# GEOMETRICAL ROOM GEOMETRY ESTIMATION FROM ROOM IMPULSE RESPONSES

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## Abstract

**❑ Room geometry estimation from corresponding Room Impulse Responses (RIRs) has attracted much attention in recent years, and a key challenge is to find the first order image source locations from the RIRs under different environments. Unlike the existing approaches which require a priori knowledge of the room or require some ideal conditions, this paper proposes an intuitive geometrical method based on the acoustical image source model. The proposed approach does not need any a priori knowledge of the room, only the RIRs from one arbitrary source location to five arbitrary receiving locations. The first order image sources of the walls in a room are identified first, then the room geometry is estimated based on the wall locations using a geometrical approach. Simulations with 2D and 3D convex polyhedral rooms demonstrate the feasibility and the precision of the proposed approach is discussed.**

## 1. Introduction

❑ Room geometry estimation from RIRs has attracted significant research interest in recent years, as room geometry information is useful for acoustic modeling, source localization and separation, forensic applications, spatial sound reproduction and architectural design etc.

❑ Finding the first order image source locations in reverberant environments is a challenging research area, but critical to room geometry estimation. The proposed geometrical approach has been evaluated for a series of 2D and 3D room simulations and found to be very effective, finding image source locations using simple geometric concepts.

❑ The principle of the image source method can be extended to find the reflective surface or wall location by estimating the image source location: If we know the exact image source location, then the reflective surface can be estimated. By estimating all the reflective surfaces, the room geometry can thus be estimated.

## 2. Proposed method

### 2.1. Real and image sound source location determination

❑ In a convex 3D room with 4 microphones A, B, C and D located at ($x_A$, $y_A$, $z_A$), ($x_B$, $y_B$, $z_B$), ($x_C$, $y_C$, $z_C$) and ($x_D$, $y_D$, $z_D$), the distances from these microphones to an unknown real or image sound source at $P = (x, y, z)$ are related to their locations by Eq.(1), if the distances $a$, $b$, $c$ and $d$ and the microphone locations are known

$$\begin{cases}(x-x_A)^2+(y-y_A)^2+(z-z_A)^2 &= a^2\\(x-x_B)^2+(y-y_B)^2+(z-z_B)^2 &= b^2\\(x-x_C)^2+(y-y_C)^2+(z-z_C)^2 &= c^2\\(x-x_D)^2+(y-y_D)^2+(z-z_D)^2 &= d^2\end{cases} \qquad (1)$$

❑ Assuming the numbers of peaks in RIRs with microphone A, B, C and D are $N_A$, $N_B$, $N_C$, and $N_D$ respectively, then the number of candidate sound sources are $N_A \times N_B \times N_C \times N_D$. The distance from each candidate sound source to each of the microphones can be obtained from its RIR by estimating its time of arrival. For some candidate sound sources, if there is no solution for Eq. (1), these candidate sound sources are removed from the candidate list.

❑ However, some sound sources in the candidate list may not correspond to actual real or image sound sources. An extra microphone is thus proposed in this approach to remove incorrect candidate sound sources.

❑ Assume the extra microphone E is located at ($x_E$, $y_E$, $z_E$), which can be used with any 3 of the existing 4 microphones to form a new equation similar to Eq. (1). By following the same procedure, another 4 sets of sound source candidate list can be obtained. By comparing the 5 sets of candidate sound source locations, the actual real and image sound source locations can be determined according to the source locations common to all sets. To further improve the accuracy, more microphones can be used.

