The Sonel Mapping Acoustical Modeling Method

Department of Computer Science and Engineering
Ph.D Dissertation Oral Exam

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redefine THE POSSIBLE.

Overview (1):

- **Motivation/Introduction**
  - Goal of this work
- **The Physics of Sound**
  - What is sound ?
- **Sonel Mapping**
  - A two-stage acoustical modeling method
- **Experimental Results & Examples**
  - Graphical illustrations
- **Summary**

Motivation & Introduction

Motivation (1):

- **Sound is Essential to Immersive Environments**
  - Allows users to orient themselves
  - Increases situational awareness
  - Helps increase immersion and hence presence
  - Can enhance perception of poor visual cues
- **Spatial Sound Often Ignored and When Present**
  - Cues are poor → don't always reflect natural cues
  - "Far field" acoustical model assumed → but near field is important too!
  - Emphasis is typically placed on the visual senses

Motivation (2):

- **Spatial Sound Often Ignored (cont.)**
  - Consider the following quote from Wayne Witanen, J. Martin Graetz and Steve Russel in 1962
    - Creators of SpaceWar! the first computer game

    "Although sound support had originally been planned it was never included in the original game in favor for other features that are deemed much cooler and more important…
  - Although the situation has improved somewhat, unfortunately, sound is, in many situations, still overlooked!

Goal of this Work (1):

- **Good Sound Modeling Methods Are Essential**
  - Just as computer graphics requires good modeling and rendering methods to build the virtual environments that people want to explore, the same applies to acoustical modeling
    - Good sound modeling techniques are important
- **Sound, just as Light is a Wave Phenomena**
  - Many differences but many similarities → computer graphics as a field has advanced beyond the field of acoustical modeling

Goal of this Work (2):

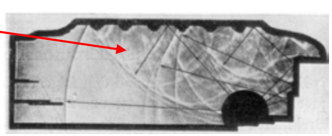
- **Develop a System Capable of "Accurately" Modeling the Acoustics of an Environment**
  - Many applications → virtual environments/virtual reality, simulators, room design, games, etc…
  - Apply advancements, developments and the vast knowledge base associated with the field of computer graphics (realistic image synthesis) and optics to acoustical modeling
    - This has lead to the development of the sonel mapping acoustical modeling method

The Physics of Sound

What is Sound ? (1):

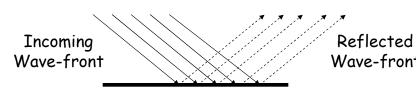
- **A Mechanical Wave Phenomenon**
  - Requires a medium to propagate (e.g. air)
  - Variations in air pressure caused by vibrating object
  - Waves emitted from the source propagate through the environment and interact with objects/surfaces
    - Real world is continuous, complex objects, etc. → it is very complicated to exactly recreate/model!

Propagating acoustic (sonar) waves

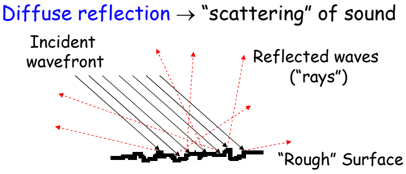


What is Sound ? (2):

- **Sound/Surface Interaction**
  - Specular reflection → angle of incidence = angle of reflection

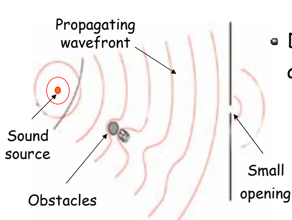


  - Diffuse reflection → "scattering" of sound



What is Sound ? (3):

- **Diffraction**
  - Bending of sound waves around corners & obstacles
  - Spreading out of sound waves through small openings
  - Allows us to hear sounds around corners & barriers

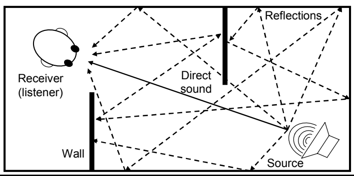


  - Dependent on wavelength and obstacle size
    - Increases as the ratio between wavelength and obstacle size increases

