ON THE INVERSE SONIFICATION PROBLEM

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Abstract. The inverse sonification problem is discussed in this paper in order to identify new features in its capability to discover hidden details in the medical images. In contrast to the direct problem of sonification that convert the data points into audio samples, the inverse problem is turning back the sound representation into images in order to obtain clarity, good contrast and low noise. The technique is exercised on several images used for surgical operations.

Key words: inverse problem of sonification, medical imaging.

1. INTRODUCTION

A major interest was devoted in the last years to improve the quality of the medical imaging [1–3]. The computed tomography, magnetic resonance imaging, nuclear imaging, and ultrasound-positioned medical imaging have continually improved to facilitate the diagnoses and surgery.

A recent technique that leads to major image enhancements is the inverse problem of sonification [4–9]. The direct problem of sonification is converting the imaging data into sound representations and the inverse problem is turning back the sound samples into imaging data. We have to say that by reversing the sonification operator known in the literature, only the old image is obtained.

So, to improve the medical image and further to discover new elements into it, a new sonification operator is applied [10]. The result of this procedure is another image which is better than the first one in term of clarity, contrast and noise. In addition, the hidden details which did not exist in the old image can appear.

The hidden details appearing after sonification into an image are due to the fact that the mapped data which typically contain imperfections and blurring area are filled with details through continuity solutions in the adjacent areas, so that the final image may contain new elements, new details that do not appear in the

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original image. Utility of the inverse sonification technique was highlighted on a large number of medical images used to surgical operations.

The sonification theory is known since 1952 when Pollack transforms for the first time the information knowledges into a visualization tool [11,12].

Remarkable results in the field of direct problem of sonification can be found in [13–18].

The paper is organized as follows: Section 2 is devoted to description of the direct and inverse problems of sonification. The applications are presented in Section 3, and the Section 4 contains conclusions.

2. DIRECT AND INVERSE PROBLEMS OF SONIFICATION

The direct problem, as known in the literature, is based on the linear theory of sound propagation [19, 20]. The sonification operator S^0 that transforms the image data *D* into sound signals Y^0 is defined as

$$S^0 : D \to Y^0 , \quad S^0 : x(t) \to y^0(t^0, x(t), p^0) , \tag{1}$$

where $x(t)$ is the point data to be transformed into sounds, *t* is the data time, t^0 is the sonification time, and $p^0 \subseteq P^0$, are the sonification parameters.

The $x(t)$ is divided into non-overlapping M elements of different length as

$$x_i(t) = \begin{cases} x(t + t_{i-1}) & \text{for } \ 0 \le t \le (t_i - t_{i-1}) \\ 0 & \text{else} \end{cases} \tag{2}$$

for $t_0 = 0$ and $t_M = T$. The duration of each element is $T_i = t_i - t_{i-1}$. Each element $x_i(t)$ is sonified as a single event $y_i^0(t^0)$

$$y^0(t^0) = \sum_{i=1}^{M} y_i^0(t^0 - t_{i-1}^0), \quad t_{i-1}^0 = \frac{t_{i-1}}{k^0} . \tag{3}$$

The form for the sonification signal $y^0(t^0)$ given by S^0 is

$$y_i^0(t^0) = | x_i(\Delta^0 t^0) | \sin\left(2\pi \int_0^{t^0} f_{ref} \, 2^{(x_{trend}(t_{i-1}) + x_i(\Delta^0 t^{0'}))} \mathrm{d}t^{0'} \right), \tag{4}$$

where Δ^0 determine the length of the sonic event T_i^0 , $x_i(\Delta^0 t^{0'})$ is the mean free segment and $x_{trend}(t_{i-1})$ is the trend signal at $t_0 = 0$ for pitch modulation.

If $\Delta^0 = k^0$ the adjacent events do not overlap but for $\Delta^0 \le k^0$ they overlap. For the timbre control is introduced the operator H^0

$$\begin{gathered} y_i^0(t^0) = a_i(t^0) H^0 < \sin\left(2\pi \int_0^{t^0} f_{ref}\, 2^{b_i(t^{0'}))} \mathrm{d}t^{0'} \right) >, \\ b_i(t^{0'}) = \left(\alpha^0 x_{trend}(t_{i-1}) + \beta^0 x_i(\Delta t^{0'}) \right), \\ a_i(t^0) = | x_i(\Delta^0 t^0 |^{\phi^0}, \quad \phi^0 \ge 1, \end{gathered} \tag{5}$$

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 φ^0 has the role of the amplitude modulator.

The inverse problem is built up for a new sonification operator, because by inverting S^0 the same image is obtained. The new sonification operator is based on the nonlinear theory of sound propagation.

