Topic 14-2: Construct a Room Impulse Response (RIR) using Ray Tracing (RT) Simulation Methods

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1. Introduction

Room acoustics plays a crucial role in various audio applications, including virtual reality, architectural acoustics, and spatial audio rendering. The ability to simulate and analyze how sound propagates within an enclosed space is essential for understanding reverberation, absorption, and reflection effects. This project aims to implement a **Room Impulse Response (RIR) simulation** using **Ray Tracing (RT) methods** to model sound propagation and reflections within different room environments. The simulation will analyze how different room sizes and acoustic treatments affect sound behavior, providing insights into frequency-dependent absorption and higher-order reflections.

2. Project Description

The objective of this project is to develop a room acoustics simulation tool that computes the **Room Impulse Response (RIR)** for various room configurations. The simulation will model the **sound propagation and reflections** using **Ray Tracing (RT)** methods. The project includes:

- Simulating **four rooms** with different sizes.
- Implementing various **acoustical treatments**, including:
    - Furnished room
    - Empty room
    - Big room with acoustical treatment
    - Big room without acoustical treatment
- Evaluating a single **sound source and receiver position** to analyze reverberation and absorption effects.
- Incorporating **octave band frequencies** for actual absorption coefficients of materials.
- Handling **higher-order reflections** to improve simulation accuracy.

3. Methodology

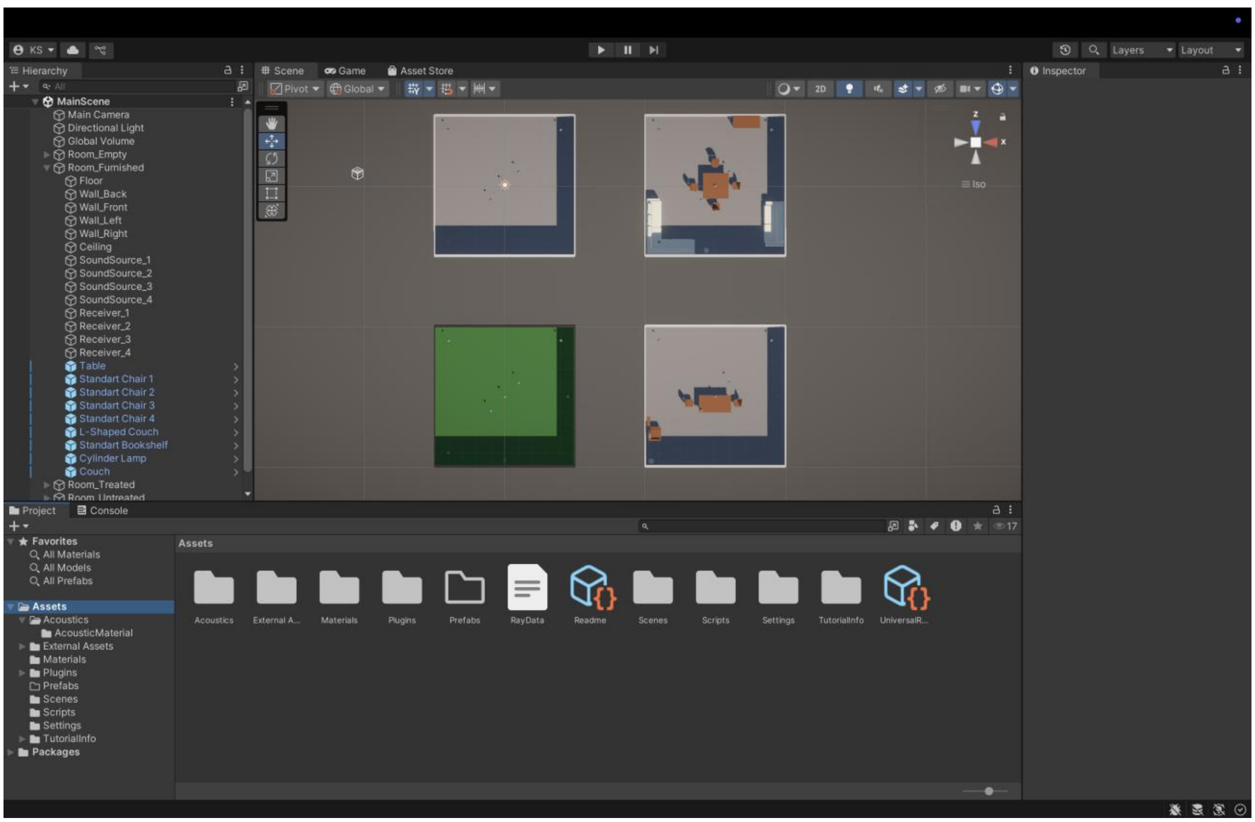
The simulation is designed using a structured approach to model and compute the Room Impulse Response (RIR) efficiently.

