributions from C1 and C2 at a collision step. But their own distributions, in directions to boundary cells C1, change the direction for opposite and re-enter to the cell. So, at the streaming step the pre-boundary cells C3 get the incoming distributions from the water cells B, from boundary cells C1, C2, and, in addition, some of their own distributions are returned as they meet a wall (body surface). During the evaluation of the dynamic system the lattice cells change the status and pass from one group to another.

The time step and the lattice size should be properly chosen because the system can become unstable. In the LBM the indication of instability of a solution is the appearance of negative values of equilibrium distributions at the collision step.

Physically, the model described above is not accurate because mass is not strictly conserved. On the other hand, the deviation is little and the method is simple. The important feature of Lattice-Boltzmann Method, the support of moving boundaries, is used here and the movement issuing from the object is successfully transferred to the water space.

3.3 Jellyfish Propagation in a Water Space

One more advantage can be gained from the proposed application of the Lattice-Boltzmann Model, the body propagation in liquid. Having known the velocities of boundary cells, we know, roughly speaking, the forces with which the body acts on the liquid in these cells.

The propagation can be calculated based on the momentum conservation law at the interaction of two bodies having masses m_1, m_2 and velocities v_1, v_2 correspondingly, $m_1v_1=m_2v_2$.

In the case of a jellyfish swimming, a strong simplification can be done. According to a biological model, the jellyfish propagation is generated by a cylindrical jet of water from the bell cavity. Approximately, one can consider the two-object system: the jellyfish and the cavity water; see Fig.4.

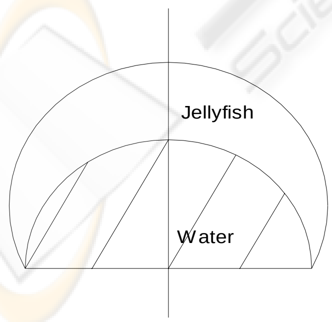

Figure 4: Two-object system: the jellyfish and the bell cavity water.

Here it does not matter what to consider, masses or volumes, as the water and jellyfish densities are almost equal. We know the volume of pushed water, at each step it can be approximated as a sum over boundary cells C1:

$$\Delta V = \frac{1}{2}\sum_i v_i l_{cell}{}^2 \Delta t,$$

here v_i is the cell velocity, l_{cell} is the cell size, Δt is the time step. Having this change of volume, we can calculate the height of a column of water pushed by jellyfish. The base of the column is taken as a circle with the jellyfish aperture radius R_a. The height of the column is $h = \frac{\Delta V}{\pi R_a{}^2}$, the velocity of the cavity water is approximately taken as $v_w \approx \frac{h}{\Delta t}$. Now the movement conservation law is used. Considering the volumes in place of masses, $v_j = v_w \frac{V_w}{V_j}$ is the jellyfish velocity at the current step, where $V_w = \frac{1}{2}\cdot\frac{4}{3}\pi Ra^3$ is the approximate cavity water volume, and the jellyfish volume V_j is approximately a sum of all inner cells (group A + group C2). The jellyfish transition is calculated as $\Delta l = v_j \Delta t$.

This model is non-correctly physically based during jellyfish opening, but gives visually pleasing results.

4 RESULTS

In this section we present the results of our model application to underwater virtual words. Scenes are modeled in Maya 6.0. A plug-in calculating the velocity field in water, generated by a jellyfish swimming is written in Maya API.

Let us consider the general parameters of the scenes. In Fig.5 the jellyfish, the dynamic body, is presented in the scene and the size of the lattice is shown. The jellyfish is oriented normally to the ground, but the orientation axis can be chosen differently. It also can be changed during the animation simulation as a function of some factor(s). The bell diameter of relaxed jellyfish is about 40 cm, and the field lattice cube size is 80 cm. In the present results the size of lattice cells is 2 cm. The lattice size is enough for movement transition to the environment, and the values of cell velocities near the lattice borders are almost negligible. These parameters allow a frame rate about 1,1 frames per second (cell size 2 cm) and 0,43 frames per second (cell size 1 cm) on Intel Celeron 2.8GHz with 512 Mb RAM. It is not a real time simulation but an interactive time, where the evolution of the scene can be followed.

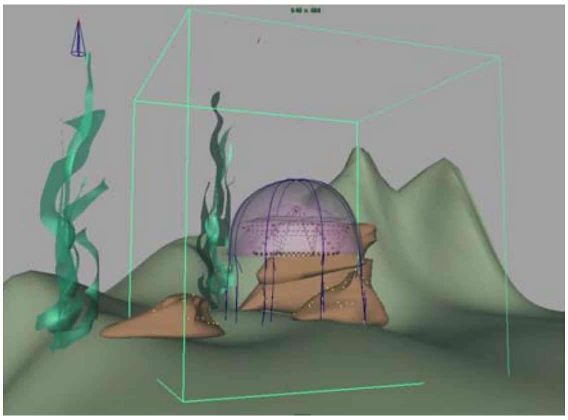

Figure 5: The size of the lattice in comparison with the scene.

