Real-time Flow Visualization using Projection Mapping Technique

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Abstract. Flow visualization is a fundamental topic in scientific visualization and has been the subject of active research for a long time. Usually, information begins from numerical simulations, for example, those of computational fluid dynamics, and should be investigated by methods for perception to acquire a comprehension of the flow. With the rapid rise of computational power for simulations, the interest in further developed visualization strategies has thrived. The idea is to attain advanced visualization through the means of projection mapping. When incorporated with the properties of the fluid, whose flow is to be studied, we can create a visual simulation by extracting the real-time variations data through sensors and feed it to the projector, which results in a visualization method in the 3D plane. The complete process is made visible as the image is projected through light and also in space. Real-time Flow Visualization using Projection Mapping methods will help attain the same results as the conventional methods at less cost. As this process is crucial for many industries in the testing and design sectors, the desired output must be obtained within the given time constraint. This method will help to optimize the complete process. The result can be used to derive the necessary conditions for the best design and performance of the object or vehicle.

1. Introduction

Flow visualization is a technique that makes the particle flow visible to our bare eye as most of them are invisible to get their numerical information [1]. Mathematical computations and experiment can examine the flow of the particles. Flow visualization methods are used to deliver analytic data near the movement around the model [2]. Flow visualization provides information on the entire subject instantly clear without the need for data processing.

In tentative methods, flow is envisioned using three methods. Surface flow visualization, particle tracer method, optical method. These flow visualization methods have been quite helpful in making the data clear, but the experimental setup is usually time-consuming and very expensive.

Projection mapping is related to movie mapping, is a mapping method used to convert things, often asymmetrical shapes, into a plane where a movie projection can occur [3]. These things may be composite industrial surroundings, such as structures, small indoor items, or acting stages. With the help of specific software and tracking sensors, a two- or three-dimensional body is spatially mapped on the simulated program, which imitates the actual environment it is projected on. Projection mapping intends to deliver a new involving experience for the audience through a visual imitation. The overview uses technology to control lighting onto the changeable exterior type and turn usual objects into collaborating 3D displays.
Flow visualization using the projection mapping technique can help us understand the flow of the medium along the surface in real-time through visual interpretation. The projection mapping adapts to the real-time input given to the system, it is easier to create an interactive environment susceptible to the immediate changes in the flow of the medium and can further be used to produce a real-time flow visualization, through which necessary data can be derived with regards to the medium for further studies and calculation on the same field.

2. Methodology

The methodology involves four major components; Program/Content, Mapping, Visualization/Display, Calculation.

The programs for the particular particle or medium we want to study the flow visualization will be executed and projected onto space using projectors (from more than one place). The code visualizes the water body as a mesh. Each element of the mesh has a particular vector associated with it. The waves are created using the sine wave piling equation based on the basic sine equation. The Bump Mapping Technique achieves the depth of the wave and the detailing. The sine wave piling algorithm is used to design the water simulation [4]. It is a Fourier composing method to pile up several sine waves with different frequency and amplitude.

The basic sine wave equation is given as:

\[ Y(x, y, t) = A \cdot \cos(w \cdot (x \cdot \cos + y \cdot \sin)) + wt \cdot t + FI; \]  

Where 
- \( A \) = Amplitude of the waves 
- \( w \) = Spatial angular frequency 
- \( wt \) = Temporal angular frequency 
- \( FI \) = Initiatory phase 

The sine wave piling equation, which is derived from the equation mentioned before, is:

\[ H(x, y, t) = \sum_{i=1}^{n} A_i \times \sin((D_{ix} \times x + D_{iy} \times y) \times \frac{L_i}{2\pi} + t \times S_i \times \frac{2\pi}{L_i}) \]  

In equation (2), \( A_i \) is the amplitude of number \( i \) sine wave; 
- \( L_i \) is the wavelength of that wave; 
- \( D_{ix}, D_{iy} \) are the direction of it; 
- \( S_i \) is the speed of it; 
- \( t \) is time.

Bump mapping is a computer graphics technique where at each pixel; a heightmap is considered as a basis to look up a perturbation that is normal to the surface of the object being rendered, and the same is applied before calculating the contrast and the illumination at different parts and positions of the object [4].

