ON THE TRAJECTORIES CONTROL OF A HYBRID ROBOTIC SYSTEM

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Abstract : *The contribution of this research is to advance a new sonification operator capable to solve the inverse problem of sonification in order to capture hardly detectable details in medical images. The direct problem of sonification is converting data points into audio samples by a mapping which involves three processes - data, acoustics parameters and sound representations. The inverse problem is reversing back the sound samples into data points in order to gain in clarity and contrast in medical images, and by reducing the noise, new hidden details to be discovered. This approach is exercised in the control of the surgical instrument trajectories for a cooperative surgeon-robot hybrid system. The objective of the cooperation between the surgeon and the robot is to stop the surgical instrument to reach some forbidden frontiers.*
Keywords : *Acoustics, auditory display, sonification operator, surgery hybrid robot.*

1. INTRODUCTION

The sonification uses a parameter mapping to translate the set of data points into acoustic signals [1, 2]. For example, Parseihian et al [3] translate target distance to pitch, timbre, and tempo in various combinations to assist the guidance activities. Silva et al [4] translate properties of graphical objects to acoustic parameters to communicate visual information to visually disadvantaged people. Roodaki et al. [5] mapped the pressure to the timbral parameters of an acoustic sygnal to assist people with visual object tracking tasks.
The nano-guitar built by Cornell University physicists from the crystalline silicon no larger than a single human blood cell, invites the bacteria inside a person to play and thus to be easily detected and tracked with a stethoscope [6]. The quantum whistle is a nano-scale sound which is able to discover oscillations in superfluid gases that are predicted by quantum theory [7-10].
The sonification allows new insights into some diseases such as the Alzheimers's dementia [11] and therapies in body movements such as walking, turning, rising arms or legs [12]. The theory of sonification has applications in robotics, imaging, surgery, audio engineering, audiology, computer science, informatics, linguistics, mathematics, music, psychology, and telecommunications, because of its unified set of principles or rules [13-19].
The inverse problem of sonification, i.e. the reversing back the sound samples into new images is less studied so far and not found in the literature to our knowledge. The using of known sonification operator in this inverse approach does not bring any improvement in the image, in the sense that by reversing the audio signals the same image is obtained.This paper introduces a new sonification operator capable to solve the inverse problems of sonification.

2. DIRECT PROBLEM OF SONIFICATION

We present in this paragraph the direct problem of sonification as known in the literature [19-22].
The sonification operator S^0 transforms the point data space D into the sound signals space Y^0, $S^0 : D \to Y^0$, or $S^0 : x(t) \to y^0(t^0, x(t), p^0)$, where $x(t)$ is the 1D point data to be transformed into sounds depending of the data time t, t^0 is the sonification time, and $p^0 \subseteq P^0$, $P^0 = \{k^0, \Delta^0, f^0_{ref}, \alpha^0, \beta^0, \phi^0, \varepsilon^0, g^0, \gamma^0, H^0\}$. The parameters of P^0 are: k^0 the time compressor factor with the sonification time interval $T^0 = T / k^0$, $\Delta^0 \geq 0$ the dilation factor, f^0_{ref} is the reference frequency, $\alpha^0, \beta^0 \geq 0$ the pitch scaling parameters, $\phi^0 \geq 1$ the power distorsion factor, $\varepsilon^0 \geq 0$ the threshold for the amplitude, g^0 the gain function, γ^0 the decay parameter and H^0 the timbral control function.

The one-dimensional data stream $x(t)$ can be divided into non-overlapping segments of different length, depending on application. The variable of the data domain are t, t_i, T. The data domain is a signal $x(t)$ expressed as a sequence $x(n)$ at the sampling rate f_s. The duration of $x(t)$ is T seconds, then $x(n)$ consists of $N = T \times f_s$ samples. The time points t_i which are the frontiers between segments $x_i(t)$ are determined function of the application. If $t_0 = 0$ and the last time $t_M = T$, a possible division in M segments of $x_i(t)$ is

$$x_i(t) = \begin{cases} x(t + t_{i-1}) & 0 \le t \le (t_i - t_{i-1}) \\ 0 & \text{else} \end{cases} \tag{1}$$

For which the duration of each segment is $T_i = t_i - t_{i-1}$ Each segment $x_i(t)$ is sonified as an single sonic event $y_i^0(t^0)$ which might be longer or shorter than T_i and depending on p^0

$$y^0(t^0) = \sum_{i=1}^{M} y_i^0(t^0 - t_{i-1}^0),\ t_{i-1}^0 = \frac{t_{i-1}}{k^0}\ . \tag{2}$$

The general form for the sonification signal $y^0(t^0)$ is

$$y_i^0(t^0) = | x_i(\Delta^0 t^0) | \sin\left(2\pi \int_0^{t^0} f_{ref}\, 2^{(x_{trend}(t_{i-1}) + x_i(\Delta^0 t^{0'}))} \mathrm{d}t^{0'} \right), \tag{3}$$

where the second term $x_i(\Delta^0 t^{0'})$ is the mean free segment, and $x_{trend}(t_{i-1})$ the trend signal at the starting point for pitch modulation. Parameter Δ^0 determine the length of the sonic event T_i^0 function on T_i If $\Delta^0 = k^0$ adjacent events do not overlap but for $\Delta^0 \le k^0$ they overlap.

