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PHYSICALLY-BASED SIMULATION OF LIQUIDS IN INTERACTIVE ENVIRONMENTS

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1. Introduction

Matter in the liquid state of aggregation is referred to as a liquid. The physical behaviour of liquids is discussed within the framework of the fluid mechanics described. The numerical and most accurate simulation possible of the flow behaviour of liquids is an important part of the research and Development[1]. Because of the complex dynamics of liquids, However, such physical simulations are too computationally intensive for interactive applications, such as virtual reality environments or computer games[2].

The general motion of fluids (gases and Newtonian liquids) is physically described by the Navier-Stokes equations[3]. The Navier-Stokes equations can be formulated in a compressible and an incompressible form. Change of the volume of substance under external pressure, this property is called compressibility. Vice versa incompressibility denotes the property when under external pressure no volume change occurs. Real materials are always compressible[4]. On a macroscopic level, however, gases are classified as compressible and liquids and solids are generally considered incompressible because of the degree of compression is so small that it can often be neglected. For this reason, only the incompressible Navier-Stokes equations are considered in this work[5].It should be mentioned that the incompressible consideration is not the representation of effects that result from density fluctuations. For example, the representation of sound propagation or extreme temperature gradientsnot possible with the incompressible representation. such effects however, are of secondary importance in computer graphics[6, 7].

The performance improvements of standard PC hardware have exceeded the ambitions of research on liquid representation on these systems also towards interactive or real-time presentation. It is designated that real-time systems as computing systems whose processing results are available within a specified period of time. Computer graphics adapt existing physical simulation methods, to realize realistic animations of virtual liquids[8]. The aim of this efforts is an automatic, realistic, and plausible dynamic and representation. To achieve comparable realism with classic animation techniques, it is normally associated with a great deal of time and effort. In real-time environments, where the user interacts with the environment, there is no significant alternative to simulations since the interaction is unpredictable. Usually approximating physical simulation methods with classic animation methods are combined, so that for the simulation methods in computer graphics in term of physically-based method is used. Despite the use of physics-based simulation techniques for the animation of liquids require generation Photo-realistic results. However, it takes many minutes or hours per image (e.g. [9, 10]). Because in addition to the simulation, there is one

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constantly changing surface of the liquid and optical depict characteristics to extract realistically. These three steps are computationally expensive.
Real liquids have a variety of physical properties, for example, complex and sometimes chaotic movements and behaviors. In addition, the surface is subject to permanent change in dynamic situations. Moreover, most Liquids in general and transparent liquids in particular exhibt complex optical properties such as reflection, refraction and absorption of light waves. The realistic representation of these features is computationally expensive[11].Correspondingly, the liquid representation in computer graphics can be divided into three steps to be carried out independently of each other (see figure 1).

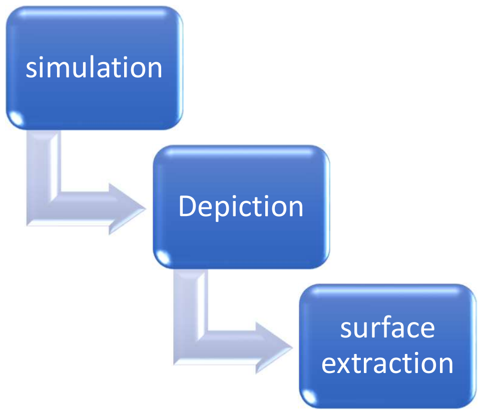

Figure 1. The general liquid pipeline.

The basic problem of the interactive liquid representation consists in the efficient execution of the general liquid pipeline. In non-interactive environments, i.e. environments in which there are no limitations on the computation time, the procedure is usually to start with a high-resolution to carry out physical flow simulation. The resulting free Surface is extracted at high resolution — for example with the help of a marching Cubes algorithm [[12]]. The resulting surface is then rendered realistic using techniques such as ray tracing [[13]] and photon mapping [[14]].The goal of research efforts in the field of interactive representation is to execute the three steps of the general liquid pipeline in real time while still achieving realistic results. Although already considerable Advances in interactive representation have been made, new techniques needed to liquids: more detailed and larger quantities. To be able to represent in real-time environments, these two points also represent Existing three-dimensional, interactive liquid simulations are significantly different problems[15]. In a way, these two points are mutually dependent. Of the Effort increases with simulated fluid volume, so detail decreases and vice versa. The aim is therefore to find a compromise that is as balanced as possible between quality and performance.
At this point, water is explicitly mentioned, since it is necessary for computer graphics probably represents the most frequently represented liquid. Just the representation of transparent water with its very low viscosity and the resulting high dynamics is a particular challenge.
This work presents new methods for liquid representation in interactive environments. New methods were suggested to display more details or to increase the simulated liquid volume.

