LOCALIZATION OF PLANAR ACOUSTIC REFLECTORS THROUGH EMISSION OF CONTROLLED STIMULI

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ABSTRACT

This paper concerns the problem of localizing three-dimensional planar obstacles through multiple emissions and acquisitions of acoustic stimuli. The solution is based on the estimation of the Times Of Arrival (TOAs) of the acoustic signal at multiple microphones. These measures are converted into geometric constraints acting directly on the parameters of the planar reflectors. The combination of multiple constraints leads to the definition of a cost function. The minimum of the cost function are the searched line parameters. Some experiments show the feasibility of the proposed approach for the localization of single and multiple reflectors. This paper extends the technique in [1] to the localization of three-dimensional reflectors.

1. INTRODUCTION

The role of the environment in audio space-time processing is crucial, since it greatly influences the propagation of sound. As an example, reverberations can affect the performance of a rendering system or of a localization algorithm. However, when the geometry of the environment is available, reverberations can be compensated. As an example, in [2] the authors take advantage of the knowledge of the room geometry to compensate its effect in sound field rendering applications. A further example is given in [3], where the authors make use of the room geometry model to improve the accuracy of sound source localization algorithms.

The problem of estimating the geometry of the room is therefore important. In the last few years many solutions relying on acoustic signals have appeared. In [4] the authors present a solution for the estimation of the room geometry, which is based on a ℓ_1 least squares regularization. In [5] the authors adopt a technique that is based on the inverse mapping of the acoustic multi-path propagation problem. In [1] the authors present a solution for the localization of obstacles in a two-dimensional configuration. In particular, given source and microphone location, the measurement of the Time Of Arrival of the reflective path is converted into a quadratic constraint that acts on the parameters of the line on which the reflector lies. A cost function that combines multiple constraints is then defined and a minimization procedure leads to the searched solution. All these approaches work, however, on the horizontal plane, which poses some limits in a real scenario: source and microphones are, in fact, bound to lie on the same plane and reflectors must lie on vertical planes, which is not always the case in everyday environments. In this paper we extend the methodology in [1] to localize planes in a three-dimensional configuration and to allow the positioning of sources and sensors in an arbitrary configuration.

An interesting evolution of the technique in [1] is presented in [6], where a blind approach to localize acoustic reflectors is presented, where the position of the source is not known in advance. The channel between the source and each microphone in the array is blindly estimated. From this knowledge, using TDOA-based techniques, the source location is inferred. This information is used to convert the Time Difference Of Arrival related to the reflective paths into Time Of Arrival. A methodology similar to [1] is then adopted for the reflector localization.

As in [1], the Time Of Arrival is converted into a quadratic constraint that directly acts on the parameters of the reflective plane. While a line in 2D can be unequivocally parameterized by three numbers, planes in a 3D geometry are unequivocally described by four parameters. We initialize the minimization procedure that leads to the reflector localization through a generalized Hough transform that allows the source and the receiver to be located in arbitrary positions, which represents an improvement of the Hough transform proposed in [1]. Besides extending the algorithm in [1] to a 3D geometry, in this paper we provide a generalization of the Hough transform to arbitrary configurations of source and receivers.

The rest of the paper is organized as follows: Section 2 describes the data model and the problem formulation. Section 3 describes the derivation of the constraint from the acoustic measurements and the localization of the reflector from such constraints. Section 4 shows some experimental results. Finally, Section 5 draws some conclusions.

2. DATA MODEL AND PROBLEM FORMULATION

In this Section we introduce the data model and we formulate the problem of reflector localization. We assume that M sources are present in the environment at locations $\mathbf{x}_1,\dots,\mathbf{x}_M$ and their signal is acquired by N microphones, located at $\mathbf{x}_1,\dots,\mathbf{x}_N$. We assume that sources are synchronized with the microphones and a single source is active at time. Figure 1 summarizes the notation. When

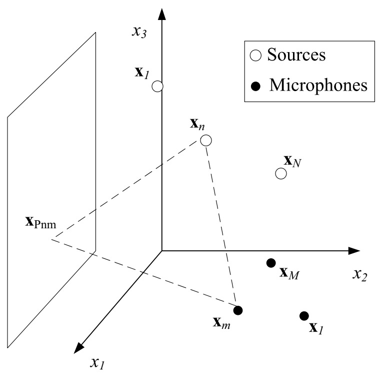


Figure 1: Problem formulation: sources and receivers are located in space. Reflective paths coming from a wall are acquired. We intend to localize the wall by the analysis of the Time Of Arrival of the reflective paths.