To introduce control of timbre, the operator H^0 acts as the sine function, so

$$y_i^0(t^0) = a_i(t^0) H^0 < \sin\left(2\pi \int_0^{t^0} f_{ref}\, 2^{b_i(t^{0'})} \mathrm{d}t^{0'} \right) >,\quad b_i(t^{0'}) = \left(\alpha^0 x_{trend}(t_{i-1}) + \beta^0 x_i(\Delta t^{0'}) \right), \tag{4}$$

where $a_i(t^0)$ is the amplitude modulator, f_{ref} is the base frequency for the pitch range of sonification and $b_i(t^0)$ is a pitch modulator. The amplitude modulator is defined as

$$a_i(t^0) = | x_i(\Delta^0 t^0 |^{\phi^0}\ ,\ \phi^0 \ge 1\,, \tag{5}$$

where φ^0 has the role of amplitude modulator. For exceeding a threshold ε^0 around the mean of the amplitude, a half-wave rectification is included

$$a_i(t^0) = g\left(| x_i(\Delta^0 t^0 |, \varepsilon^0 \right)\ ,\qquad g(x, \varepsilon^0) = \begin{cases} x - \varepsilon^0 & x \ge \varepsilon^0 \\ 0 & \text{else} \end{cases} \tag{6}$$

A common form of (5) or (6) is

$$y_i^0(t^0) = a_i(t^0) \sin\left(2\pi \int_0^{t^0} 2^{b_i(t^{0'})} f_{ref} \mathrm{d}t^{0'} \right). \tag{7}$$

2. NEW SONIFICATION OPERATOR

The basic idea of new sonification operator is the nonlinear equation of sound propagation whose solutions are expressed as cnoidal functions and not as trigonometric functions. The cnoidal functions are much richer than the trigonometric or hyperbolic functions, that is, the modulus m of the cnoidal function, $0 \le m \le 1$, can be varied to obtain a sine or cosine function $(m \cong 0)$, a Stokes function $(m \cong 0.5)$ or a solitonic function, sech or tanh $(m \cong 1)$ [26, 31].

Let us to consider 3D digital image B seen as a collection of N pixels or dots seen as the smallest controllable elements of an image. We suppose that B is embedded in Euclidean space E^3, has the volume Ω_1 and surface Γ. A Cartesian coordinates X_K, $K = 1,2,3$ is taken as a reference frame at time $t = 0$, to locate a pixel $P \in B$ in Ω_1. The B forms N-dimensional set of data $D = \{d_1, d_2, ..., d_N\}, d_i \in R^N$.

The B may be subjected to external force vector $f(t)$ written as the sum of the excitation harmonic force $F_p(t)$ and the generation sound force $F_s(t)$. The last force is introduced to build the sonification operator. Given a known primary force vector F_p we want to determine the unknown function F_s such that the acoustic power radiated from B is a minimum. B may occupy at a later time t a new configuration $b \in E^3$ with position vector of Cartesian coordinates x_k, $k=1,2,3$. The response of B to the force vector f is a configuration b defined by the motion of a point $P \in B$ at time t. This motion is described by

$$x_k = x_k(X_1, X_2, X_3, t)\,. \qquad (8)$$

At frequency ω the velocity can be written in complex notation $v(t) = V\exp(\mathrm{i}\omega t)$. Similarly, the force is $f(t) = F\exp(\mathrm{i}\omega t)$. The response of B is written in terms of the complex mobility matrix (inverse of impedance) $\Sigma(\omega, \omega_j, \phi_j, \eta_j) = \dfrac{v(\mathrm{i}\omega)}{f(\mathrm{i}\omega)}$, $j = 1,2,...,M$ or $v = \Sigma F$, where v is the velocity vector, F the point-force vector exciting B normal to Γ. The index j refers to the j vibration mode, ω is the harmonic excitation frequency, ω_j is the j th natural frequency, η_j is the damping loss factor associated with the j th natural frequency and ϕ_j is the mass normalized modal displacement vector perpendicular to Γ in air [23, 24].