Let us consider a digital image *B* of area *A*, seen as a collection of *N* pixels $D = \{d_1, d_2, ..., d_N\}, d_i \in R^N$. The *B* is subjected to the force $f(t)$ expressed as a 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. The response of *B* to $f(t)$ is a new configuration *b* defined of all points $P \in B$ at the time *t* resulting by vibration of *B*. The vibration of *B* is described by decoupled Burgers equations [21]

$$\frac{\partial v}{\partial x} - \frac{\beta}{c_0^2} v \frac{\partial v}{\partial \tau} - \frac{b}{2\rho_0 c_0^3} v \frac{\partial^2 v}{\partial \tau^2} = 0, \tag{6}$$

where $x = (x_1, x_2, x_3)$, $v = (v_1, v_2, v_3)$ is the acoustic velocity vector, $\tau = t - x / c_0$ is the retarded time, where *t* is time, c_0 is the velocity of sound propagation in the linear approximation, $b = (b_1, b_2, b_3)$ are the dissipation coefficients, ρ_0 is density of medium, $\beta = (\beta_1, \beta_2, \beta_3)$ is nonlinearity coefficient [22–25].

Given a known force F_p, we determine F_s such that the acoustic power radiated from *B* to be minimum. The acoustic power radiated from *B* is written as

$$W = \frac{A}{2} v^T p, \tag{7}$$

where *v* is the velocity verifying (6) and *p* the acoustic pressure vector, *A* is the area of the rectangular picture, and the subscript *T* represents the Hermitian transpose [26]. Equation (6) admits the cnoidal solutions [27]

$$v_i = \sum_{j=1}^{l} a_j \mathrm{cn}^j(m_i,\eta_i) + \frac{\sum_{j=1}^{l} b_j \mathrm{cn}^j(m_i,\eta_i)}{1+\sum_{j=1}^{l} c_j \mathrm{cn}^j(m_i,\eta_i)}, \quad i = 1,2,3, \tag{8}$$

where $\eta_i = k_{1i}x_1 + k_{2i}x_2 + k_{3i}x_3 - \omega_i t + \tilde{\phi}_i$, $0 \le m \le 1$ is the moduli of the Jacobean elliptic function, ω is frequency and $\tilde{\phi}$ the phase, k_1, k_2, k_3 are components of the wave vector. In the following we stop to $l = 2$, and we will see that there are no sensible improvements in solutions for $l > 2$.

The function $F_s(t)$ is determined from

$$\frac{\partial W}{\partial F_s} = 0. \tag{9}$$

The unknown parameters

$$P_j = \{m_j, \omega_j, k_{1j}, k_{2j}, k_{3j}, \tilde{\phi}_j, a_1, b_1, c_1, a_2, b_2, c_2\}, \quad j = 1,2,3, \tag{10}$$

are find by a genetic algorithm which minimizes the objective function $\Upsilon(P_j)$ given by

$$\Upsilon(P_j) = 3^{-1}\sum_{j=1}^{3} \delta_{1j}^2 + \delta_2^2, \tag{11}$$

with

$$\delta_{1j} = \frac{\partial v_j}{\partial x_j} - \frac{\beta_j}{c_0^2} v_j \frac{\partial v_j}{\partial \tau} - \frac{b_j}{2\rho_0 c_0^3} v_j \frac{\partial^2 v_j}{\partial \tau^2}, \quad \delta_2 = \frac{\partial W}{\partial F_s}, \tag{12}$$

where δ_{1j} and δ_2 are the residuals of (6) and (9) which must tend to zero.

The genetic algorithm is working until it is reached a non-trivial minimizer, which will be a point at which (11) admits a global minimum.

The quality of results depends on the values of Υ. The required precision is taken to be six places after the decimal point. The genetic parameters are: number of populations 200, ratio of reproduction 1.0, number of multi-point crossover 1, probability of mutation 0.5, and maximum number of generations 500.

Once determined the function F_s, the sonification operator S is written as

$$S(D,t) = F_s(\tilde{D},t) + \frac{F_s(\tilde{D},t)}{1+F_s(\tilde{D},t)}, \tag{13}$$

where $D=\{d_1,d_2,...,d_N\}, d_i \in R^N$ is the point data of the original image, $\tilde{D}=\{\tilde{d}_1,\tilde{d}_2,...,\tilde{d}_N\}, \tilde{d}_i \in R^N$ is the point data domain of the final image, and *t* is the sonification time. Data *D* is arranged under the form of a matrix with arbitrarily number of boxes (Fig. 1). Each box of the matrix may contain different colors and nuances, borders, line and curved lines.

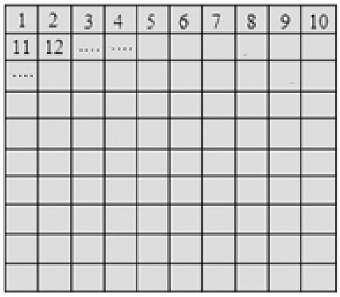

Fig. 1 – Data matrix with arbitrarily number of elements.