First, for each pixel, the bumps are converted into vectors present on the bump map. In left figure 1, a zoomed-in view of the bump-map is shown; the lighter pixels stand out compared to the dark ones. A vector is computed for each pixel. These vectors represent inclines of the surface at a pixel. In figure 1, on the right side, the red vectors point in the downhill direction.

Figure 1. Details of Bump Mapping
One widely used method to calculate these vectors is to calculate the X and Y gradient of a pixel:

\[
x_{\text{gradient}} = \text{pixel}(x-1, y) - \text{pixel}(x+1, y);
\]
\[\text{(3)}\]

\[
y_{\text{gradient}} = \text{pixel}(x, y-1) - \text{pixel}(x, y+1);
\]
\[\text{(4)}\]

The \(x_{\text{gradient}}\) and the \(y_{\text{gradient}}\) is used to adjust the normal vector of the polygon at particular points. In the figure 2 a bump map and polygon are shown. They all show U and V vectors. After the simple adjustment, we can see the new Normal vector is:

\[
\text{New Normal} = \text{Normal} + (U \times x_{\text{gradient}}) + (V \times y_{\text{gradient}});
\]
\[\text{(5)}\]

The brightness of the polygon at a given time is calculated using the New_Normal [4].

The object, be it a plane or a vehicle, will be brought into the frame, mapped by the Kinect sensor. The program is updated with real-time data to display the variation in the flow due to the object. The projection of simulation data is achieved using projection mapping; the complete process flow is shown in figure 3. Projection-Mapping is also called Spatial Augmented Reality and is used to create illusions in the real world [4]. After that, the process of visualization takes place. TouchDesigner Software is used to map the display onto the screen. The program's executable file is exported to the software, which is then projected onto the designed setup with the help of a projector. The sensor will capture the movement in the frame, and changes are made in the program accordingly. The result of the program is being projected virtually in the space. Thus, we can see the flow variation which will take place with our bare eyes.

When it comes to calculation, depending on the parameters required, it can be point-based or surface-based. The streamlines of the flow can be observed. The tangential stress along with the transition of the boundary layer can be found out. Along with these, the diffusion of mass and change in density can be calculated. Flow visualization is a classic sub-field of scientific visualization, and we can use it in studying the vortices or the turbulent nature of fluid [5]. As we are considering light as the source to depict the motion of a fluid, delay in terms of data acquisition and processing is less or non-
existent. The idea is to attain information on unsteady motion by considering various fluids and cases. This will also help in understanding the flow characteristics of fluids.

3. Real-time Implementation (System Description)

The complete system can be divided into 5 steps, and the flow of the process is shown in Figure 4.

![Flow of Implementation Process](image)

**Figure 4.** The flow of Implementation Process

3.1. Simulation Code

The simulation code is a processing code. Processing is software that helps visualize the code. Using the techniques mentioned in the methodology, water simulation code is executed. The input to this code is the data from the Kinect sensor. The software uses Kinect library to utilize the various functions of the Kinect v2 and handpick the features relevant to the program. The user interface of the software is shown in Figure 5.

![User Interface of Processing Software](image)

**Figure 5.** User Interface of Processing Software
3.2. Kinect Calibration

The Kinect SDK user interface is figure 6. Kinect calibration is done with the help of the Kinect SDK, which Microsoft provides. In this process, check for the configuration and verification of the sensor. Also, test the sensor with regards to depth readings, color readings, previews and resolutions. This enables us to understand the input capacity of the sensor, which is to be noted for later use in the base code. The Kinect and Projector are calibrated to have the same focal center. Gray codes are projected onto the screen. Given the coordinate mapping functions of the Kinect SDK, this Gray code pattern is used to establish the precise mapping from a 3D point in the Kinect camera’s coordinate frame to the corresponding point in the projector’s image [6].

![Figure 6. Kinect SDK User Interface (UI)](image)

3.3. Skeletal Tracking and Depth Mask

Skeleton Tracking Depth Mask code from Kinect v2 library is used to retrieve the data of the joints and the positions of the parts of the body. Kinect SDK can also be used to make use of this feature of the Kinect sensor. Further concentrate on a particular part of the body (in this case, hands) and proceed with the code and calculations. Figure 7 presents the output of the skeleton tracking program and joint chart for Kinect v2.