3.1 Tools and Technologies Used

- **Programming Language**: Python, C#
- **3D Modeling and Visualization**: Unity (for visualization)
- **Ray Tracing Engine**: Custom-built ray-tracing algorithm using vector mathematics
- **Material Absorption Data**: Based on octave band frequency-dependent coefficients
- **Data Analysis**: Python

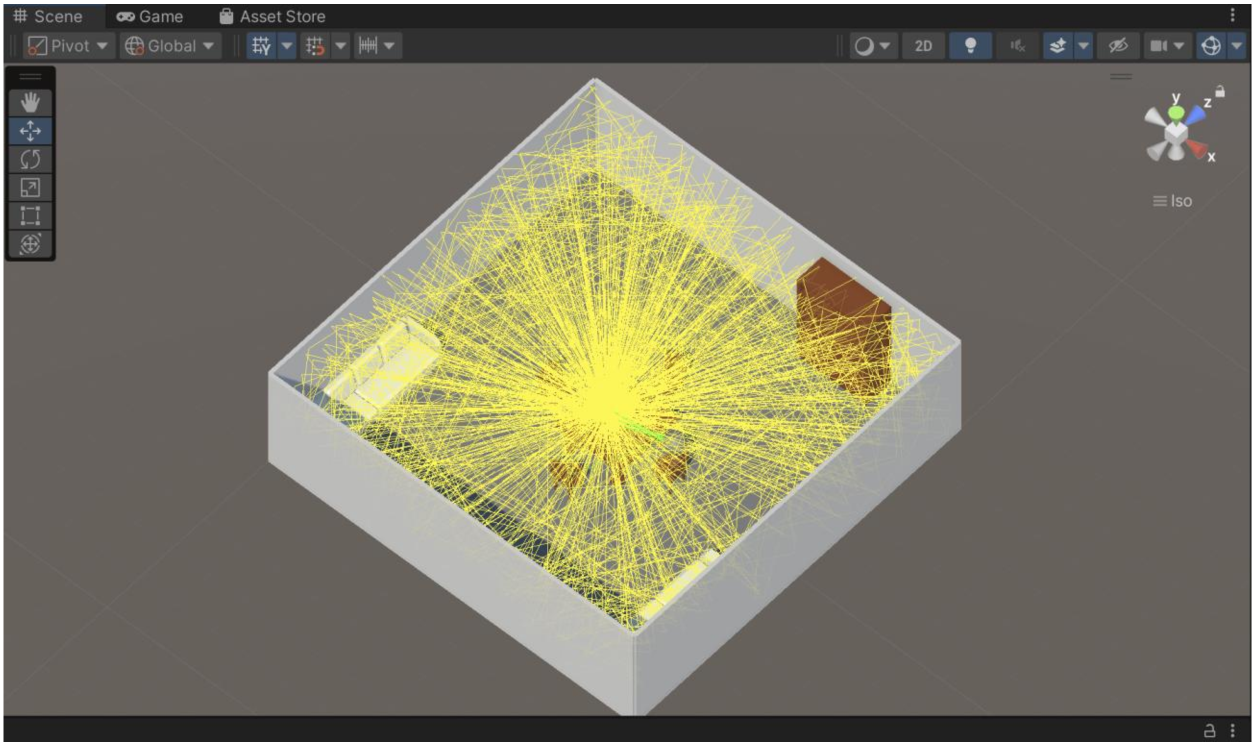
3.2 Room Modeling

- Define four room geometries of different sizes.
- Assign surface materials with varying absorption coefficients based on octave band frequencies.



