Sonel Mapping: Acoustical Modeling Utilizing an Acoustic Version of Photon Mapping

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Overview (1):

- **Introduction/Motivation**
  - Importance of Sound Localization
  - Spatial sound and virtual environments (VEs)
- **Research Objectives**
  - Ultimate goal of this work
- **Photon Mapping**
  - Introduction
  - Two stages

Overview (2):

- **Acoustic Photon Mapping - Sonel Mapping**
  - Method overview
  - Modeling the acoustic reflection phenomena
  - Current status
- **Conclusions**
  - Summary
  - Future research directions

Introduction

Importance of Sound Localization:

- **Hearing Provides Info. About our Environment**
  - Spatial sounds give detailed info. of our surroundings
    - Determine direction and distance to objects
    - Warn of approaching dangers e.g. predators
  - Unlike vision, hearing is omni-directional
    - Can hear in complete darkness!
  - Can guide the more "finely tuned" visual system
    - Eases the burden of the visual system

Spatial Sound in a VE (1):

- **Importance of Spatial Sound in a VE**
  - Conveys basic info. to the the users
    - e.g. footsteps in small room vs. outside (large field)
  - Allows users to orient themselves
  - Increases situational awareness
  - Maintains a sense of environmental realism
    - Helps increase immersion and hence presence
  - Can enhance perception of video quality
  - Can provide a sense of ambience - mood and emotion

Spatial Sound in a VE (2):

- **Spatial Sound Often Ignored in a VE**
  - When present, typically:
    - Cues are poor and don't always reflect natural spatial cues
    - "Far field" acoustical model assumed – source at infinity, plane waves
  - Emphasis typically placed on visual senses
    - Graphics
    - Stereo vision, etc…

Spatial Sound in a VE (3):

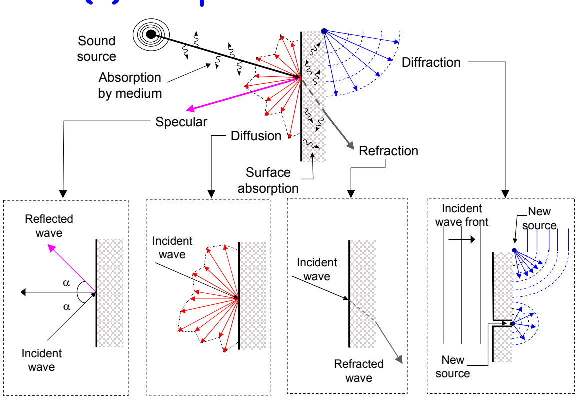
- **Sound, just as Light is a Wave Phenomenon**
  - Many differences but also many similarities!
  - Computer graphics and acoustical modeling techniques share many of these similarities
    - Various graphics based techniques can be used (appropriately modified) for acoustic modeling
  - Goal of both fields is to model the interaction of waves as they propagate from source to receiver
  - Despite similarities, computer graphics has advanced far beyond acoustic modeling
    - Greater dominance placed on visual cues

Research Objectives

Goal (1):

- **Develop Sound Synthesis Methods Inspired by Computer Graphics Based Approaches**
  - Develop an acoustical modeling approach capable of accurately modeling the various reflection phenomena which occur in our natural environment
    - Specular, diffuse, diffraction, refraction
  - Why re-invent the wheel → take advantage of the wealth of computer graphics-based knowledge and apply it to acoustical modeling
    - In particular, consider photon mapping → arbitrary geometry, speed etc.