The general character of the jellyfish propulsion in water is presented in Fig.6, where the velocity of the jellyfish and its aperture diameter are shown. Comparing these data with the biological data (McHenry and Jed 2003) in Fig.7, the similarity of movement character is to be pointed. The velocity of jellyfish propulsion in our model depends on the lattice cell size, which gives more or less precision in calculation of a pushed water volume. Using constant coefficients in the model allow regulation of the jelly propulsion velocity according to biological data or a desired movement.

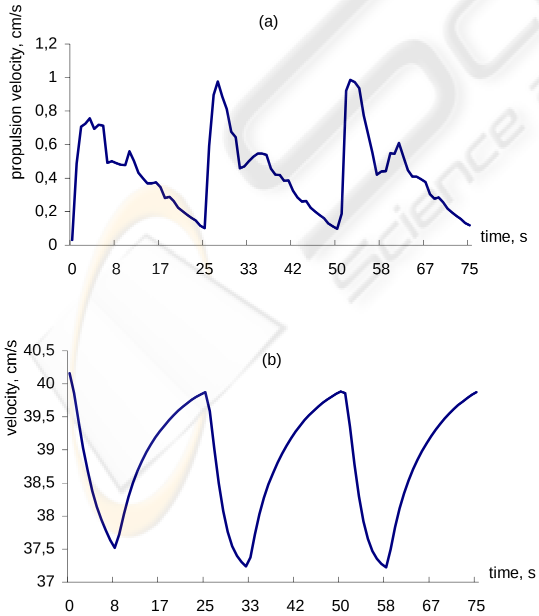

Figure 6: The jellyfish propulsion velocity (a) and the bell diameter (b) in dependence of time.

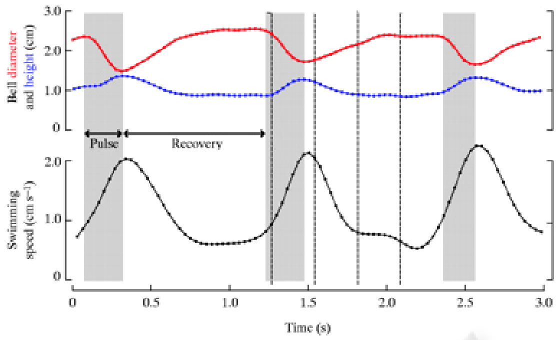

Figure 7: Representative kinematics of swimming in jellyfish Aurelia aurita, (McHenry and Jed 2003).

Further more, let us consider two scenes animated by jellyfish movement. In the first scene, the jellyfish make the particles move in the water, presented as small spheres.

Figure 8 (a): Particles animated by jellyfish movement, frame = 1.

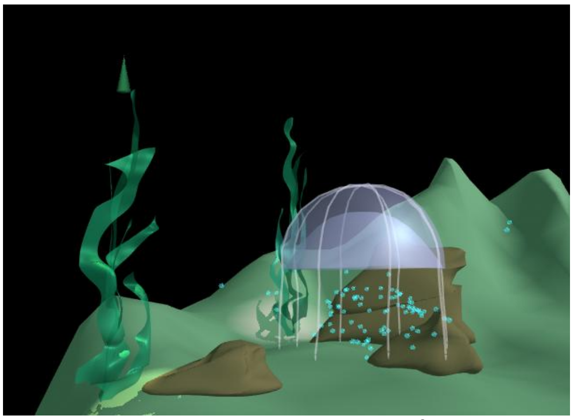

Figure 8 (b): Particles animated by jellyfish movement, frame = 400.

In Fig.8, four screenshots are given at frames: a) 1, b) 400, c) 1400, d) 2000, the video is joined to the article and available on http://www.msi.unilim.fr/ basilic/Publications/2006/ATG06. The ordered

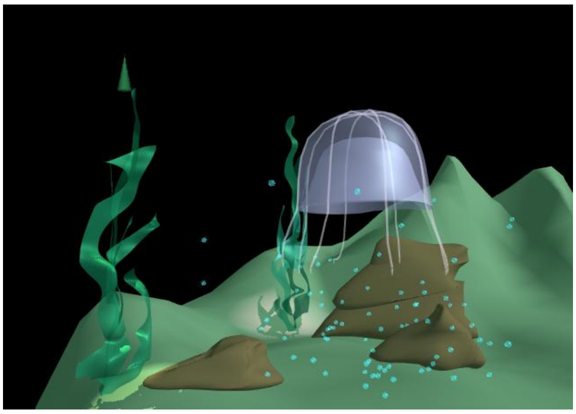

Figure 8 (c): Particles animated by jellyfish movement, frame = 1400.

