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Real-Time Modelling of the Action of Wind on Liquid Surfaces

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Abstract

This work in progress aims to model the appearance of the surface of various liquids, when force from a virtual wind is applied. The physical effects caused by a wind force include waves and spray. The appearance of these effects is dependent upon the physical characteristics of a liquid, such as viscosity and surface tension. Much of the realistic work carried out in this area has depended upon non real-time methods such as frame-by-frame rendering and animation. Alternatively, supercomputers have been used to process visualisation models which use large quantities of data. This study aims to produce realistic effects with an attractive appearance, in real time. Work will also be carried out to explore the possibilities of modelling breaking waves in real time.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling

1. Introduction

The graphical representation of liquids remains an ongoing problem for computer science. Currently, the only means of representing a fully realistic, animated liquid surface is by following physical models which are computationally expensive and very complex. The most physically accurate models depend upon on solutions to the 3D Navier-Stokes fluid differential equations; however, this degree of physical accuracy is currently almost impossible to accomplish and often not required.

There are many applications for visual representations of liquids, from scientific modelling to entertainment, and each type of application will have widely differing requirements of a model. In scientific modelling, the aim of visualisation is often to reveal areas of interest from within very large data sets. Within the entertainment industry, photorealistic liquid is integrated into scenes within movies and games. Many techniques have, therefore, been developed to create solutions to specific representational challenges.

This variety of techniques has given rise to different types of realism being developed in the different models. In [Fer03], three types of realism were identified for static images of simulated fluid: physical realism, photo realism and functional realism. These types were discussed and expanded in [AM02], in order to cover dynamic behaviour: in physical realism, the simulation is based on the laws of physics; in photo realism, it is based on the generation of visually convincing scenes; in functional realism, it is based on conveying the information that a dynamic object is present.

The realistic modelling of breaking waves is a further unsolved problem, and modern methods are still time consuming. In [MMS04], for example, a human animator uses a library of 2D breaking wave shapes to define the 3D shape of a breaking wave at a particular moment. The computer system then uses a 3D Navier-Stokes solver to compute the evolution of the wave dynamics. The animation of fluid with splash and foam was examined in [TFK*03], and each realistic frame took approximately 10 seconds for simulating and 20 seconds for rendering.

This study aims to produce a trade-off between non-realistic, physically-accurate representations of wave motion, and photorealistic but non-physical dynamic liquid surfaces. The dynamic behaviour of the liquid approximates physics laws, whilst the surface has a realistic appearance. The simulation will allow the representation of the movement of liquids of differing physical properties when a virtual wind force is applied. In addition, the intention is to produce a simulation that will run in real time. Finally, the possibilities of modelling breaking waves in real time will be explored as a basis for future work in this area.

The system is designed to be interactive, in that the user will be provided with a means to change the physical properties of the virtual liquid to be modelled, as well as wind direction and force. There are some standard liquid settings provided as pre-set; for example, water, honey, and mercury.

2. Properties of liquids

The principal physical properties of a liquid which visually affect the action of wind on its surface are surface tension, viscosity, and density.

Surface tension is caused by the force of attraction between the molecules of a liquid. For molecules which are completely surrounded by other molecules, this force of attraction is equal in all directions. However, the molecules on the surface are subjected to a net force which pulls them back into the liquid. This force gives rise to the effect whereby a drop of a liquid will attempt to form the shape with the smallest surface area, i.e. a sphere. Also, a well-known effect of surface tension is to produce a "skin" on the surface of water which is strong enough to support the weight of certain insects. In general, the lower the surface tension of a liquid, the larger the waves for a given wind force. Water and mercury have particularly high surface tensions.

The viscosity of a liquid is a measure of its resistance to flow and is highly temperature dependent. The higher the viscosity of a liquid, the greater the damping effect on waveforms. There has been some previous work carried out on the viscous damping of water waves, mainly in relation to the wake produced by a moving ship. These studies are examined in [TSL02]. Richard and Raphaël [RR99] investigated how wave resistance is modified by liquid viscosity by imagining a rigid cover, completely fitting the liquid surface and able to apply a pressure. Generally, with a more viscous liquid, waves are more rapidly damped. Chandrasekhar [Cha61] showed mathematically that with increasing viscosity, the larger the drops of liquid when sprayed from a nozzle.

The density of a liquid measures its relative "heaviness". For a high density liquid, the greater the energy needed to be transferred by the wind, in order to produce waves. The waves will also tend to be rapidly damped, because of the action of gravity. Therefore, as a general rule, a lower density liquid will produce higher waves, for a given wind speed.