![Figure 7. (a) The output of skeleton tracking program, (b) Joint chart for Kinect v2](image)
3.4. Projection-Mapping

Projection-Mapping is achieved using the TouchDesigner Software and the projector. The projection mapping concept was established to accurately map the world, utilizing more than one dimension [7]. The software maps the object to be used as a screen, and then the display is projected onto the screen. Without any screens or lenses, the projection mapping presents the virtual layer directly onto the physical object [8]. The projected images are bound within the limits of the screen. Thus spaces that lie beyond the screen are not projected by the projector. This technique helps in concentrating only on a particular part of the screen. It also enables us to use various regular and irregular shapes as a screen, which, when used properly, helps attain a 3D effect of the projected images. Figure 8 and 9 present an overview of TouchDesigner Software UI and Mapping and projecting onto an irregular object, respectively.

![Figure 8. TouchDesigner Software UI](image)

![Figure 9. Mapping and projecting onto an irregular object](image)

3.5. Display and Output

The setup includes three components. Kinect sensor, projector and the screen, as shown in figure 10. Among these, the Kinect and the projector are connected to the system. When the code is executed, the water simulation is displayed by the projector. The Kinect captures the changes, and the same can be
seen on the screen. Figure 11 shows the water flow output and projected display when the flow occurs due to interaction between the projection and sensor.

![Figure 10. Setup of the project](image)

![Figure 11. Simulation code output and projected display of interaction between the fluid and the user through the sensor resulting in flow visualization.](image)

4. **Hardware Description**

A brief description of the projector and the Kinect v2 sensor, along with its adapter, is given below. The basic requirements for the project were to keep the whole setup cost-effective. The products mentioned below were cheaper than the other alternatives present in the market.

4.1. **Projector**

Figure 12 IBS T5 smart projector HD 3D Wi-Fi mira cast 3200 lumens home cinema portable projector. It has an LCD chipset and has a lamp life of 60000 hrs. The maximum projection distance is 40ft. It has a resolution of 800x480 pixel and a maximum brightness of 4700 lumens.
4.2. Kinect v2 Sensor

The Microsoft Xbox One Kinect Sensor features an exceptional 1080p Full HD camera with advanced infrared technology for capturing accurate motion capture data. The Kinect Sensor features a microphone array with built-in noise isolation. This feature can be used to command and control the Xbox and a TV with our voice and gestures. This is one of the methods to achieve a projector depth camera system to execute the process of projection mapping [9]. The outlook of the Microsoft Xbox One Kinect Sensor is in figure 14.

4.3. Adapter

The adapter is compatible with the Xbox One S and Windows 10 PC. The adapter comes with a USB 3.0 cable which enables the user to use it with both the systems which are mentioned before. As Microsoft has discontinued manufacturing the adapter as a part of the sensor, the adapter is an individual component. The Xbox One Kinect Adapter is shown in figure 15.
5. Other Approaches

The sine summing method has been considered to achieve the fluid motion for the simulation code. During our research, we came across various other methods to achieve fluid simulation. These methods are currently used in computer graphics. The theory and methodology can be applied to the present code to transform and obtain fluid simulation. Two of these approaches briefly discussed.

5.1. Linear Wave Theory for water simulation

A topic that is mainly used in the field and study of ocean surface waves and coastal engineering. The initial assumption in this theory includes that the height of the wave is small compared to the depth and the wavelength of the water [10]. The water height of a single wave is given as:

\[ \eta(x,t) = A \cos(k \cdot x - \omega t + \theta_0) \]  

Where \( A \) is the wave amplitude, 
\( x \) is a point in the plane, 
\( k \) is the wave vector defining the direction of the wave, 
\( k = ||k|| \) Where \( k \) is the wavenumber and \( \lambda = \frac{2\pi}{k} \) is the wavelength 
\( \omega \) is the frequency and \( \theta_0 \) is the phase shift

![Wave diagram](image)

**Figure 16. Linearized (Airy) Wave Theory**

Relation between the wavenumber \( k \) with the frequency \( \omega \) as per the dispersion relation is

\[ \omega = \Omega(k) = \sqrt{(g + \frac{\gamma}{\rho})k} \]  

where \( g \) is the gravitational acceleration 
\( \gamma \) is the surface tension, 
\( \rho \) is the water density.