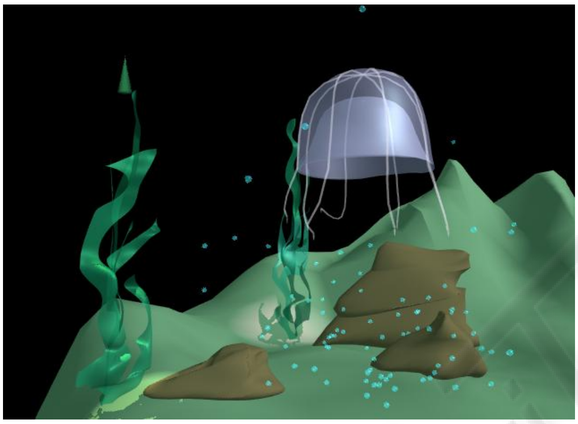

Figure 8 (d): Particles animated by jellyfish movement, frame = 2000.

group of particles is intermixed by water flow. Water movement also influences the tentacles. The behavior of influenced objects looks quite natural.

In Fig.9, four screenshots from the underwater scene with plants and some particles, placed in the water, are shown; the video is joined to the article and available on http://www.msi.unilim.fr/basilic /Publications/2006/ATG06. The movement of the green plants closest to the jellyfish can be easily seen. In the underwater scene also appears the task of a proper modeling of influenced objects. The particle systems are well suited for this. Here, for example, the green plants are modeled as particle systems with particles placed in control points and each particle is connected by springs with the closest ones. Generally, this model should be complicated, mostly by increasing the number of springs. In this scene the simulation is visually pleasing and gives a realistic impression of water flow pushing the plants.

Figure 9 (a): Underwater scene animated by jellyfish movement, frame = 1.

Figure 9 (b): Underwater scene animated by jellyfish movement, frame = 400.

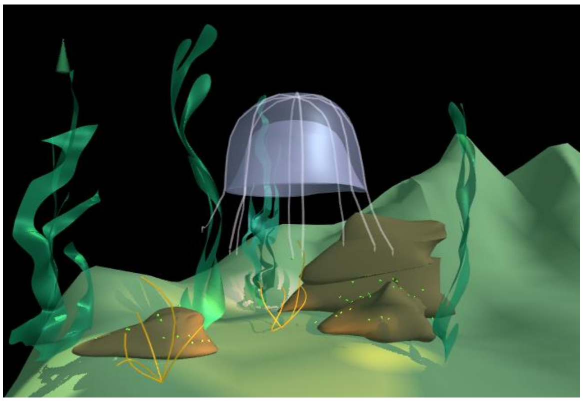

Figure 9 (c): Underwater scene animated by jellyfish movement, frame = 1400.

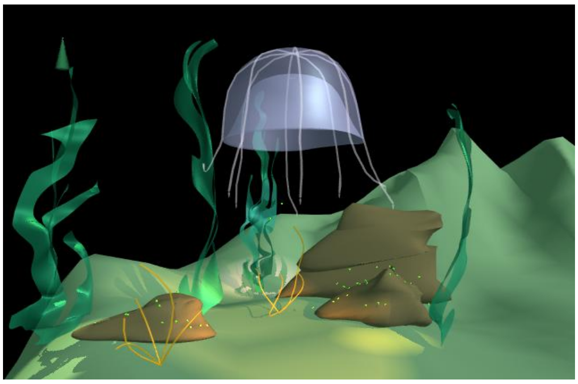

Figure 9 (d): Underwater scene animated by jellyfish movement, frame = 2000.

5 CONCLUSIONS AND FUTURE WORK

In this paper we presented a simplified physical model, based on the Lattice-Boltzmann method, for the simulation of a movement transformation from a dynamic soft body to a liquid. It is applied to a jellyfish in underwater scenes. The field is realized as finite lattice surrounding a jellyfish.

The special boundary conditions on the body surface are elaborated for this task. They are devoted to the aim of visually realistic presentation of the body motion transferring to the environment. Attention is also paid to the simplicity of the model.

Compared to previous work in this domain, the following points should be mentioned:

- The special boundary on the body surface, which depends only on the local properties of the surface. Independence of the boundary cells from the rest lattice cells allows taking into account the body as a generator of the motion.
- The modeling of body propagation in the water.

In a future work, the implementation of body trajectory changes, in order to avoid obstacles, can be considered. This can be done as a function of an obstacle bounding box coordinates and a body bounding box coordinates. Some minimum distance can be presented and, if needed, the correction vector may be added to jellyfish transition at each time step to keep this distance. Also, the full interaction can be considered, the reciprocal influence of the body and the liquid.

As a disadvantage, we can mention the possible instability of the solution that is usual for liquid modeling. The time step, the cell size, as well as the coefficients for the LBM model should be properly set in order to avoid instabilities.

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