a single planar reflector is present in the acoustic scene, the microphone n will acquire the direct path coming from the source n along with an echo associated to a reflective path. If the laws of optical acoustics are valid, the reflective path undergoes the Snell's law. The reflection point is denoted by $\mathbf{x}_{P_{nm}}$. The signal acquired by the microphone m when the source n is active is

$$x_{n,m}(t) = \alpha_{d,n,m} s_n(t - \tau_{d,n,m}) + \alpha_{r,n,m} s_n(t - \tau_{r,n,m}) + \nu_{n,m}(t), \quad (1)$$

where $\alpha_{d,n,m}$ and $\alpha_{r,n,m}$ are the attenuations of the direct and reflective paths, respectively; $\tau_{d,n,m}$ and $\tau_{r,n,m}$ are the corresponding times of flight; and $\nu_{n,m}(t)$ is an additive noise. In order to infer the TOAs we need to estimate the impulse response from source to receiver, and one possible method to accomplish this task is the cross-correlation between the signal generated by the source and the signal received by the sensor. Under the hypothesis of unity energy of the signal $s(t)$ we have

$$\begin{gathered} h_{m,n}(t) = x_{n,m}(t) \otimes s(t) = \\ \alpha_{d,n,m}\delta(t - \tau_{d,n,m}) + \alpha_{r,n,m}\delta(t - \tau_{r,n,m}) + r_{\nu_{n,m}}(t), \end{gathered} \quad (2)$$

where $h_{n,m}(t)$ represents the estimated impulse response between the source and the receiver, $r_{\nu_{n,m}}(t)$ is the cross-correlation between the signal $s(t)$ and the noise $\nu_{n,m}(t)$, while $\delta(t)$ is the Dirac function.

We observe the presence of two sharp peaks in the impulse response. TOAs are estimated by picking peaks in $h(t)$, i.e. we select the most relevant local maxima. We notice that the first peak is related to the direct path, while the second one is related to the reflective path.

Our problem is to estimate the position of the planar surface that generated the reflective path by observing its Time Of Arrival in multiple impulse responses. More specifically, a plane is represented by the parameters $[p_1, p_2, p_3, p_4]$ so that a point $[x_1, x_2, x_3]^T$ is on the plane if and only if

$$p_1 x_1 + p_2 x_2 + p_3 x_3 + p_4 = 0\,. \quad (3)$$

In order to simplify the notation and the following discussion, we use a homogeneous notation for points and planes. Equation (3) then becomes

$$\boldsymbol{p}^T \boldsymbol{x} = 0\,, \quad (4)$$

where $\boldsymbol{p} = [p_1, p_2, p_3, p_4]^T$ are the plane parameters and $\boldsymbol{x} = [x_1, x_2, x_3, 1]^T$ are the coordinates of the point using a homogeneous notation. We notice that homogeneous coordinates are a class of equivalence, as both $\boldsymbol{x} = [x_1, x_2, x_3, 1]$ and $k\boldsymbol{x} = [kx_1, kx_2, kx_3, k]$, $k \neq 0$ belong to the plane $\boldsymbol{p}$. With the homogeneous notation at hand, therefore, our goal is to estimate the plane parameters $\boldsymbol{p}$ from the observation of multiple TOAs of reflective paths bouncing once on them.

In the following we denote the homogeneous coordinates of sources and receivers with $\boldsymbol{x}_m$ and $\boldsymbol{x}_n$, respectively. Given the impulse response $h_{n,m}(t)$ with multiple peaks, we extract from it only the first peak (in order of time) after the direct path. As a consequence, each impulse response is used for the localization of a single reflector.