Sonel Mapping

Sonel Mapping (1):

- **A Probabilistic, Particle-Based, Two-Stage Acoustical Modeling Method**
  - Approximate mechanical wave propagation with a collection of small discrete packets (sonels)
    - Carry information relevant to mechanical wave propagation → trace sonels through environment as they interact with objects / surfaces

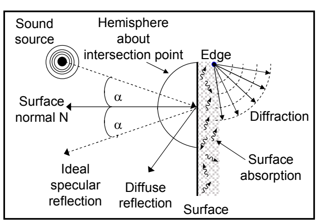


Sonel Mapping (2):

- **A Probabilistic, Particle-Based, Two-Stage Acoustical Modeling Method (cont.)**
  - Greater computational efficiency in comparison to available deterministic approaches
    - Computational requirements scale linearly and not exponentially
  - Store particles (sonels) in the sonel map → "efficient" data structure to avoid "re-tracing"
  - Inspired by two "lines of research"
    1. Photon mapping → image synthesis method
    2. Huygens'-Fresnel principle → optics-based method

A Problem (1):

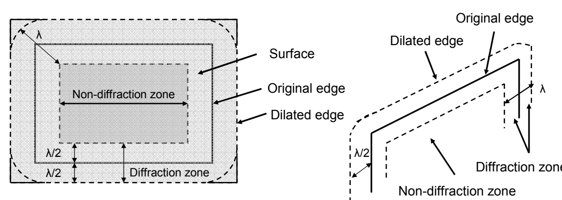
- **Multiple Interactions**
  - When a sonel strikes a surface it can do many things
    - Tracing the sonel will involve splitting it into multiple sonels when it strikes a surface → difficult and expensive



- **Solution**
  - Only one interaction at each sonel-surface interaction point is chosen

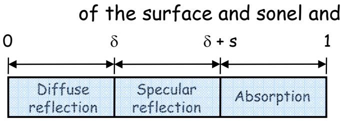
Diffraction/Non-Diffraction Zone (1):

- **Determining the Type of Interaction**
  - Each surface is dilated by an amount equal to $\lambda/2$
  - Each surface is divided into two regions
    - Non-diffraction zone and diffraction zone
    - Sonel/surface interaction depends on which zone sonel is incident on



Non-Diffraction Zone (1):

- **Russian Roulette**
  - One of specular / diffuse reflection or absorption is chosen probabilistically based on the parameters of the surface and sonel and a random number ξ



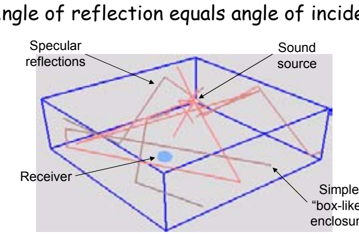
$\delta \rightarrow$ diffuse reflection coeff.

$s \rightarrow$ specular reflection coeff.

  - Only one interaction is chosen instead of multiple interactions with deterministic approaches
    - Leads to tremendous computational savings!
    - Paths of arbitrary length can be explored unlike traditional deterministic approaches

Non-Diffraction Zone (2):

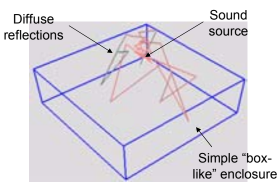
- **Specular Reflections**
  - Assume ideal specular reflections
  - Angle of reflection equals angle of incidence



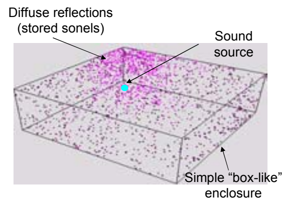
Simple example of specular reflections only in a simple "box-like" environment

Non-Diffraction Zone (3):

- **Diffuse Reflections**
  - Assume ideal (Lambertian) reflections
    - Reflection direction is completely random
  - Diffuelsy reflected sonels are stored in sonel map