From this point of view, this work first presents an abstract view of the liquid representation. novel methods were designed, which contributions in all three steps of the interactive liquid representation.

2. Physical basics

The general motion of fluids (gases and Newtonian liquids) becomes physically described by the Navier-Stokes equations. The Navier-Stokes equations can be expressed in a compressible and an incompressible. Changes a substance under external pressure its volume, this property is called compressibility. Vice versa incompressibility denotes the property when under external pressure no volume change occurs. real materials are always compressible.
On a macroscopic level, however, gases are classified as compressible and liquids and Solids are generally considered incompressible because of the degree of compression is so small that it can often be neglected. For this reason, only the incompressible Navier-Stokes equations are considered in the following. It should be mentioned that the incompressible consideration is not the representation of effects that result from density fluctuations. for example, the representation of sound propagation or extreme temperature gradients is not possible with the incompressible representation. such effects however, are of secondary importance in computer graphics.
The incompressible Navier-Stokes equations of viscous flows cease System of nonlinear second-order partial differential equations and consist on the one hand of the principle of momentum:

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) = -\nabla p + \mu\triangle\mathbf{v} + \rho\mathbf{F}_{\text{ext}}$$

and the continuity equation describing mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0.$$

Since liquids are considered to be incompressible, the density can be assumed to be constant ($\partial\rho/\partial t = 0$). In order to conservation of mass results from the continuity equation:

$$\nabla\cdot\mathbf{v} = 0.$$

these are divergence-free flows, so that with constant density, mass cannot be created or destroyed in any volume element. Consequently, the volume of liquid flowing into a given volume corresponds to that in same period outflow volume.
The simulation of rigid bodies is necessary so that objects move naturally within the framework of a liquid simulation and at the same time be able to interact with it. The goal is, for example, the representation of floating objects. The physics of rigid bodies represents a branch of mechanics. The movement of a rigid body is divided into a translation part x(t) and a rotation part R(t). x(t) describes the position of the center of gravity with a translation speed v(t) and R(t) describes the rotation of the body around the center of gravity an angular velocity ω(t). R(t) represents a 3 × 3 rotation matrix. The orientation of ω(t) describes the current rotation axis of the rotation and the absolute value |ω(t)| represents the rotation speed.

For objects that move through a liquid with the help of a drive (e.g. boats), a dynamic buoyancy is created, which is divided into two components: dynamic buoyancy (orthogonal to the flow direction) and drag force (parallel to the flow direction). These forces are for example responsible for the typical movement of motor boats. These forces can be calculated according to the surface normal of the object. an efficient one method for calculating the forces is given in [16].

The visual appearance of transparent liquids is largely determined by the interplay marked with light. The term optics refers to classical optics, which is the study of light in the wavelength range that of the human eye can be perceived.

The calculations of reflected and refracted rays are described somewhere else[17]. These are used to determine the change in direction of sight and light rays. Visible rays refer to the rays emanating from the point of view and light rays to those from theLight source outgoing rays. The latter are necessary for the generation of caustics, which represent a distinctive feature of transparent liquids. The law of reflection states that incident and reflected ray with the same angle of incidence and lie in one plane with it. A calculation of the reflection vector using analytic geometry, below Abandonment of trigonometric functions, enables an efficient calculation of the reflection vector.

Likewise, When electromagnetic radiation passes through a layer absorption effects occur, which increase the intensity of the reflected and reduce refracted radiation. Only part of the incident radiant flux Φ_e becomes detected behind the layer as transmitted radiant flux Φ_t. It depends on the layer material and on the wavelength λ of the radiation. The radiant flux inside a layer increase exponentially with penetration depth x.

3. Simulation method

The existing works on fluid simulation in computer graphics deal with the surface extraction and the representation. The majority of existing work, however, focuses on non-real-time methods, because of the complexity is high and each of the three steps to have to be carried out accordingly, Moreover, it is correspondingly time-consuming to execute. Generally, the existing methods can be classified as height-field based or three-dimensional. The three-dimensional methods is the high cost of the simulation and of surface extraction. Therefore, the results in interactive environments are still relatively undetailed or represent little fluidity, since only low-resolution discretizations can be used. Also, the accurate representation of three-dimensional liquids is complex, since the representation of optical properties such as reflection, refraction or Caustics required - for realistic results an expensive Ray tracing method is recommended.