### 2.2. Room geometry estimation

***Table 1.*** *The proposed room geometry estimation method*

**Inputs:** 5 RIRs from one sound source location to 5 microphone locations and the relative location of the microphones

**1.** Determine and list all actual real and image sound source locations according to the approach described in Section 2.1.
**2.** Identify the real sound source location (S) by finding the nearest source location to all microphones from the source location list.
**3.** Label all the image source location as $ISL_1$, $ISL_2$, $ISL_3$, …, $ISL_N$ sequentially according to the distance between the real and image sound sources.
**4.** Confirm the first wall ($Wall_1$) as the bisecting plane between sound source (S) and $ISL_1$.
**5.** Estimate the locations of the rest of walls,

For $n$ = 2 to $N$
- Estimate candidate $wall_n$ as the bisecting plane between S and $ISL_n$
- Find the reflective point $P_n$ by intersecting a line from a microphone to $ISL_n$ and the candidate $Wall_n$

Check whether $P_n$ and S are at same side of all confirmed walls
- If Yes, the candidate wall is confirmed as a real wall
- If No, the candidate wall is not a real wall and $ISL_n$ is not a first order image source

End

**6.** Solve all the confirmed walls for room vertices
**Output:** Vertices of the room

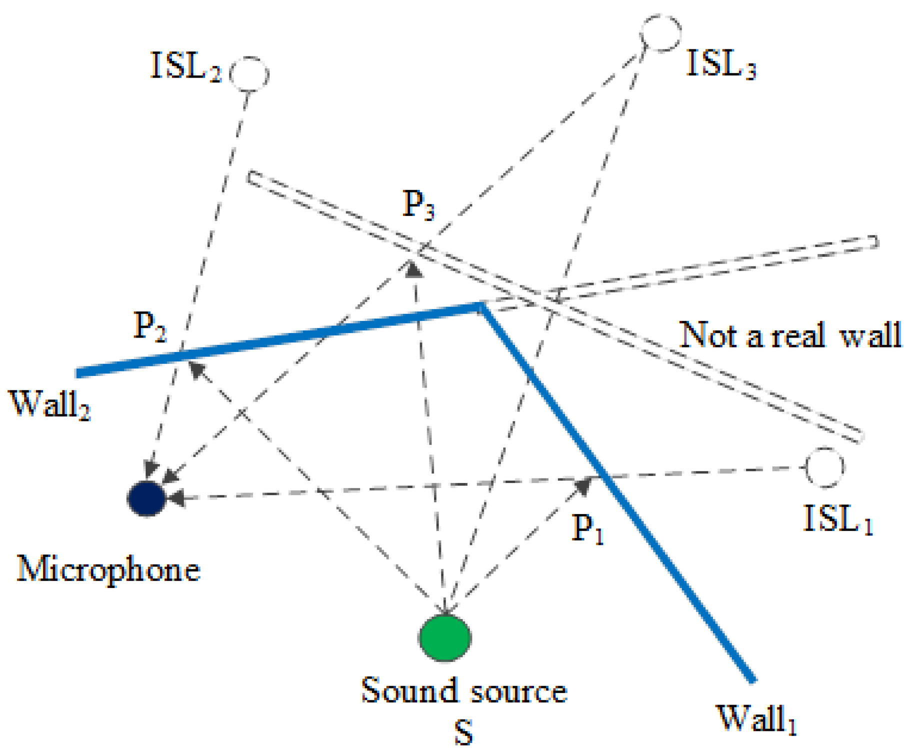



***Fig. 1****. Room geometry estimation with the proposed method*

## 3. Simulation results

### 3.1. Image source location estimation

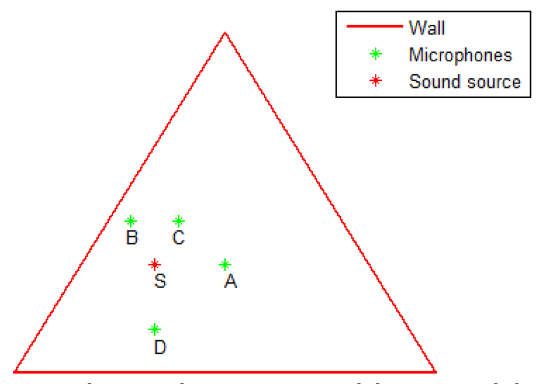
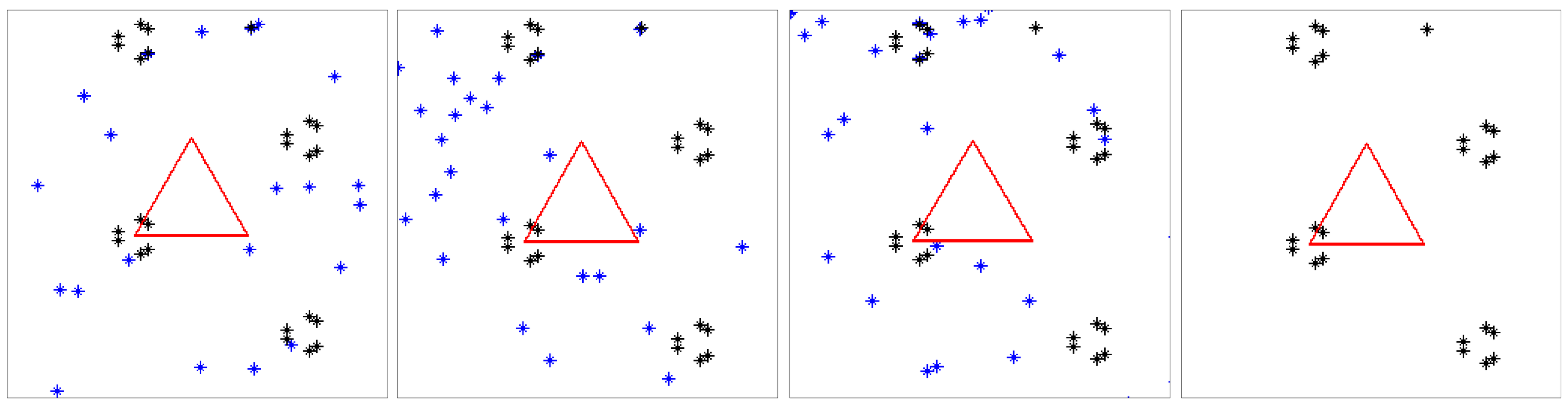
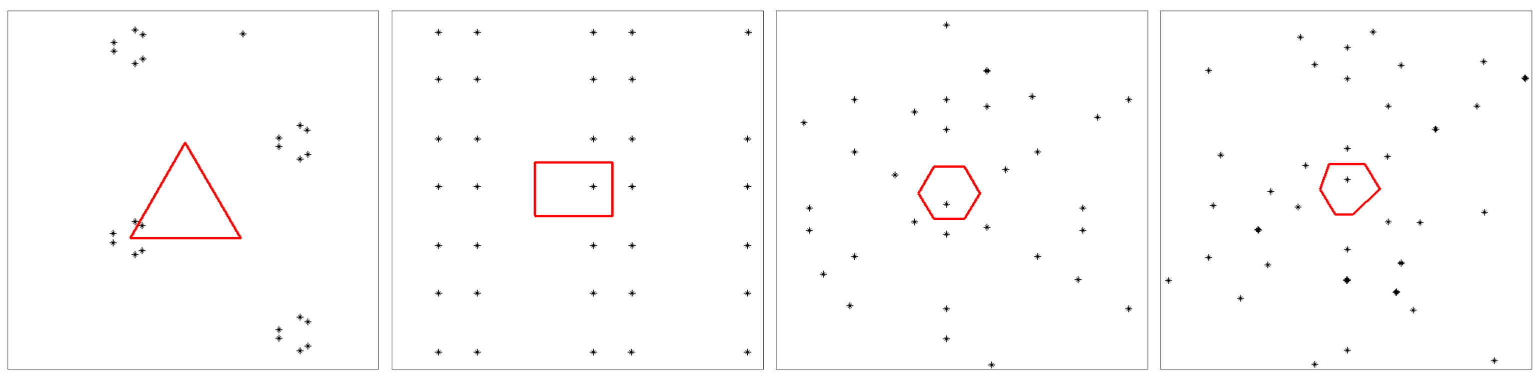