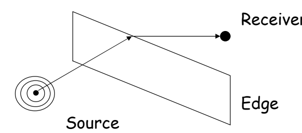
Diffuse reflections only in a simple “box-like” environment



Sonels stored in the sonel map

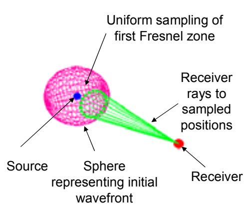
Diffraction Zone (1):

- **Focus of this Work is Edge Diffraction**
  - Concerned with the behavior of a wave when it encounters an edge
    - Edges are commonly found in acoustical modeling applications → typical in offices, homes, theatres, concert halls etc. e.g., sound waves bending around corners, doors etc.



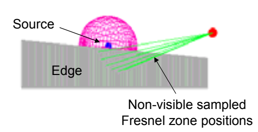
Diffraction Zone (2):

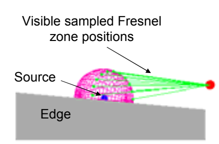
- **Huygens-Fresnel Principle: Initial Wavefront**
  - Wavefront emitted from source propagates until reaching position of diffracting sonel on edge
  - Divided into a number of Fresnel zones → adjacent Fresnel zones are separated by $\lambda/2$
  - Each Fresnel zone contains secondary sources
  - Total energy reaching the receiver → sum the energy of the secondary sources in the first Fresnel zone



Diffraction Zone (3):

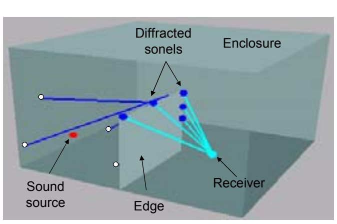
- **Sampling the First Fresnel Zone**
  - Account for obstruction of wavefront by occluder
    - Sample first Fresnel zone by sending out “shadow” (or “feeler”) rays from the receiver to determine how much of the first zone is visible
    - Weigh the energy of the first zone reaching the receiver by the percentage of “visible” rays





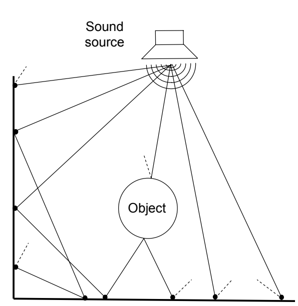
Diffraction Zone (4)

- **Graphical illustration**
  - Direct path between sound source and receiver is occluded but sonels diffracted at the edge still reach the receiver



A Two Stage Approach (1):

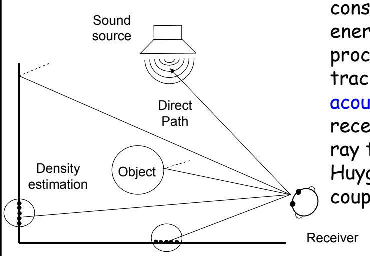
- **Stage One - Sonel Tracing Stage**



- Purpose of the sonel tracing stage is to populate the sonel map
- Sonels are emitted from the sound source and traced through the environment while recording any interactions with any surfaces/objects they may encounter
- Diffuse reflected sonels are stored in the sonel map

A Two Stage Approach (2):

- **Stage Two – Acoustical Rendering Stage**

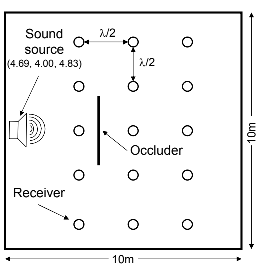


• Once sonel map has been constructed, the complete energy transmission process is computed by tracing out "receiver acoustic rays" from the receiver using Monte-Carlo ray tracing and the Huygens'-Fresnel principle coupled with the sonel map

Results

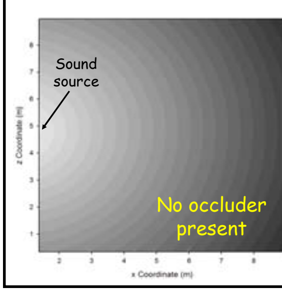
Graphical Illustrations (1):