In interactive environments, however, for a quick Representation, approximate methods are used. Altitude field-based methods are usually based on two-dimensional simulations and can therefore be executed much more efficiently. Also the top Surface extraction is more efficient for height fields since no three-dimensional effects have to be taken into account. For this reason, much more detailed results can be obtained with height-field-based methods in interactive environments. However, the disadvantage of the height-field-based method is the fact that no three-dimensional effects, such as splashing water or breaking waves, can be represented, and the liquid is therefore always appearing flat.

In order to reduce these disadvantages while at the same time being able to achieve interactive results, a general approach to the Fluid simulation presented in interactive environments using both two- and three-dimensional simulations in a single simulation environment. In addition, the use of empirical methods in order to be able to represent complex effects that occur for a physical Simulation in interactive environments would be too expensive. Therefore, Concrete realizations using different simulation methods must be developed.

In this work, an SPH simulation is used for the three-dimensional flow simulation. However, the use of an FDM simulation is also possible. To simulate the surface waves, the wave equation used and solved with an FD method. The simulation with the SPH method leads to liquids that consist of relatively few particles. hence, , suitable potential functions are chosen for the representation, so that the distance between particles remains visually invisible. Nevertheless, this under-discretization leads to the effect that detailed liquid properties cannot be represented. These include physical and visual properties. So, waves of small amplitude or wavelength cannot be represented with few particles. In addition, the damping of the SPH simulation in interactive environments means that surface waves are unrealistic and become steamed quickly. Furthermore, a coupling of an SPH simulation consisting of a few particles and, for example, a floating object in Real-time environments only represent low-frequency wave trains. High frequency waves could only be generated with the SPH method using a multiple of the particles during emulation. However, such simulations then could be no longer executed in real time. However, The representation of high-frequency waves are solved with a two-dimensional solution of the wave equation . By using two simulations, such a detailed Fluid simulation can be achieved, which is a full flow simulation also can include detailed surface waves. The methods used are summarized in Figure 2 .

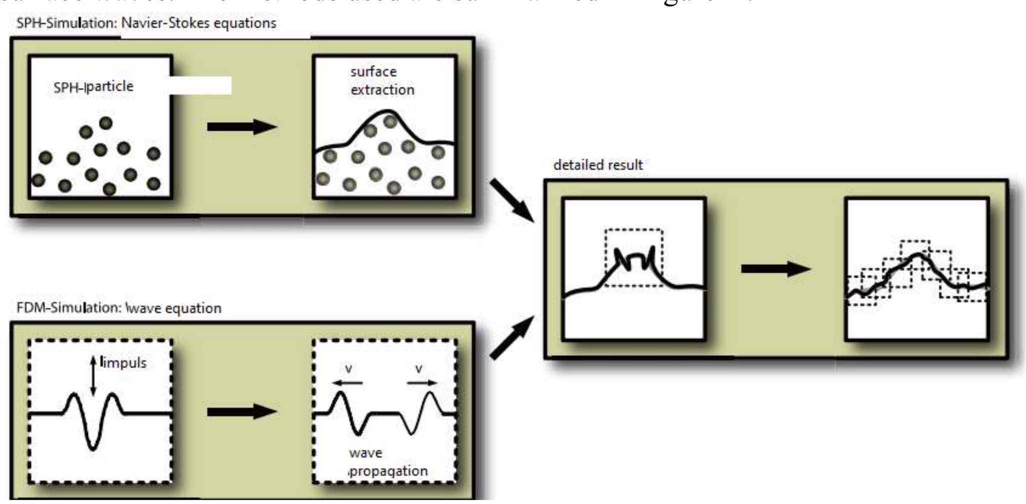

Fig. 2.: Principle: The global flow is determined using an SPH simulation (above, 2D Cross-section). An additional surface simulation complements surface detail (below, 1D example). The combination results in detailed surfaces (right).

For the temporal synchronization of both simulations, the ratio of both Simulation time steps Δt_{WG} and Δt_{N-S} restricted to an integral ratio N_t: $\Delta t_{N-S} / \Delta t_{WG}$, Thus, N_t surface simulation steps are performed per volume simulation step.