3.3 Ray Tracing Implementation

- **Stochastic Ray Tracing (SRT):** Implements random sampling of ray paths to model energy dispersion and simulate reverberation accurately.

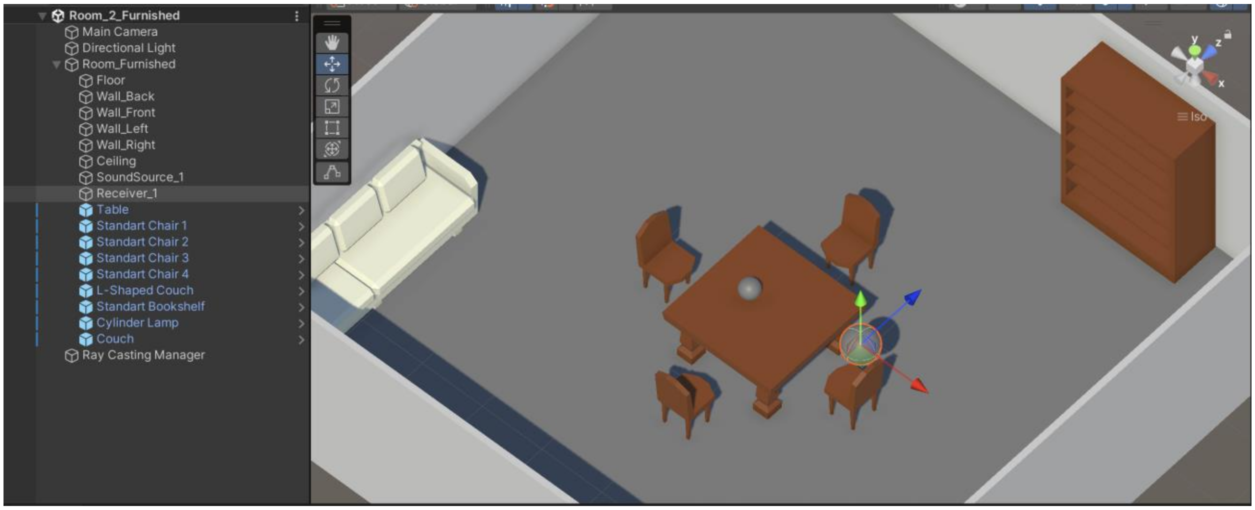


3.4 Frequency-Dependent Absorption

- Assign absorption coefficients to different room surfaces using **octave band frequencies**.
- Compute the sound energy loss for each frequency band at each reflection.