Goal (2): Graphical Overview



Photon Mapping

Introduction (1):

- **Developed by Henrik Jensen (mid 90s)**
  - Efficient alternative to pure Monte Carlo ray tracing techniques to approximating the rendering equation.
  - Decouples illumination solution from scene geometry
    - Handle arbitrary geometry and complex models
    - Can also handle caustics
    - Rendering equation's terms calculated separately providing greater flexibility as parts of the rendering equation can be approximated using other techniques
    - Faster than pure Monte-Carlo methods

Introduction (2):

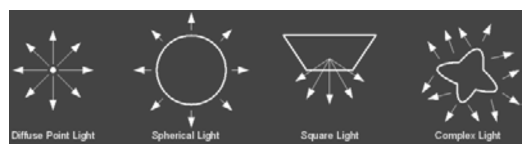
- **Description**
  - Photon Mapping → algorithm that generates, stores & uses illumination as "points" (photons, the basic quantity of light)
  - Photon Map → data structure used to process these "points"
  - Two-pass global illumination algorithm
    1. Photon Tracing → Building photon map by tracing photons from light sources through the model
    2. Rendering → Rendering the model using info in photon map to make rendering more efficient

Stage One – Photon Tracing (1):

- **Overview**
  - For each light source, create set of photons & emit photons from light
    - Scatter (trace) them through scene
    - Eventually they are absorbed or lost
  - When a photon hits a surface, decide how much of its energy is absorbed, reflected and refracted based on the surface's material properties.
  - Primary goal → populate photon maps used in rendering pass

Stage One – Photon Tracing (2):

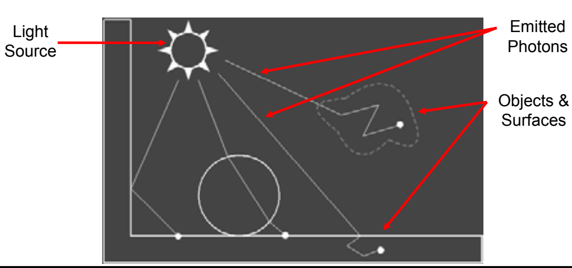
- **Various Types of Light Sources Allowed**



  - Point source → emit photons uniformly in all dirs.
  - Area light source → pick random position on surface, then pick random direction in hemisphere above this position

Stage One – Photon Tracing (3):

- **Photon "Scattering"**
  - When surface encountered, break it into "smaller" photons and re-emit → potentially very costly!
    - Use Russian-Roulette instead



Stage One – Photon Tracing (4):

- **Russian Roulette**
  - Probabilistically decide whether photons are reflected, refracted or absorbed when they encounter surface
    - Rather than reflect two photons at half power, reflect one at full power
  - Reduces both computational and storage costs while still obtaining correct result.
  - Power of reflected photon is not modified.
  - Correctness of overall result converges with more samples

Stage One – Photon Tracing (5):

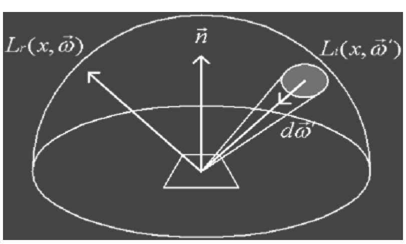
- **What is the Photon Map**
  - Representation of all the stored photons in model
  - Decoupled from geometry of the model
    - Photons not associated with particular geometry but rather kept in separate structure
  - Photons only stored when they encounter diffuse surface
    - Storing photons on specular surfaces wont give much info → probability of having matching incoming photon form specular surface is small

Stage One – Photon Tracing (6):

- **Photon Representation**
  - Each photon contains at least the following information
    - Position (x,y,z)
    - Power
    - Incident direction

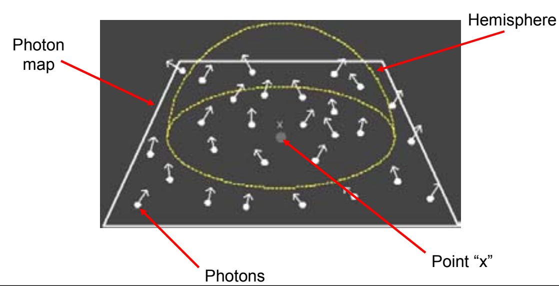
Stage Two - Rendering (1):

- **Rendering Equation Reminder**



Stage Two - Rendering (2):

- **Density Estimation to Estimate Illumination**
  - Query nearest N photons from the photon map



Stage Two - Rendering (3):