As we said before, the medical image is divided into elements and each element contains colors, nuances, borders and geometric lines. Each element received a code which contains 24 digits, in accordance to two maps that contain attributes of the nonlinear coefficients and the attributes of the dissipation coefficients, respectively.

The maps are associated to the organ, diagnosis, tumor, and to the origin of the medical image. The code contains information from which the values of nonlinearity and dissipation coefficients are built. This is done automatically. If there is ambiguity, the human factor intervenes and decides the reevaluation of these digits.

After sonification, the code of each element is changed due to the improvements earned to the contrast and clarity, and to the noise reduction. The digits of each element's code are redefined and the new image is built. The blur arias are getting a special attention. By continuity of the cnoidal solutions in the vicinity of the blurred area, this area is recovered with color, border borders and geometric lines. The sonification uses the genetics algorithms for evaluating the codes and the computer codes for propagation of the information from element to element, taking into account the border interactions.

The inverse sonification problem is beneficial to be applied to medical imaging used to surgical operations, where the surgeon and the robot are working together in order to stop crossing the critical boundaries in order to minimize the vascular damages and bleeding [28–30].

3. APPLICATIONS

To see how the blurred or blurred portions of an images can be removed after sonification, and especially completed with color and component elements, we choose the image from Fig. 2a where we some boxes are empty. The solution of (6) can be extended by continuity in the white boxes starting from their adjacent boxes I order to fill them with color and other details. Thus, we obtain the final image shown in Fig. 2b.

The inverse sonification problem is applied next on a medical image of a fictive rat liver with severe loss of architecture and disturbances zones between 10 and 50 μm at the microscopic scale [31].

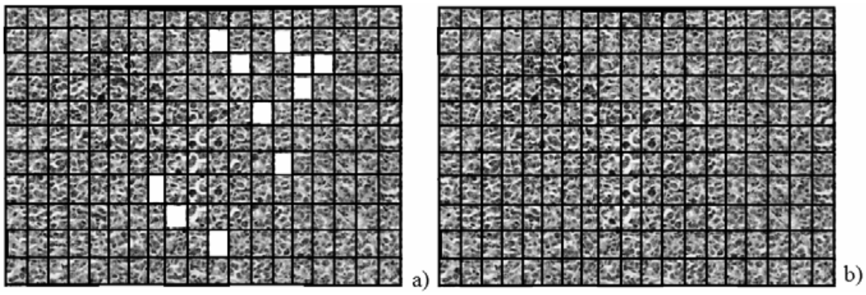

Fig. 2 – a) An image with white boxes representing the blurred portions of an images; b) white areas are filled with color and details after sonification.

We consider a fictive image of fibrotic rat liver sample inspired from a study of effects of ginkgo biloba leaf extract against hepatic toxicity induced by methotrexate in rat [31] and a study nonalcoholic steatohepatitis in the fatty rat livers by magnetic resonance (MR) [32].

We intentionally hide an area in this image (shown in black in Fig. 3a). Figures 3b and 3c are two different images with hidden area used for sonification. The application of the inverse sonification operator to these images was successful in the sense that the initially hidden area is recovered by the sonification operator (Fig. 3d).

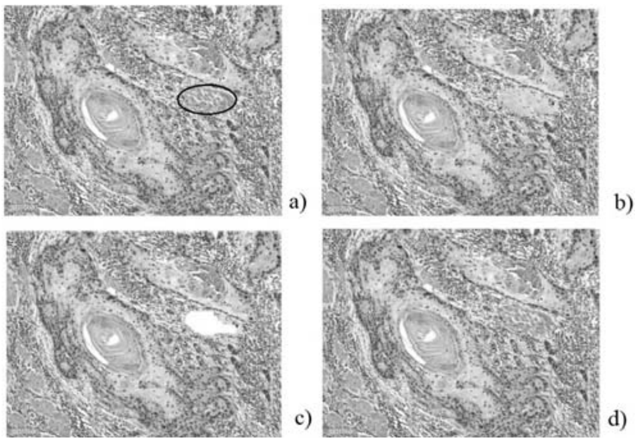

Fig. 3 – a) The MR image of a liver rat; b) c) Two images with a hidden area used for sonification; d) The initially hidden area is found by the sonification technique.

4. CONCLUSIONS

This paper discusses the inverse sonification problem in order to identify new features in its capability to discover hidden details in the medical images. In the sonification process, the mapped data which contain small blurred areas with cavities and white regions due to the inaccuracies of the original medical images, are completed and filled with color and geometric elements through continuity by the solutions in adjacent areas, so that the final image may contain new elements, new details that do not appear in the first image. The sonification procedure is applied to a MR image in which we hide intentionally a small area. The final result is a new image in which initially hidden area is rediscovered.

Another advantage of the sonification operator is that it does not distinguish between the data time and the sonification time.

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