After the peak picking stage, the TOAs are organized into a set

$$\boldsymbol{\tau} = \{\tau_{r,1,1}, \tau_{r,1,2}, \ldots, \tau_{r,n,m}, \tau_{r,N,M}\},$$

where n and m are the indexes of the microphone and source, respectively. When multiple walls are present in the environment, we approach the problem by dividing the problem of estimating the geometry of the environment into sub-problems, each devoted to the localization of a single reflector. As a consequence, we need to know from which reflector each TOA in $\boldsymbol{\tau}$ comes from. A labeling issue arises, therefore, in dividing the set $\boldsymbol{\tau}$ into the new sets $\boldsymbol{\tau}_1, \ldots, \boldsymbol{\tau}_L$, each collecting the TOAs from individual reflectors. We address the issue of multiple reflectors localization in Section 3 using a generalized Hough-like transform.

3. REFLECTOR LOCALIZATION FROM ACOUSTIC MEASUREMENTS

This Section concerns the localization of the reflectors from acoustic measurements. First we investigate on the case of a single reflector, we then extend the discussion to the case of multiple reflectors.

We assume, for the moment, that all the TOAs in $\boldsymbol{\tau}$ are associated to the same reflector. The source is in $\boldsymbol{x}_m$ and the receiver is in $\boldsymbol{x}_n$ and the TOA estimated in one of the impulse responses is $\tau_{n,m}$, where the subscript r is omitted for reasons of compactness in the notation. The length of the reflective path from $\boldsymbol{x}_m$ to $\boldsymbol{x}_n$ is $\tau_{n,m}c$, where c is the sound-speed. We assume that the laws of optical acoustics are valid, therefore the reflection undergoes the Snell's law. The time of flight $\tau_{n,m}$ is the sum of the propagation time from $\boldsymbol{x}_m$ to the reflection point (denoted by $\boldsymbol{x}_{P_{m,n}}$) and from $\boldsymbol{x}_{P_{m,n}}$ to $\boldsymbol{x}_n$. This means that the locus described by all the possible reflection points $\boldsymbol{x}_{m,n}^{(P)}$ associated to associated to the TOA $\tau_{n,m}$ is an ellipsoid, whose foci are $\boldsymbol{x}_m$ and $\boldsymbol{x}_n$ and whose major diameter is $c\tau_{n,m}$.

Ellipsoids, as all the other quadrics, have a convenient formulation using homogeneous coordinates, as already described in [1] and [6] for the 2D geometry. A generic 3D point $\boldsymbol{x} = [x_1, x_2, x_3, x_4]$ (where the fourth variable k adopted in the notation used for (3) has been "absorbed by x_4) belongs to a quadric with parameters$[a_{n,m}, b_{n,m}, c_{n,m}, d_{n,m}, e_{n,m}, f_{n,m}, g_{n,m}, h_{n,m}, i_{n,m}, l_{n,m}]^T$ if and only if

$$\begin{gathered} a_{n,m}x_1^2 + bn,mx_1x_2 + cn,mx_2^2 + dn,mx_1x_3 + en,mx_2x_3 + \\ fn,mx_3^2 + gn,mx_1x_4 + hn,mx_2x_4 + in,mx_3x_4 + ln,mx_4^2 = 0. \end{gathered} \quad (5)$$

A more compact representation of a quadric is possible using a matrix notation. In fact the quadric constraint becomes

$$\boldsymbol{x}^T \mathbf{C}_{n,m} \boldsymbol{x} = 0\,, \quad (6)$$

where

$$\mathbf{C} = \begin{bmatrix} a_{n,m} & b_{n,m}/2 & d_{n,m}/2 & g_{n,m}/2 \\ b_{n,m}/2 & c_{n,m} & e_{n,m}/2 & h_{n,m}/2 \\ d_{n,m}/2 & e_{n,m}/2 & f_{n,m} & i_{n,m}/2 \\ g_{n,m}/2 & h_{n,m}/2 & i_{n,m}/2 & l_{n,m} \end{bmatrix}. \quad (7)$$

is the quadric matrix.

The problem is now to estimate the quadric matrix (or, equivalently, its parameters) from the knowledge of $\boldsymbol{x}_n$, $\boldsymbol{x}_m$ and of the major diameter $\tau_{n,m}$. In [1] and [6] a solution that is based on the computation of the minor diameter of the ellipsoid is presented. However, this methodology envisions to pass through intermediate results. Here we propose, instead, a different technique that directly from the positions of source, receiver and TOA extracts the parameters of the quadric.