The acoustic power radiated from B is written as

$$W = \frac{1}{2} v^T A v\,,\; A = \sum_{i=1}^{M} \lambda_i q_i q_i^T\,, \qquad (9)$$

with v the velocity vector and A the acoustic impedance which is positive definite and Hermitian matrix, written in term of its M eigenvalues $\Lambda = \mathrm{diag}(\lambda_1, \lambda_2, ..., \lambda_M)$ and eigenvectors $Q = [q_1, q_2, ..., q_M]$.

We have

$$W = \frac{1}{2} F^T \Sigma^T (Q \Lambda Q^T) \Sigma F\,, \qquad (10)$$

where the superscript T refers to Hermitian transpose conjugate operation.

The mobility matrix is used in [23, 24] to minimize the total sound power radiated from a structure subjected to a harmonic excitation force. Along this paper, the mobility matrix is used to define the sonification operator.

By setting $\dfrac{\partial W}{\partial F_s} = 0$, we determine the functions F_s under the form

$$F_s(d_j) = \mathrm{cn}(m_j, k_{1j}x_1 + k_{2j}x_2 + k_{3j}x_3 - \omega_j t + \tilde{\phi}_j)\,, \qquad (11)$$

where n is the finite number of degrees of freedom of the cnoidal functions, $0 \le m_j \le 1$ is the modulus of the Jacobean elliptic function, ω_j are frequencies and $\tilde{\phi}_j$ the phases, k_{1j}, k_{2j}, k_{3j} are components of the wave vector [26]. The sonification operator $\Psi(D,t) : \Omega_1 \times T_0 \to \Omega_2 \times \overline{T}_0$ transforms dataset D to M -dimensional sound signal, where Ω_2 is a subset of R^n representing the sound domain, T_0 is the interval of time associated to D, and $\overline{T}_0$ is associated to Ω_2. This operator is defined as

$$\psi(D,t) = \sum_{j=1}^{N} \left(\beta_j F_s(d_j) + \frac{\gamma_j F_s(d_j)}{1 + \zeta_j F_s(d_j)} \right), \qquad (12)$$

where β_j, γ_j, ζ_j, $j = 1,2,...,n$, are parameters that are determined from a genetic algorithm.

The inverse sonification operator is given by $\Psi^{-1}(D) = \tilde{d}$, where $\Psi^{-1}(D) : \Omega_2 \times T_0 \to \Omega_1 \times T_0$, and $\tilde{d}$ the new inverse sonification image $\tilde{D} = \left\{ \tilde{d}_1, \tilde{d}_2, ..., \tilde{d}_N \right\}, \tilde{d}_i \in R^N$.

By applying the inverse sonification algorithm, a new digital image is obtained, and this image has superior properties to the original one in terms of clarity and contrast, and by reducing the noise, new hidden details are discovered in the image.

3. RESULTS

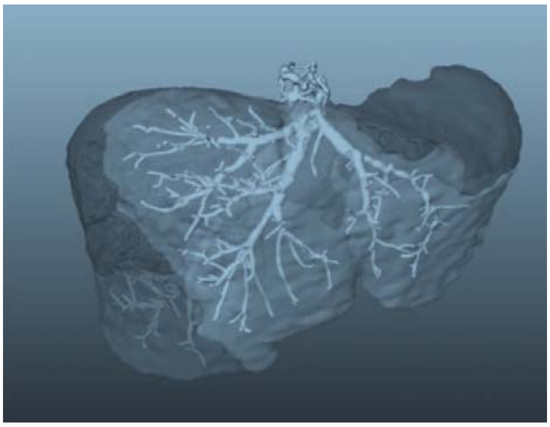
In the robotic surgery hybrid system, the goal of the robot is to stop the tool-tip to cross the critical boundaries Γ in the working space Ω, helping the surgeon to resolve conflicting trajectories towards the final point.

The Γ contains, in the first place and near other forbidden areas, the hepatic veins (Figure 1) [29]. The surgeon manipulates freely the tool-tip in Ω without robotic interference, but, when the tool-tip located at the distance d to Γ, reaches its neighborhood to a distance $D < d$ from Γ the robot attenuates the speed of the tool-tip proportionally to D (Figure 2). Different trajectories of the tool-tip are shown by different colours [30].

The choice of trajectories is based on the medical images.

In the case of imaging a tumor in the liver, the signal would be the difference between the tumor and the surrounding tissue, and the noise could be assessed as a standard deviation in the nearby surrounding tissue.

Without contrast it is impossible to visualize structural details of the liver. Our results have shown that the inverse sonification technique improve the spatial resolution and contrast and also, reduces the noise.