The liquid surface has to be extracted from both simulations. In addition, a height-field based approach is used. The two-dimensional wave equation typically has a higher one Surface resolution than the three-dimensional flow simulation. In principle could the liquid surface of the SPH simulation be with the same resolution, how those of the surface simulation are extracted. Since the flow simulation is relatively undetailed, it makes sense to generate the SPH surface with a lower resolution for reasons of efficiency, according to the details presented.

First the restriction is introduced that the surface resolution of the solution of the wave equation is an integer multiple of the surface resolution, i.e. The solution of the SPH simulation is comparable to the procedure in the previous section for surface generation. So a quick combination can take place, since no time-consuming floating-point number operations are carried out. Thus, for the surface generated from the SPH simulation, the Magnitude $X_{SPH} \times Y_{SPH}$ and the more detailed surface of the wave equation of magnitude

$X_{WG} \times Y_{WG}$ in relation to the discrete value $N_{surface}$:

$N_{surface} = X_{WG} / X_{SPH} = Y_{WG} / Y_{SPH}$

This constraint is not a major constraint: due to the smoothing that occurs, the exact size of the height field is arbitrary and small Changes in size are not or at least hardly noticeable. Then the low-resolution SPH height field is bilinear on the size of the height field of the wave equation is extrapolated and both can be superimposed directly.

4. Results and discussion

The presented method was implemented in C++ using OpenGL 2.0 and the associated shader language GLSL. runtime measurements given in Table 5.4 and usually achieve real-time performance with a display resolution of 950 × 950. The measurements were carried out on a dual-core 2.6 GHz AMD Athlon 64 CPU with 2GB RAM and one on the ATI Radeon x1900 Chip based GPU (512MB). The implementation was done using of multi-threading. A core simulates the physics with SPH and treats User input and the other core solves the wave equation, extracts the surface, creates caustics using the method above, and represents the scene. The parallelization is thus realized as follows:

- Core 1: SPH simulation, interaction
- Core 2: wave equation, surface extraction, caustics, fountain, representation

Performance can be improved using GPU-based implementations - as was realized with other methods. In general, the running time depends on the following parameters:

- Number of SPH particles used,
- XSPH × YSPH (surface resolution),
- XWG × YWG (simulation and surface resolution).

Measurements show that 40–70% of the runtime for the simulation with the SPH method can be used for surface resolution(see table1) — if less than 4000 particles are used in the shown prototype implementation. Thus, surface details basically hardly represent. The technique ,presented her,e of combining 3D Flow simulation and 2D surface simulation solves this problem and achieves detailed surfaces with good performance. the advantages of the presented method lie in:

- volume interactions (e.g. movement of a water glass, objects),
- surface interactions (e.g. rain, moving objects),
- global currents (e.g. Bach)
- Movements of objects with the current (for example leaves)

example	N-S (SPH)	N-S (SPH) (XSPH × YSPH)	WG (FDM) (XWG × WG)	Cores	FPS (1/s)
5.2a,b,c	-	-	300 × 300	1	46
5.13c	2000	50 × 50	-	2	102
5.14	2000	50 × 50	400 × 400	2	30
5.18a	2000	50 × 50	200 × 200	2	85
5.18b	2000	50 × 50	200 × 200	2	93
5.19b,c	2000	50 × 50	200 × 200	2	75

Table 1.: Runtime measurements of the presented algorithm for the given examples (in FPS). the number of SPH particles, the lattice sizes of the SPH and wave equation height fields and the number of cores used are given.

For example, the low viscosity of real water can hardly be achieved in real time with a Navier-Stokes-based simulation — because of large time steps and correspondingly high damping. Therefore, liquids resemble real-time environments in their movements, for example, often more oil than water. This Disadvantage is reduced with the presented method because the viscosity due to of the detailed low-attenuation surface waves appears low. on the other hand, liquids with high viscosity can be directly represented by reducing the simulation time step and increasing the damping. A limitation lies in the high-field-based representation of the three-dimensional simulation — so three-dimensional effects can be simulated even though they are not represent directly. Detaching liquid particles, for example, must be treated explicitly.