In addition to these properties, related to the amount of force transferred from a wind to a liquid, there are visual physical properties to consider. These include colour, transparency and reflectance.

3. Wave formation

In a fluid, the energy that forms waves is known as the disturbing force; in this case, the force is transmitted by a virtual wind. The dominant force which tends to flatten the waves is called the restoring force.

When a wind interacts with a smooth liquid surface, friction eventually begins to make the surface move. Eddies and small ripples develop, and these enhance the interaction of wind and liquid by increasing aerodynamic drag. These small waves are known as capillary waves, and their main restoring force is surface tension. The larger the waves become, the more surface area they offer to the wind and the more wind stress they receive. These larger waves are known as gravity waves, because gravity is their main restoring force. In the case of open seawater, the energy transferred to the water by the wind increases with the fourth power of the wind speed, and the amplitude of the waves increases to the third power of the wind speed [Ant00]. Waves transmit energy, but not liquid; in this study, therefore, the behaviour of the surface, rather than fluid flow, will form the main focus.

The shape of waves varies with their size. Capillary waves tend to have rounded crests and V-shape troughs. As wave size increases, they become more rounded, longer and more closely resemble sine waves. The larger gravity waves are also covered with the smaller capillary waves. The size of waves is dependent upon the wind velocity, wind duration and fetch (the area and distance over which the wind has travelled).

In shallow liquid, waves tend to break because of friction with a sloping solid surface underneath. This friction causes the leading edge of the wave to be slowed more quickly than the trailing edge, so that the trailing edge overtakes the leading edge and produces a breaking wave as it collapses over the top.

Waves are described in terms of, amongst other parameters, wavelength (the horizontal distance between successive wave crests), amplitude (height) and frequency (number of waves to pass a point per unit time). If a wave is damped, its amplitude decreases with time.

In real-world interactions of liquid and natural wind forces, extremely complex surface effects can arise from the combination of constantly varying wind speed, angle and direction and interactions with obstacles and boundaries. Not all of these interactions are fully understood in the field of hydrodynamics. This study, therefore, will concentrate on modelling the effects of a steady, monodirectional wind force.

4. 3D wave generation

As can be seen from the discussion above, there are many factors to include in a liquid simulation with visual realism. In summary, these are: the height, shape, frequency and damping of the waves; the colour, transparency and reflectance of the surface; spray and breaking waves.

In the current stage of the project, experiments are being carried out using an indexed triangular mesh to represent the surface of the liquid. The advantage of using a mesh, rather than a particle method, is that particle methods have a much higher cost in terms of CPU time and storage. A particle method, therefore, is unlikely to be suitable for the creation of a real-time model. It can also be difficult to control a sur-

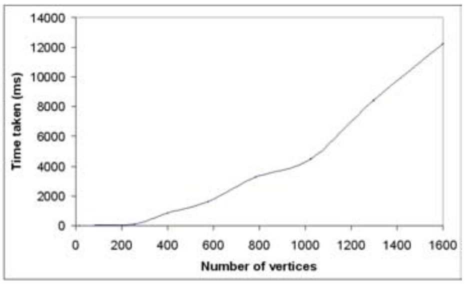

Figure 1: *Time taken in milliseconds to produce the maximum waveform from a flat grid for different vertex counts, for a particular wind force.*

face smoothly using particles, and a realistic surface is a basic goal of this system. However, relatively small numbers of particles will be needed for spray representation.

The modelling of a dynamic surface as a mesh is a well-known method in computer graphics, and several techniques are available for reducing their computational cost. Here, the use of an indexed triangular mesh saves memory by removing redundancies with recording vertices, i.e. each distinct vertex and its properties is recorded only once. There is, however, a disadvantage to using indexed meshes; the array of indices must be examined before a vertex can be rendered.

Particle systems are frequently used to represent liquid spray and other fuzzy effects such as clouds, smoke, water, and fire. This method was introduced in [Ree83], as a scheme for modelling fuzzy objects such as fire, clouds and water; an object is represented dynamically as clouds of primitive particles that define its volume. Several authors, as in [FM00], have combined these techniques in the creation of a particular fluid model.