A generic 3D point $\boldsymbol{x} = [x_1, x_2, x_3, 1]^T$ (where the fourth coordinate has been set to 1 for the sake of simplicity in the derivation) is on the ellipsoid with foci in $\boldsymbol{x}_n = [x_{n1}, x_{n2}, x_{n3}, 1]^T$ and $\boldsymbol{x}_m = [x_{m1}, x_{m2}, x_{m3}, 1]^T$ and major diameter $c\tau_{n,m}$ if and only if

$$\begin{gathered} \sqrt{(x_1 - x_{n1})^2 + (x_2 - x_{n2})^2 + (x_3 - x_{n2})^2} + \\ \sqrt{(x_1 - x_{m1})^2 + (x_2 - x_{m2})^2 + (x_3 - x_{m2})^2} = c\tau_{n,m}\,. \end{gathered} \quad (8)$$

By expanding eq.(8) and comparing it with eq.(5) (where $x_4 = 1$ for uniformity with (8)) we obtain the quadric parameters

$$\begin{aligned}
a_{n,m}&=4[(x_{1,m}-x_{1,n})^2-T^2],\\
b_{n,m}&=8[(x_{1,m}-x_{1,n})(y_{1,m}-y_{1,n})],\\
c_{n,m}&=4[(y_{1,m}-x_{2,n})^2-T^2],\\
d_{n,m}&=8[(x_{1,m}-x_{1,n})(x_{3,m}-x_{3,n})],\\
e_{n,m}&=8[(x_{2,m}-x_{2,n})(x_{3,m}-x_{3,n})],\\
f_{n,m}&=4[(x_{3,m}-x_{3,n})^2-T^2],\\
g_{n,m}&=4[T^2(x_{1,n}+x_{1,m})-(x_{1,m}-x_{1,n})(x_{1,m}^2-x_{1,n}^2+x_{2,m}^2+x_{3,m}^2-x_{2,n}^2-x_{3,n}^2)],\\
h_{n,m}&=4[T^2(x_{2,n}+x_{2,m})-(x_{1,m}-x_{1,n})(x_{1,m}^2-x_{1,n}^2+x_{1,n}^2+x_{3,n}^2-x_{1,n}^2-x_{1,n}^2)],\\
i_{n,m}&=4[T^2(x_{3,n}+x_{3,m})-(x_{1,m}-x_{1,n})(x_{3,m}^2-x_{3,n}^2+x_{2,m}^2+x_{1,m}^2-x_{1,n}^2-x_{2,n}^2)],\\
l_{n,m}&=[(x_{1,m}^2+x_{2,m}^2+x_{3,m}^2)+(x_{1,n}^2+x_{2,n}^2+x_{3,n}^2-T^2)]^2\\
&\quad-4(x_{1,m}^2+x_{2,m}^2+x_{3,m}^2)(x_{1,n}^2+x_{2,n}^2+x_{3,n}^2),
\end{aligned}$$

where $T = c\tau_{n,m}$.

Equation (6) constrains, therefore, the reflection point to lie on the surface of the ellipsoid. This formulation, however, is not convenient when we are interested in finding the parameters of the plane. However, the dual form of the quadric comes at our help. More specifically, a plane $\boldsymbol{p} = [p_1, p_2, p_3, p_4]^T$ is tangential to the quadric $\mathbf{C}_{n,m}$ if and only if

$$\boldsymbol{p}^T \mathbf{C}_{n,m} \boldsymbol{p} = 0\,. \tag{9}$$

Summarizing, the knowledge of the source and receiver position and of the reflective TOA places a constraint on the reflector, that is bound to be tangential to the ellipsoid $\mathbf{C}_{n,m}$. By measuring multiple TOAs (from different positions of receiver and/or source) referred to the same reflector, we can bound the reflector to be tangential to multiple ellipses, one for each TOA.