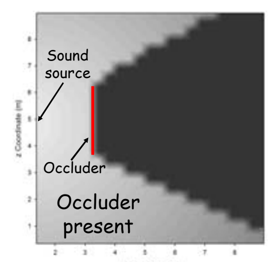
- **Simple "Box-Like" Room**
  - Sound energy propagation for a stationary sound source and various receiver & occluder set-ups
  - Grid of receiver positions on the x-z plane (const. y)
    - Spacing between positions on both axis is one half of a wavelength



Graphical Illustrations (2):

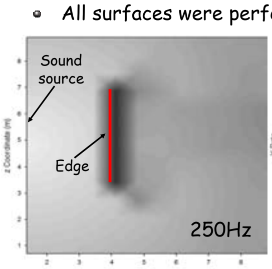
- **Direct Sound (500Hz)**
  - All surfaces were perfect absorbers → direct sound only

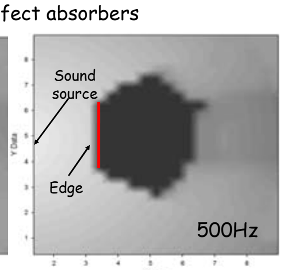




Graphical Illustrations (3):

- **Obstruction (Edge)**
  - Obstruction present blocking direct path of some receivers → diffraction present
  - All surfaces were perfect absorbers



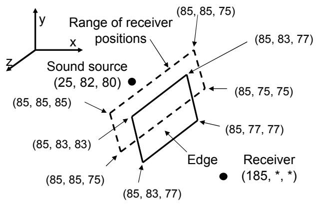


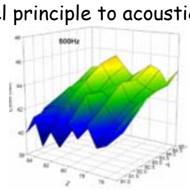
Experiments (1):

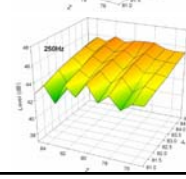
- **Validation of Sonel Mapping**
  - Reverberation time (RT_{60}) computed with sonel mapping vs. theoretical results (Sabine's formula)
    - Percentage difference between estimated and predicted times were very small → 0.56% to 5.00%
  - Russian roulette vs. deterministic approaches
    - Compute RT_{60} at various positions using deterministic approach and Russian roulette and compare the time to compute each solution
    - Difference of 510% – 3570%
    - Russian roulette is much more efficient → paths of arbitrary length can be explored

Experiments (2):

- **Validation of Sonel Mapping (cont.)**
  - Applying the Huygens'-Fresnel principle to acoustical diffraction modeling

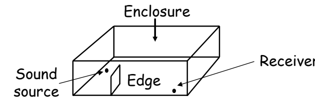


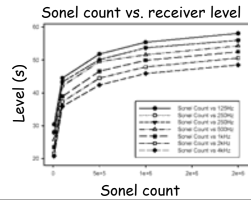


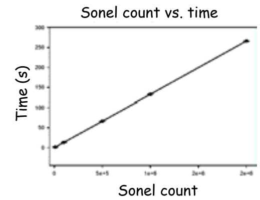


Experiments (3):

- **Validation of Sonel Mapping (cont.)**
  - Effectiveness of sonel mapping as a whole







Conclusions

Summary (1):

- **Sound is Crucial in Immersive Systems**
  - Incorporating accurate and realistic environmental sound information requires effective and efficient acoustical modeling
    - Sonel mapping is such an approach
  - Sonel mapping is a stochastic, particle-based energy transport model applied to acoustical modeling
    - Photon mapping and Huygens'-Fresnel principle
    - Can model various acoustical phenomena in an efficient manner

Future Work (1):

- **Various "Open Problems" Remain**
  - Would like to address the acoustical modeling of sounds in the very near field (e.g., less than one meter)
    - Can allow for modeling effects such as one person whispering in the ear of another → accurately modeling this is a difficult task!
  - User Tests
    - Perform user-based studies and account for the "human factor" → ultimately, a human will be the end user!

The End…

Thank You!

Any Questions ?