The computer currently being used for experimentation is a consumer-level machine running Microsoft Windows XP Professional. It has the following specifications: Genuine Intel 3192 MHz processor; 1GB memory; NVIDIA GeForce FX 5600XT graphics card. At this stage, Java3D is being used as a relatively simple means of drawing and manipulating a grid. The use of Java3D may, however, exact an unacceptable overhead in terms of processing time, and C++ will be used to access the OpenGL libraries, if this proves to be the case.

A graph of current performance is shown in Figure 1. It shows the time taken from initial application of the virtual wind to the flat grid, up to maximum perturbation; times are compared for increasing numbers of mesh triangles. These times are given for the current, experimental version of the code and include debugging methods and unoptimised sections. The final version will, therefore, transform the grid more rapidly.

Figures 2 and 3 show examples of the triangle mesh being used in this study. The size of the grid in the images is 40 by 40 vertices. In figure 3, a basic texture in the form of a

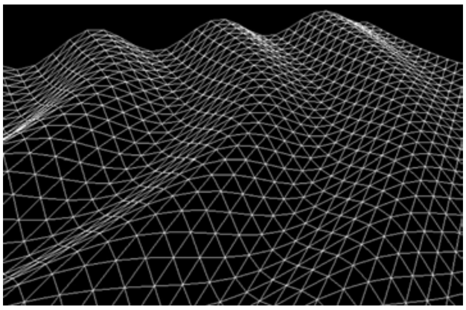

Figure 2: *Example of the mesh being perturbed by a virtual wind.*

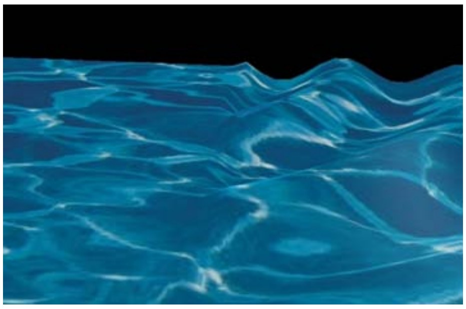

Figure 3: *Example of virtual wind effect on a water surface.*

photograph of a water surface is being applied, for the purposes of illustration during testing.

In figure 2, the surface has a wind force applied towards the top left of the image. As the waves are restored by gravity and other forces, they become damped. This effect can be seen towards the bottom right of the image. This particular liquid representation assumes infinite depth and no boundary effects. Figure 3 shows the effect soon after applying a virtual wind force, before the waves have propagated across the entire surface.

The actual generation of capillary waves on the surface of larger waves would be prohibitive in processing time. Therefore, the final version of the system will exploit the technique of bump mapping, as originally developed in [Bli78]. This technique provides a cost-effective means of simulating the appearance of capillary waves covering the gravity waves, by perturbing the surface normal.

A standard wave generating algorithm is being used in the figures above. The efficiency of this algorithm is in the process of being improved upon, so that the processing time for the wave simulation takes as little time possible. This will be important when particles are included for spray illustration. Spray will be produced when the virtual wind reaches a critical speed and angle, and these critical values will be dependent upon the physical properties of the liquid. The visual properties of the spray will also depend upon the liquid properties, particularly viscosity.

The effect of restoring forces has been represented by a damping factor, which can be altered in order to represent some of the effects of viscosity and density. A further factor takes into account the degree of transference of energy from the wind to the liquid, representing further effects of density. Other factors will be introduced as necessary, enabling the properties of the visualisation to be changed as required, by user interaction.

This system works effectively as a stand-alone illustration of the action of wind force on liquid surfaces. However, it is easily adaptable and will fit into existing virtual environments if provided with suitable data points for the area of the mesh from the existing topography. The data points will then be used to generate a mesh over the required area. If liquid depth is also provided, suitable breaking waves will be produced at the boundaries. Wind data will need to be provided by the host environment, as well as information about the physical properties of the liquid to be visualised. It is therefore envisaged that this system will also function as an external plug-in for liquid rendering in virtual environments, by the provision of an API.

5. Summary

This work aims to produce a system for generating a realistic liquid surface with animated wind effects, in real time. In its current version, the system developed can show the visual effect of wind on liquids such as water while taking into consideration a limited set of physical parameters. The software platform makes it easy to visualise wave forms for a variety of liquids with different physical properties and can be controlled by the user by adjusting parameters for surface tension, viscosity and density, as well as wind direction and speed. The results of this visualisation are realistic and already comparable with the best attempts in the field. On the next stage of the project, texture mapping will be added, and spray and breaking waves will be investigated. The final version of the system will be usable both as a stand-alone visualisation and in conjunction with existing virtual environments.

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