We end up, therefore, with an equation system in which the vector of the plane parameters $\boldsymbol{p}$ is the unknown term:

$$\begin{cases}
\boldsymbol{p}^T \mathbf{C}_{1,1} \boldsymbol{p} & = 0\\
\boldsymbol{p}^T \mathbf{C}_{1,2} \boldsymbol{p} & = 0\\
\ldots & \\
\boldsymbol{p}^T \mathbf{C}_{N,M} \boldsymbol{p} & = 0
\end{cases}$$

In a real scenario Times Of Arrival are affected by errors, such as quantization or presence of spurious signals, which alter the correct value. We resort, therefore, to a cost function $J(\boldsymbol{p})$ that combines all the individual constraints

$$J(\boldsymbol{p}) = \sum_{m=1}^{M} \sum_{n=1}^{N} ||\boldsymbol{p}\mathbf{C}_{n,m}\boldsymbol{p}||^2\,. \tag{10}$$

In order to avoid the trivial solution $\boldsymbol{p} = \mathbf{0}$, we impose that the solution has unitary norm. The estimated plane $\hat{\boldsymbol{p}}$ is therefore

$$\hat{\boldsymbol{p}} = \arg\min_{\boldsymbol{p}} J(\boldsymbol{p}) \text{ subject to } ||\boldsymbol{p}|| = 1\,. \tag{11}$$

The minimization is accomplished using the same approach adopted in [1].

3.1 Extension to multiple reflectors

When multiple reflectors are present, the impulse response contains multiple reflective paths and becomes

$$\begin{aligned}
h_{m,n}(t) = x_{n,m}(t) \otimes s(t) = \qquad\qquad\qquad\qquad (12)\\
\alpha_{d,n,m}\delta(t-\tau_{d,n,m}) + \sum_{r=1}^{R} \alpha_{r,n,m}\delta(t-\tau_{r,n,m}) + r_{v_{n,m}}(t),
\end{aligned}$$

where R is the number of reflections that reach the microphone. In this scenario, we have to associate each TOA in the set

$$\boldsymbol{\tau} = \{\tau_{1,1,1}, \tau_{1,1,2}, \ldots, \tau_{r,n,m}, \ldots, \tau_{R,N,M}\},$$

to a specific reflector in the environment in order to obtain sets of TOAs $\boldsymbol{\tau}_1, \ldots, \boldsymbol{\tau}_L$, one for each reflector. We neglect the presence of multiple reflections, i.e. paths that bounce on more than one reflector.

We tackle the association problem using a Hough-like transform, which generalizes the one presented in [1], where the speaker was located on a circular path around the microphone.

Consider one microphone and one source, located in $[x_{1k}, x_{2k}, x_{3k}]^T$. For simplicity in the derivation we consider the microphone in the origin of reference system. The spherical coordinates of the source are ρ_k (distance from the origin), θ_k (co-elevation) and Φ_k (azimuth). A planar reflector is present in the environment. If we cast from the origin a line perpendicular to the reflector, it intersects the plane at a point. We denote the spherical coordinates of the point with ρ, θ and Φ. We notice that these coordinates define the reflector in an unique way, therefore in this Section we use spherical coordinates to represent a plane. The notation used for the derivation of the Hough transform is summarized in Figure 2 The TOA τ_k of the reflective path bouncing on the reflector is related to the distance between the image source (obtained by mirroring the source against the reflector plane) and the receiver, and it is given by

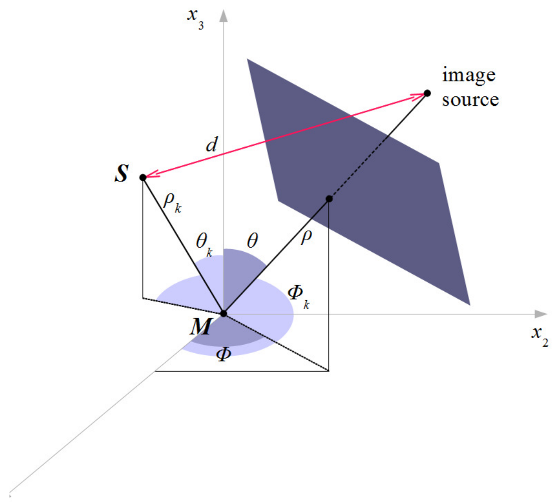


Figure 2: TOAs are computed through the distance d between the source and the image source respect to the microphone (or viceversa) by using spherical coordinates: ρ, θ, Φ for the reflector and ρ_k, θ_k, Φ_k for the k-th position of the source.

$$\begin{aligned}
\tau_k(\rho,\theta,\Phi) = \frac{1}{c}\big[&(2\rho\sin(\theta)\cos(\Phi) - \rho_k\sin(\theta_k)\cos(\Phi_k))^2\\
&+ (2\rho\sin(\theta)\sin(\Phi) - \rho_k\sin(\theta_k)\sin(\Phi_k))^2\\
&+ (2\rho\cos(\theta) - \rho_k\cos(\theta_k))^2\big]^{\frac{1}{2}},
\end{aligned} \tag{13}$$

where c is the propagation speed.