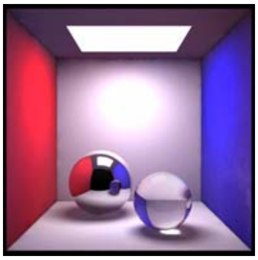
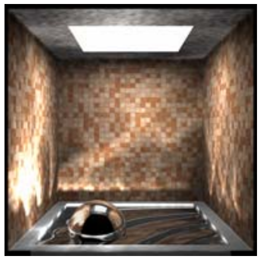
- **Density Estimation - Main Idea**
  - Get an idea of what the illumination at point "x" is by examining the nearest N photons
  - The more photons that are used the more accurate the estimate.
  - If we include photons from other surfaces, with drastically different surface normal, or from volumes in our estimate, then we can degrade the accuracy of our estimate.

Stage Two - Rendering (3):

- **Rendering Specifics**
  - Diffuse reflections
    - Use the photon map
  - Specular reflections
    - Photon map not used since it would require a large number of photons
    - Monte-Carlo ray tracing instead
  - Caustics
    - Can keep a separate photon map specifically for caustics → constructed during photon pass
    - Used the same as the global photon map

Stage Two - Rendering (4):

- **Scenes Rendered With Photon Mapping**

Sonel Mapping

Sonel Mapping – Overview (1):

- **Application of Photon Mapping to Auralization**
  - Two-pass probabilistic based method
  - Goal → model propagation of sound in an environment, while accounting for
    - Specular and diffuse reflections
    - Diffraction and refraction (to be completed)
    - Efficiency → real-time use e.g. interactive virtual environments

Sonel Mapping – Overview (2):

- **Sonel**
  - Acoustic analogue to the photon
  - "Packet" of info. propagating from source to receiver, carrying the relevant info. required to simulate mechanical wave propagation.
  - Info carried by each sonel can include:
    - Info. used by photons → direction, position, energy in addition to
    - Info. specific to sound and sound propagation → distance, phase and frequency
    - Sonel energy divided amongst discrete set of frequency bands

Sonel Mapping - Overview (2):

- **Mechanical Wave Propagation**
  - Provided sonel is appropriately modified to account for changes between particles of medium at source and particles of medium at receiver position. it is anticipated that the sonel can simulate (approximate) mechanical wave phenomena.
- **As a Start Fundamental Differences Between Sound & Light Must be Addressed**
  - Finite propagation speed of sound
  - Absorption of sound by the medium

Sonel Mapping (3):

- **Finite Propagation Speed of Sound**
  - Associate events with a particular "time"
    - Keep track of total distance traveled by a sonel
    - Can determine time as:

      t = total distance ÷ velocity of sound
    - Interactions no longer instantaneous → function of distance between source and receiver
    - Appropriate RIR "bin" b_i determined as:

$$b_i = \left\lfloor \left(t \times \frac{1}{p_s} \right) + 0.5 \right\rfloor$$

Sonel Mapping (4):

- **Absorption/Attenuation by the Medium**
  - Simplest form → attenuation of sound by medium accounted for using simple attenuation factor *m*
    - Dependent on distance *d*

$$I_d = I_0 \times e^{-md}$$

  - I_d → energy at distance d from original point whose energy was I_0
  - More complex expressions accounting for humidity, temperature, frequency etc are available and will be examined

Current State (1):

- **Can Handle Diffuse and Specular Reflections in Any Combination**
  - Two Stages:
    1. Sonel Tracing
       - → Trace sonels emitted form the sound source(s)
       - → Populate sonel map
    2. Sound Rendering
       - → Approximate room impulse response
       - → Trace acoustic rays form receiver

Sonel Tracing (Stage One) (1):

- **Sonels Emitted From Sound Source(s)**
  - Currently, omni-directional point sources
  - Sonels emitted uniformly in all directions
  - Total sound source power L (dB), divided equally amongst N_{sonel} sonels:

$$E_0 = \frac{10^{L/10}}{N_{sonel}} \times 10^{-12}$$

  - Increasing N_{sonel} → increasing accuracy

Sonel Tracing (Stage One) (2):