***Fig. 2.*** *2D geometry estimation for a triangular room with an arbitrary source and 4 microphones*



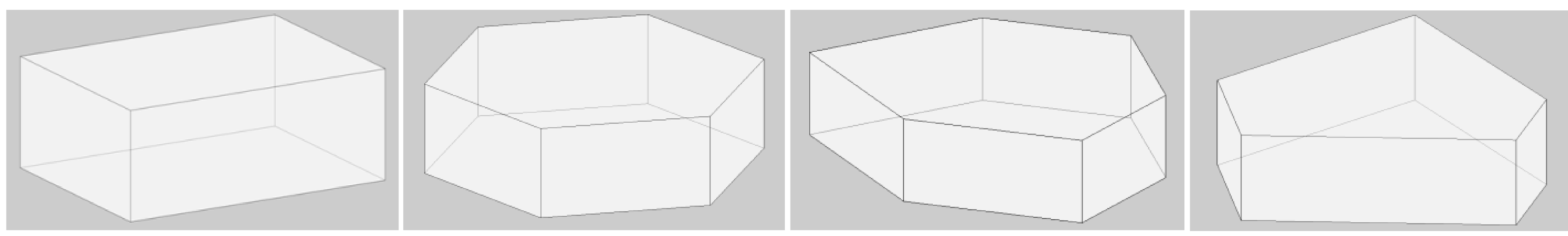
(a) (b) (c) (d)

***Fig. 3****. Estimated possible image source locations for a 2D triangular room shown in Fig. 2 using microphone group (a) {A, B, C} (b) {A, B, D} (c) {A, C, D}. (d) The image source locations estimated from locations common to (a), (b) and (c)*



(a) (b) (c) (d)

***Fig. 4.*** *Simulation results for 2D rooms with different shapes (a) triangular (wall lengths 9m each); (b) rectangular (wall lengths 12 and 9m); (c) hexagonal(wall lengths 5m each); (d) asymmetric hexagonal (wall lengths 3, 6.25, 5, 6, 4.58, 5 m). The image source locations estimated according to Section 2.1 are also shown in the figure*



(a) (b) (c) (d)

***Fig. 5****. Simulation results for 3D rooms with different shapes (a) rectangular shaped room(wall lengths 12, 9m and height 3m); (b) hexagonal prism shaped room (wall lengths 5m and height 3m); (c) asymmetric hexagonal prism shaped room(wall lengths 6,4.58,5,5,6.24,6.24m and height 3m; (d) asymmetric pentagonal prism (wall lengths 1.5, 5, 2.06, 4.3, 3.9 m and height 3m)*