Given the coordinates of the speaker; of the receiver; and the coordinates ρ, θ, Φ identifying the reflector position, we are able to compute the TOA of the reflective path.

We call the coordinates (ρ, θ, Φ) as the Hough parameter space. We define a grid $(\rho_d, \theta_e, \Phi_f), d = 1, \ldots D, e = 1, \ldots, E, f = 1, \ldots, F$ in the Hough parameter space. More specifically, $-90° < \theta_e < +90°$, $-180° < \Phi_f < +180°$ and $\rho_{\min} < \rho_d < \rho_{\max}$, where the threshold distances $\rho_{\min}$ and $\rho_{\max}$ are properly chosen. A voting function $v(\rho_d, \theta_e, \Phi_f)$ is defined on the grid. For each point on the grid, we compute the TOA associated to the potential reflector located at $(\rho_d, \theta_e, \Phi_f)$. If

$$|\tau(\rho_d, \theta_e, \Phi_f) - \tau_{n,m}| < \varepsilon \tag{14}$$

then

$$v(\rho_d, \theta_e, \Phi_f) = v(\rho_d, \theta_e, \Phi_f) + 1 \,, \tag{15}$$

where ε is an acceptance threshold properly defined. At the end of the voting procedure, the position of the L most relevant local maxima of the function $v(\rho_d, \theta_e, \Phi_f)$ that overcome the threshold V are extracted. The TOAs that contributed to the lth local maxima are used for the set $\boldsymbol{\tau}_l$. The estimation of the geometry of the environment becomes, therefore, the estimation of the plane parameters of L individual reflectors. We notice also that the position of the local maxima provide an useful initialization of the minimization procedure described in the previous Section.

The derivation of the Hough transform can be easily generalized to the case of microphones not in the origin of the reference frame. In particular, equation 13 will incorporate the position of the microphone.

We notice that the definition of the minimum and maximum distances $\rho_{\min}$ and $\rho_{\max}$ is crucial to exclude the localization of reflectors outside the range of interest. As an example, if we intend to localize reflectors within the range of $3m$ from the origin of the reference frame, we can establish $\rho_{\max} = 3$m. As a consequence, the adoption of a proper threshold $\rho_{\max}$ comes at our help also to exclude the localization of "ghost" walls derived from multiple reflections.

4. EXPERIMENTAL RESULTS

In this section we present some experimental results on real data that show the accuracy of the proposed methodology.

In order to assess the accuracy of the localization, we compare the estimated plane parameters with the ground truth ones. In particular, we adopt two localization metrics. The first is based on the comparison of

- the distance ρ and $\hat{\rho}$ between the origin of the reference frame and the actual and estimated planes, respectively;
- the co-elevation θ and $\hat{\theta}$ of the actual and estimated planes, respectively;
- the azimuth Φ and $\hat{\Phi}$ of the actual and estimated planes, respectively.

The second metric measures the co-linearity in the plane parameter space between the vectors $\hat{\boldsymbol{p}}$ and $\boldsymbol{p}$, which are the plane parameters of the estimated and hand-measured planes, respectively. This metric therefore becomes

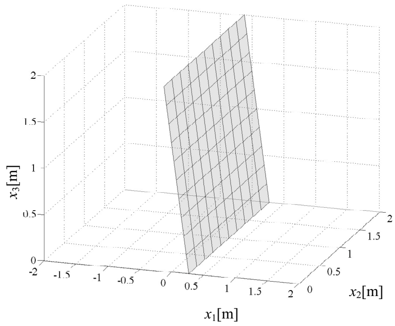
$$A = \frac{\boldsymbol{p}\hat{\boldsymbol{p}}}{||\boldsymbol{p}||||\hat{\boldsymbol{p}}||} \tag{16}$$

We carried out three tests. First, we placed in a dry room a single reflective wood panel. The goal of this test is to show the accuracy of the localization in a controlled scenario. The second setup is aimed at reconstructing the geometry of a simple environment composed by two parallel reflective wood panels placed in a dry room. We notice that, although simple, in this configuration the impulse response is characterized by multiple peaks, corresponding to multiple bouncing on the parallel walls. Finally, the third test is aimed at reconstructing the geometry of a real room.