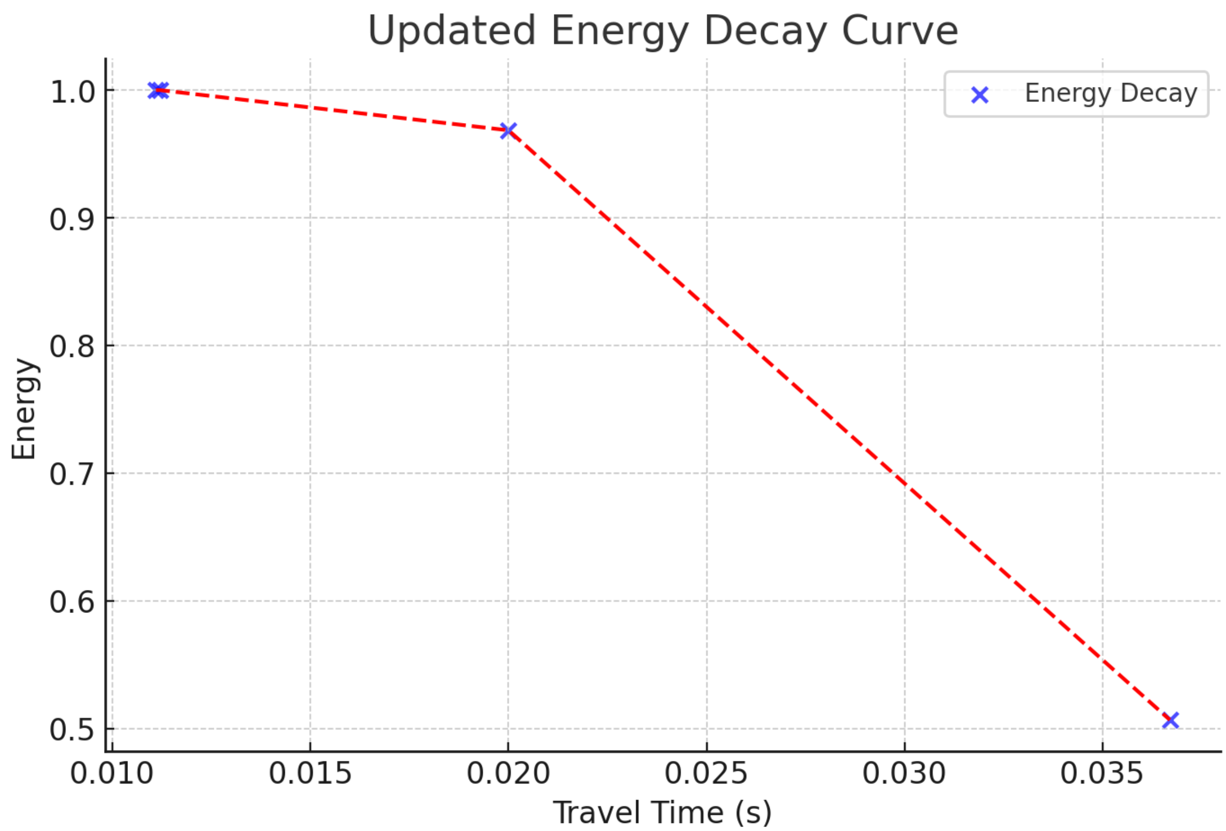
3.5 Source and Receiver Placement

- Place a sound source within the room.
- Assign a receiver position to analyze received impulse responses.
- Measure variations in reverberation time (RT60) and direct-to-reverberant ratio.



3.6 Data Processing and Analysis

- Generate **Impulse Response (IR) waveforms** for each receiver location.
- Compute key acoustic parameters:
    - **Reverberation time (RT60)**
    - **Early decay time (EDT)**
    - **Direct-to-reverberant energy ratio**
- Compare results across different room conditions.



4. Results and Discussion

4.1 Room Impulse Response Analysis

- The simulated **RIR waveforms** illustrate how sound reflections vary across room conditions.
- Furnished rooms exhibit **higher absorption** and reduced reverberation.
- Empty rooms lead to **longer reverberation times (RT60)** due to minimal absorption.

4.2 Frequency-Dependent Absorption Effects

- Low-frequency sounds experience **less absorption**, leading to longer reverberation tails.
- High-frequency sounds get absorbed faster, reducing reflections.
- Absorption coefficients vary across **octave band frequencies**, influencing room acoustics significantly.

4.3 Higher-Order Reflection Analysis

- Implementing higher-order reflections improves **realism** but increases computational complexity.
- Efficient ray-tracing methods reduce processing time while maintaining accuracy.

5. Conclusion and Future Work (before 11.03.2025)

This project implemented a **Room Impulse Response (RIR) simulation** using **Ray Tracing (RT) methods**, allowing an in-depth analysis of room acoustics under different conditions. The results demonstrate how room size, surface materials, and frequency-dependent absorption affect sound propagation. Future work may include:

- Real-time implementation using **Unity + Steam Audio** for **Auralization**.

4. References

1. D. Schröder, *Physically Based Real-Time Auralization of Interactive Virtual Environments*, RWTH Aachen University, 2011. [Online]. Available: https://publications.rwth-aachen.de/record/50580/files/3875.pdf
2. Steam Audio Documentation, "Steam Audio: A 3D Spatial Audio Solution for Games and VR," *Valve Corporation*, 2024. [Online]. Available: https://valvesoftware.github.io/steam-audio/