The method described here uses an SPH simulation to represent the flow and an FDM simulation to solve the wave equation. FD method for three-dimensional flow simulation can also be used. If a corresponding surface is generated, the detailed surface simulation can then be mapped based on this surface. For interactive environments, however, recommend an SPH simulation because it can be run efficiently — especially for small amounts of liquid. Also for

the wave equation ,the FDM approach may be chosen. For example, the Wave Particles method can be used for the approximation.
Simulating a breaking wave has long been a topic in computer graphics. The representation of the large amount of liquid involved and the high level of detail represent the main difficulties. For interactive procedural approaches have been presented so far ([18]). The complete three-dimensional simulation of the required amount of liquidin real time is difficult to achieve with today's computing technology. The strength Self-similarity of a real breaking wave is the starting point for presented layering for virtual representation. Only a two-dimensional SPH simulation is performed, which significantly accelerates the Simulation. The sets of all particle positions of the last n time steps of the simulation stored as particle layers $(P(t_j), j = -n, \ldots, 0)$.
A breaking wave is constructed from this two-dimensional dataset. For this purpose, the layers s_i are arranged along the z-axis (i: z-position index, see Fig. 3). The shape of the wave is given by the function f(i) and
$s_i = P(t_{f(i)})$,
since the method described only simulates a two-dimensional liquid, just a few particles are enough to discretize the liquid to break the wave. However, the sum of many layers results in many particles per frame, which have to be taken into account to create a three-dimensional surface. For example, more than 100,000 displayed particles are possible in real-time environments. The surface extraction can be done, for example, with the method described later in other references, which generates a surface in real time despite the high number of particles

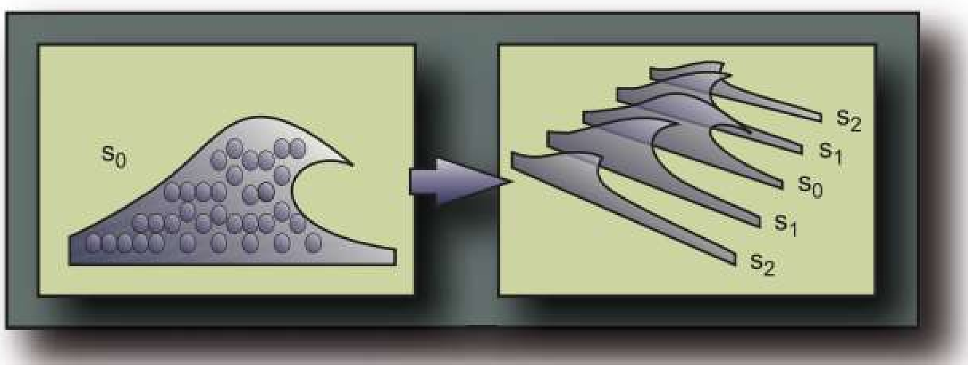

Fig. 3.: Principle of the simulation of breaking waves. Only a 2D SPH simulation will do carried out. The last n time steps (here: n = 3) of the simulation are arranged as layers. Thus, the symmetrical appearance becomes a three-dimensional one breaking wave.
The generation of a breaking wave in the Computer graphics are usually based on generating a wave running along an inclined plane. Due to dispersion, the amplitude of the wave increases and when a threshold is reached, the wave becomes unstable and breaks up. The Wave itself is created with a moving plane at one end of the reservoir. This moves horizontally and generates a wave due to the pressure.
In this work, a different approach to generating breaking waves was chosen, which is more stable than the procedure described above, since it does not involve high external induced

pressures,so the requirements in real time environment is small. An additional external force is introduced, which accelerates the fluid. Thus, as the liquid moves in a pool, it becomes accelerated towards the external force. The force field is then reversed or deactivated; a breach occurs at the pool wall. In practice gravitational field can be varied. From a physical point of view, the waves generated in this way correspond to the waves generated in a moving vessel. In addition, a virtual pool can also be moved interactively and the wave thus interactively can be broken.

5. Conclusion

We introduce new contributions to the simulation of liquid in interactive environments. It is physically-based simulation, the combination of simulation techniques is described to improve the quality or potential of virtual fluids. With the help of moving simulation grids on an ambient surface, for example, it is possible to interact with seemingly endless water surfaces. The method is also well suited for representing rivers and lakes. The shown combination of a surface wave and flow simulation in two dimensions builds on the Wave Particles method to represent flows. So additional moving Liquids can be represented. With the help of the coupling of a three-dimensional flow simulation and a surface simulation, much more detailed surfaces can be represented in real time. Achieving comparable detail using only a flow simulation is real-time. Finally, a layering of two-dimensional simulation data in combination with the presented method for the surface representation of dynamic point clouds, a realistic representation of breaking waves in real time can be reached.