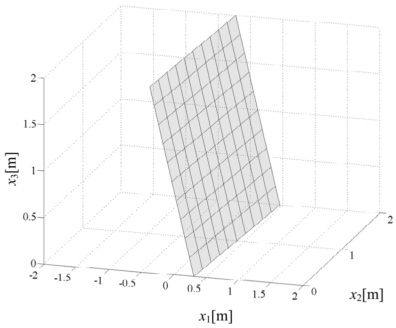
The source used for all the tests is a custom-made 2 inches loudspeaker. The signal has been acquired with up to 8 Beyerdynamic MM1 microphones. A sampling frequency of $Fs = 44100$ Hz has been adopted.

4.1 Localization of a single reflector

For this experiment we adopted a configuration of one source and six microphones. The microphones have been randomly placed. Their positions were then measured. Though random, the positions of the microphones grant that the direct path between the source and each sensor is always present. The reflective panel has been tilted at two different inclinations. Figure 3 shows the hand-measured and estimated planes for each configuration. Table 1 shows the localization results for both tilt angles.



(a) Hand-measured plane



(b) Estimated plane

Figure 3: Example of localization of a single reflector

Table 1: Localizing a single reflector tilted at two different inclinations

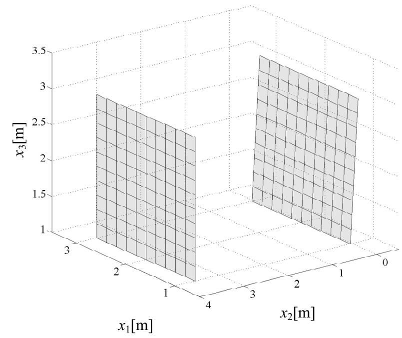
Experiment	ρ[m], θ[°], Φ[°]	$\hat{\rho}$[m], $\hat{\theta}$[°], $\hat{\Phi}$[°]	$A = \frac{\boldsymbol{p}\hat{\boldsymbol{p}}}{\lVert\boldsymbol{p}\rVert\lVert\hat{\boldsymbol{p}}\rVert}$
Position 1	(0.26,11,0)	(0.3,20,355.5)	0.9934
Position 2	(1.18,-16.6,134.6)	(0.9,-15,144)	0.9881

4.2 Localization of two parallel reflectors

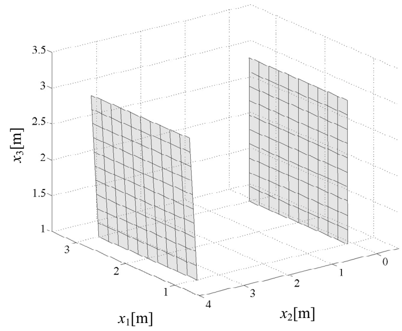
In this situation we consider the case of two reflectors that lie on parallel planes, distant 3.4m each other. As in the previous experiment, the microphones have been placed at random locations between the two walls, where also the source is located. The source is directive, therefore we acquired the impulse responses for two different orientations, each facing to one reflector at time. We notice that the situation in this experiment is more complex, as the impulse response of this simple environment exhibits multiple peaks, due to direct path, first and higher-order reflections. In order to avoid the localization of "ghost" walls related to multiple reflections we use $\rho_{\max} = 3.8$m. Figure 4 shows the localization of the reflectors. Table 2 shows the accuracy of the localization. We notice that the localization of the individual reflectors is not affected by the presence of multiple reflections.

4.3 Estimation of the room geometry

For this experiment we moved source and microphones in a reverberant room, whose bounding box is approximately $5\text{m} \times 4\text{m} \times 3\text{m}$.