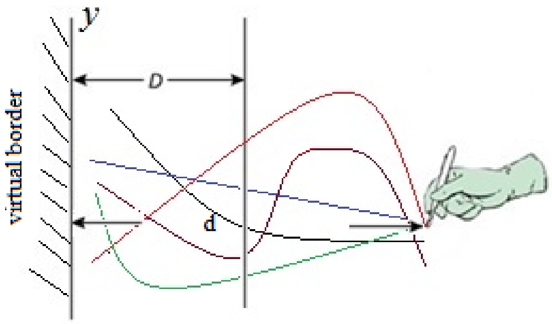
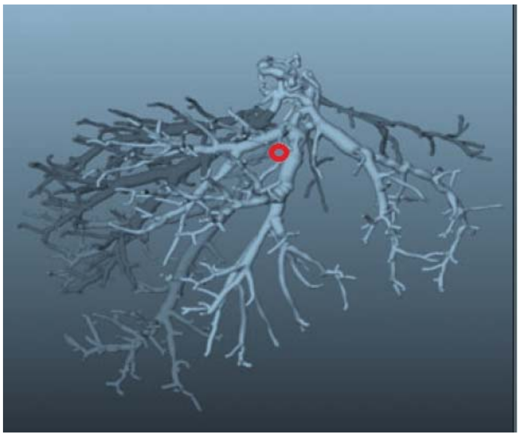


Figure 1: View of vascular territories in the liver [29]. **Figure 2**: Cooperatively control to restrict the tool-tip to cross a virtual border [30].

We consider the case of o tumor with a difficult location, i.e. in the vicinity of the portal tree of the vascular territory in the liver (Figure 3). The trajectory of the surgical instrument was established following the analyses of the image of the tumor seen on a microscope (Figure 4). White and grey denote forbidden areas while the shade of purple are safe regions. The tumor is drawn in red and the green line is the proposed safe trajectory. The inverse sonification image is shown in Fig. 5. It appears from the picture that chosen path is not recommended because it cuts the forbidden area.



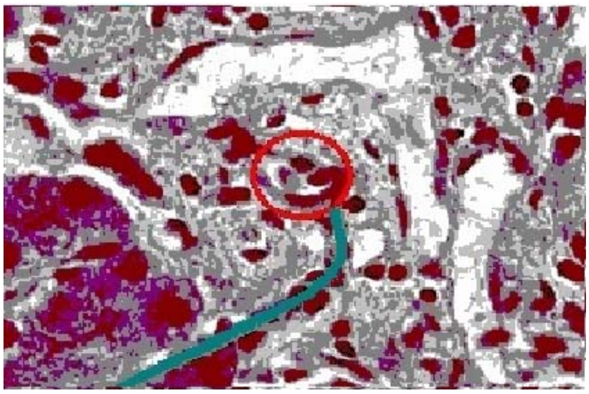


Figure 3 : Location of the tumor. **Figure 4** : Tumor image seen on the microscope.

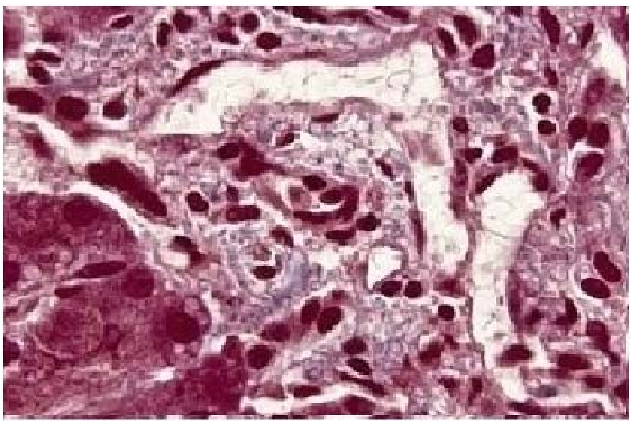


Figure 5: Inverse sonification image in the vicinity of the tumor.

4. CONCLUSION

The features of imaging which help in evaluating of imaging are spatial resolution, contrast and noise. Spatial resolution or clarity refers to smallest spacing between two elements that can be clearly imaged. The contrast is the difference between adjacent areas in an image, and random noise is imprecision in recording of the signal. There are many opinions in this regard: a screen/film combination has better spatial resolution than a CT (computed tomograhy) or MRI (magnetic resonance imaging), or a CT scanner is better than a film/screen system because it provides higher bone-to-tissue or tissue-tissue contrast, or that MRI is better than CT because of its high within soft tissue contrast. This paper advances a new sonification operator capable to solve the inverse problem of sonification, whose results consists in substantial improvement of the spatial resolution, contrast and noise and also in completing the image with details that did not exist before. The direct sonification problem is converting the data points of an image into audio samples, involving three processes-image data, acoustics parameters and sound representations. The inverse sonification problem is reversing back the sound samples into data points. This approach is exercised to control the surgical instrument trajectories for a cooperative surgeon-robot hybrid system.

Acknowledgement: This work was supported by a grant of the Romanian ministry of Research and Innovation, CCCDI - UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0221 / 59PCCDI/2018 (IMPROVE), within PNCDI III.

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