The energy density of a wave is

\[ E = \frac{1}{2}(\rho g + \gamma k^2)A^2 = \frac{\rho a^2}{2k} A^2 \]  

which is transported with the group speed

\[ c_g = \frac{\partial a}{\partial k} = \frac{\partial a}{\partial k} k \]  

The transportation energy describes how the propagation of the amplitude takes place over the surface.

5.2. Stabilized ISPH-Based Method

ISPH is an acronym for incompressible smoothed particle hydrodynamics. Primarily used in Computer Graphics and Realistic Animation, this is one among the many approaches that provide users with the accurate result at the same time considering the variable involved in random flows [11].
Based on the Lagrangian description, the continuity and Navier-Stokes equation for incompressible fluids can be written as,

\[ \nabla \cdot \mathbf{u} = 0, \quad (10) \]

\[ \frac{\partial \mathbf{u}}{\partial t} = -\frac{1}{\rho} \nabla P + \mathbf{v} \nabla^2 \mathbf{u} + \frac{1}{\rho} \nabla \cdot \mathbf{\tau} \quad (11) \]

where \( \rho \) is the density,
\( \mathbf{v} \) is the kinematic viscosity of the fluid,
\( \mathbf{u} \) is the velocity vector,
\( P \) is the pressure of the fluid,
\( t \) indicates time,
\( g \) is the gravity acceleration,
\( \mathbf{\tau} \) is the turbulence stress

Extending the above equation further, we derive an equation for smoothed particle hydrodynamics, which further extends to incompressibility using the final equation. To obtain this equation, various steps are to be followed depending on the parameters taken into consideration and the fluid.

The method has been used to simulate complex scenes with millions of sampling points. ISPH method is proven to be robust when it comes to non-linear flow. This method would only be suggested when a high processing system and large data storage capacity are available. The millions of sampling points are considered to render the final product, and large storage is a must.

6. Discussions

We have considered the boundary of the fluid body to be small. Also, the wavelength and amplitude of the wave are initially taken to be small. We can expect inaccuracies when the environment for the fluid changes. Large amplitudes of the wave will lead to the propagation of particles at the wrong speed, giving a very unrealistic, choppy water surface. The executable code is indirectly connected to the projection mapping software, and this might lead to delay in times when we don’t have enough storage or processing power. Thus, looking for an alternative or converting the complete code to suit the TouchDesigner software would help in such cases.

Flow visualization has many techniques direct, texture-based, geometric and feature-based [12]. These methods can be used as stepping stones to understand and evaluate flow visualization under different parameters and categories [13]. NASA uses other methods such as an Infrared flow visualization system to visualize transonic and supersonic flow regimes. They observe the shock impingement, boundary layer transition and surface temperature gradients through this method [14].

Computational Fluid Dynamics is used to compute the fluid simulations in the present time. The problem that users and researchers encounter while using this process is huge unstructured datasets [15]. Used in automotive industries, oceanography, meteorology and medicine, flow visualization is observed through CFD [15].

The scope for advancement in the project completely depends on the parameters to which it is exposed. Depending on the kind of flow visualization required, the model and program can be modified. This project can be converted into an automated system by choosing the suitable microcontroller compatible with Processing and TouchDesigner software. The final code can be dumped into the
microcontroller. In such a case, high processing capacity and high storage space are supposed to be considered.

7. Conclusions

Real-time flow visualization using projection mapping technology will be cost-effective and less space-consuming. As light is being used as a medium of projection and the sensor keeps updating the programs every time it captures a change or variation in the environment, this method is expected to have no latency and no error in the final output. When the output is compared with the theoretical values, there should be a minimum to no error. The objective is to attain the replica of the fluid flow and visualization of the same for an analytical and observational study.

The results of the initial simulations of the complete setup have recorded no latency. The interaction between the human and the sensor to acquire real-time data is accurate. To further precision, an auto-calibration model for the projector and the Kinect sensor can be devised. Projection-Mapping is executed manually. The automap feature of the software is also utilized to map the object. For future developments in the project, simulation code can be developed to plot charts and help calculate velocity and density coefficients. These results can be compared with the traditional methods to gauge the accuracy and identify the project's shortcomings.

Digitization of flow visualization will help all the domains that study the flow to determine various features and characteristics of the fluids and gases. These studies directly or indirectly affect the designs and different mathematical models devised to apply and use them to reference future observations.

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