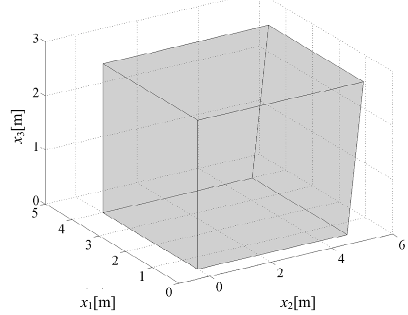


(a) Hand-measured planes

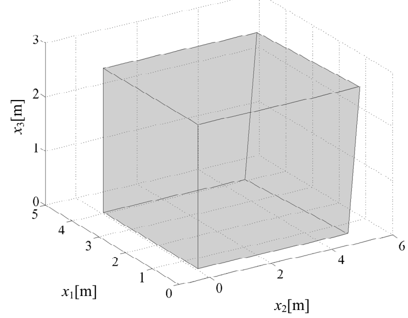


(b) Estimated planes

Figure 4: Example of localization of two parallel reflectors



(a) Actual geometry



(b) Estimated geometry

Figure 5: Example of estimation of a complex geometry

Table 2: Localizing two parallel reflectors

Experiment	ρ[m], θ[°], Φ[°]	$\hat{\rho}$[m], $\hat{\theta}$[°], $\hat{\Phi}$[°]	$A = \frac{\mathbf{p}\hat{\mathbf{p}}}{\|\mathbf{p}\|\|\hat{\mathbf{p}}\|}$
1st plane	(3.545,0,90)	(3.4,-5,90)	0.9996
2nd plane	(0.13,5,90)	(0.1,0,90)	0.9958

Four microphones are disposed in the center of the room. Six acquisitions have been performed, and for each of the acquisitions the source is moved close to each wall. As a consequence, we end up with 24 impulse responses. For this experiment, the parameters $\rho_{\max}$ and $\rho_{\min}$ have been set to 5.5m and 0m, respectively.

Figure 5 shows the actual and estimated geometries, while Table 3 details the accuracy of the localization for each of the six reflectors.

Table 3: Inference of a real environment.

Plane (n°)	ρ[m], θ[°], ϕ[°]	$\hat{\rho}$[m], $\hat{\theta}$[°], $\hat{\Phi}$[°]	$A = \frac{\mathbf{p}\hat{\mathbf{p}}}{\|\mathbf{p}\|\|\hat{\mathbf{p}}\|}$
1	(0,0,0)	(0.03,0,0)	1
2	(4.8,-11,0)	(4.81,-10,4.5)	1
3	(0.45,0,90)	(0.48,0,90)	1
4	(4,0,90)	(4.02,0,90)	1
5	(0,90,0)	(0.02,90,0)	1
6	(2.75,90,0)	(2.68,90,0)	0.99

We notice that also in this case the accuracy of the localization is not affected by the presence of multiple walls in the environment.

5. CONCLUSIONS

In this paper we have investigated on the problem of localizing planar reflective surfaces using acoustic measurements. The technique described is based on the use of multiple quadratic constraints, associated to measurements of the Time Of Arrival of reflective paths. This methodology is an improvement of a previously developed technique [1] conceived for the estimation of 2D geometries. We also discussed the problem of localizing multiple reflectors. This extension is based on a divide and conquer approach by grouping TOAs coming from the same reflector and then performing separate localizations, one for each reflector in the environment. Some experimental results show that the proposed method is capable of a good accuracy, even for complex geometries of the environment.

REFERENCES

[1] F. Antonacci, A. Sarti, and S. Tubaro, "Geometric reconstuction of the environment from its response to multiple acoustic emissions," in *proc. of 2010 IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP*, 2010.

[2] T. Betlehem and T. Abhayapala, "Theory and design of sound field reproduction in reverberant rooms," *J. Acoust. Soc. Amer.*, vol. 117, pp. 2100–2111, 2005.

[3] F. Ribeiro, C. Zhang, D. Florencio, and D. Ba, "Using reverberations to improve range and elevation discrimination for small array sound source localization," *IEEE Transactions on Audio, Speech and Language Processing*, vol. 18, pp. 1781–1792, 2010.

[4] D. Ba, F. Ribeiro, C. Zhang, and D. Florencio, "ℓ_1 regularized room modeling with compact microphone arrays," in *proc. of 2010 IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP*, 2010.

[5] S. Tervo and T. Korhonen, "Estimation of reflective surfaces from continuous signals," in *proc. of 2010 IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP*, 2010.

[6] J. Filos, E. Habets, and P. Naylor, "A two-step approach to blindly infer room geometries," in *proc. of International Workshop on Acoustic Echo and Noise Cancellation (IWAENC)*, 2010.