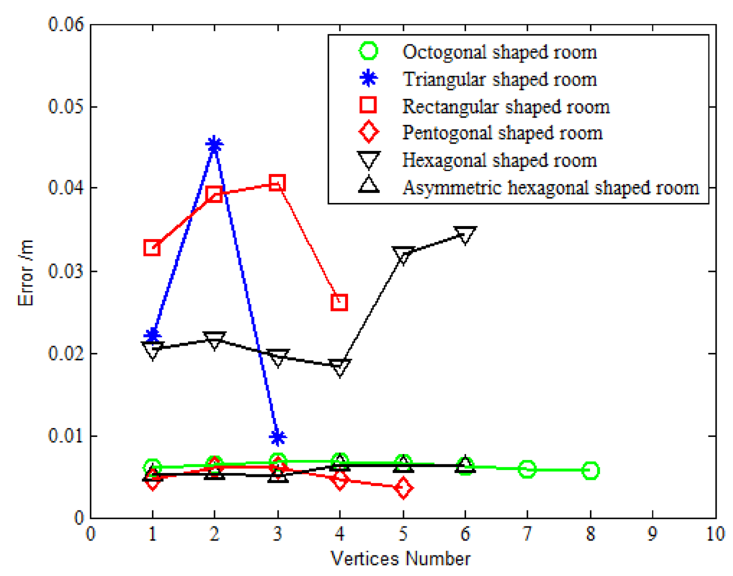



***Fig. 6.*** *Vertices estimation error for different 2D room shapes shown in Fig.4*

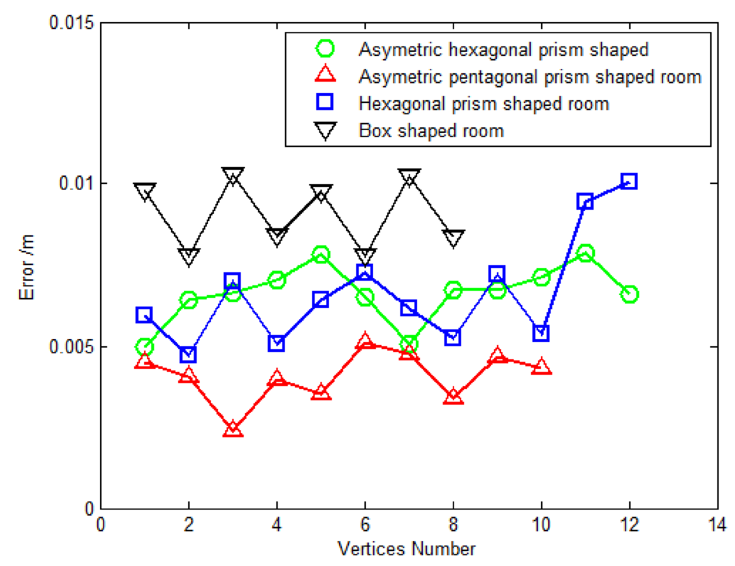



***Fig. 7.*** *Vertices estimation error for different 3D room shapes shown Fig.5*

## 4. Discussion and conclusion

❑ Finding the first order image source locations in reverberant environments is a challenging research area, but critical to room geometry estimation. The proposed geometrical approach has been evaluated for a series of 2D and 3D room simulations and found to be very effective, finding image source locations using simple geometric concepts.

❑ Simulations with 2D and 3D convex polyhedral rooms demonstrate the feasibility of the method and the results indicate that the maximum room geometry estimation errors are approximately 1 cm for 3D rooms with dimensions of; rectangular: wall lengths 12,9m and 3m in height, hexagonal: wall lengths 5m and 3m in height, asymmetric hexagonal: wall lengths 6, 4.58, 5, 5, 6.24, 6.24m and 3m in height, asymmetric pentagonal: wall lengths 1.5, 5, 2.06, 4.3, 3.9 m and 3m in height.

❑ Compared to the existing approaches, the proposed method does not depend on prior knowledge of the room (e.g., number of walls and room shape etc.), or the availability of higher order image sources, and does not restrict the angle between room walls.

❑ Future work includes investigating the relationship between room geometry estimation accuracy and sound source and microphone locations, and performing experimental verification.

## 5. Selected References

[1] J. B. Allen and D.A.Berkley, "Image method for efficiently simulating small-room acoustics," *Journal Acoust. Soc.America*, vol. 65, no. 4, pp. 943-950, Apr. 1979.

[2] F. Antonacci, J. Filos, M. R. P. Thomas, E. A. P. Habets, A. Sarti, P. A. Naylor and S.Tubaro, "Inference of Room Geometry From Acoustic Impulse Responses," *IEEE Transactions on, Audio, Speech, and Language Processing*, vol. 20, pp. 2683-2695, 2012.

[3] I. Dokmanic, R. Parhizkar, A. Walther, Y. M. Lu, and M. Vetterli, "Acoustic echoes reveal room shape," *Proceeding of the National Academy of Sciences of the United States of America*, vol. 110, pp. 12186-91,2013.