- Sonels "traced" until object/surface is encountered
- Encountering a diffuse surface
  - Store sonel in sonel map structure
  - New sonel generated and reflected diffusely by choosing random direction over hemisphere centered about intersection point
- Encountering a specular surface
  - Sonel reflected specularly (e.g. angle of incidence = angle of reflection)
  - Specularly reflected sonels are not stored but will eventually be terminated

Rendering (Stage Two) (1):

- **Estimate Room Impulse Response (RIR) using:**
  1. Previously constructed sonel map
  2. Acoustic distribution ray-tracing
- **Acoustic Rays Emitted From Receiver(s)**
  - "Traced" until object/surface is encountered
  - Encountering a diffuse surface at point "x"
    - Sonel map used to provide estimate of sound energy leaving "x" and arriving at receiver via density estimation
    - Energy is scaled to account for attenuation by medium and added to accumulating RIR and sonel is terminated

Rendering (Stage Two) (2):

- Handling Specular Reflections
  - Upon encountering a specular surface, sonel is reflected specularly but if it encounters a sound source then energy is scaled to account for attenuation by the medium and added to the accumulating RIR
- Note: at each sonel/surface intersection point, a portion of sonel energy is reflected specularly and a portion diffusely
  - Two new sonels generated and reflected
  - Energy appropriately divided based on surface coefficients → Inefficient!!! Russian Roulette instead!

Results

Experiments (1):

- **Reverberation Time (RT_{60}) Estimates**
  - Estimated RT_{60} for simple environment calculated and compared to RT_{60} predicted by Sabine's formula

    Room → 10m x 9m x 8m

    Sound source position → (9, 8, 7)

    Receiver positions → (4.0, 4.5, 4.0), (2.0, 5.5, 7.0), (3.0, 1.0, 3.0), (6.0, 6.0, 4.0)
  - As in Sabine's original formulation, assume diffuse sound field, hence diffuse reflections only
    - "Real-world" absorption coefficients for all surfaces. Two frequencies → 2kHz, 4kHz

Experiments (2):

- **Measure of Performance**
  - Percentage difference between estimated and predicted RT_{60}

$$\%dif = \left| \frac{RT_{predicted} - RT_{estimated}}{RT_{predicted}} \right|$$

  - Percentage difference between estimated and predicted very small for both frequencies of interest and all four receiver positions ranging from

    0.56% → 5.00%

Conclusions

Summary (1):

- **To Re-cap:**
  - Auditory cues are typically ignored in many VR/VE applications despite their importance in the understanding of our natural environment
    - Omni-directional
    - Can be used in the dark
  - Acoustic modeling of even small, simple environments is a difficult and "expensive" task!
    - Systems currently available focus primarily on specular reflection phenomena → easy!
    - Diffusion and diffraction handled poorly despite their importance

Summary (2):

- **Re-cap (cont…)**
  - Many similarities between light and sound
    - Image synthesis has advanced far beyond the field of acoustic modeling
    - Acoustic modeling is lagging behind!
  - Take advantage of wealth of knowledge with respect to image synthesis and apply it to acoustic modeling
    - Sonel mapping → acoustic modeling system based on successfully and widely used photon mapping method
    - Currently, can handle diffuse and specular reflections

Future Research Directions (1):

- **Modeling of Diffraction (and refraction)**
  - Huygens' principle ?
  - Geometrical theory of diffraction ?
- **Realistic Sound Source Sonel Distribution Functions Taking into Account**
  - Frequency dependency of sound source emission
  - Sound source directivity patterns
- **Develop Acoustical Complement to Rendering Equation**
  - Cover all acoustic reflection/propagation phenomena

Future Research Directions (2):

- **Russian Roulette**
  - At each sonel/surface intersection point, determine the type of interaction based probabilistically on random generated number and surface coefficients
  - Can ensure path length of each sonel is kept at manageable size yet allows paths of arbitrary length to be explored
  - Much more efficient → real-time potential
- **Greater, More Extensive Testing**
  - Human subjects

The End!