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# In the Search for a Non-Invasive Sonification Method Based on a Physically-Based Model for the Guidance of the Visually Impaired Population

En Búsqueda de un Método de Sonificación no Invasivo Basado en un Modelo Físico Para la Orientación de la Población con Discapacidad Visual

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**Abstract.** The present paper initially presents to the reader the most prominent results in the field of SSD (Sensory Substitution Devices) for the visually impaired population. Afterwards, a technical-ergonomic comparison is held, where some important academic and commercial projects in the last decade are highlighted. Several transcendental discoveries in this matter are depicted and at the end a new promising method is introduced, making use of Haralick texture features. The main finding of the present work is that this approach could present to the visually impaired texture-like properties of the image based on its physical characteristics, and even more, since the Haralick approach is mathematically rigorous, then it may render a more coherent and congruent image-to-sound algebra than previous methods. **Keywords:** Sensory substitution devices, synesthetic tools, sonification, Haralick texture features, visually impaired population.

**Resumen.** El presente artículo inicialmente presenta al lector los resultados más representativos en el campo de los Dispositivos de Substitución Sensorial para la población con discapacidad visual. Posteriormente, una comparación técnico-ergonómica es realizada, donde varios proyectos importantes, académicos y comerciales, en la última década son resaltados. Varios descubrimientos trascendentales en este tema son presentados y al final, un nuevo método es descrito, usando las características de textura de Haralick. El resultado más importante del presente trabajo es que este abordaje podría llegar a presentar a la persona con discapacidad visual propiedades de textura de la imagen basadas en sus características físicas, y aún más, debido al grado de rigurosidad matemática del método Haralick, un álgebra imagen-sonido más coherente y congruente que los métodos anteriores.

**Palabras clave:** Dispositivos de sustitución sensorial, herramientas sinestésicas, sonificación, características de textura de Haralick, población con discapacidad visual.

## 1 | INTRODUCTION

The beginning of the XXI century has outcome a huge variety of electronic devices for the assistance of the visually impaired population. Several projects have been developed throughout the world, seeking for a synesthetic solution that could serve for this purpose. Healing through sound has become a new non-invasive

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paradigm to perform actions for the enhancement of the health of the individual. The challenge of the methods relies on the quantitative calculation of sound parameters that should map the visual information, in order to eliminate redundancy and irrelevance in the sense of Shannon theory [1].

Sound can convey information either complementing the visual channel or in synergy with other sensory modalities. However, for some cases, as blind navigation, an auditory display may be used alone for sensory substitution, as it is the case of the vOICe [2] [3], the EAV – Espacio Acústico Virtual (EAV) [4], the Naviton sonification method [5], or the Sound of Vision system [6].

In the present paper, a brief review of the most important sonification strategies for this purpose are described, and then a novel approach for textures' sonification is presented.

## 2 | PREVIOUS METHODS: SOUND TO IMAGE

Image to sound strategies fall under the sonification applications, hugely described in international workshops as the yearly International Conference of Auditory Display ICAD [7]; although in a more general sense, sonification has been developed since the invention of Telephone (Bell, 1877), the Telegraph by Edison in 1878, and the interoceanic transmission of acoustic signals (Marconi, 1895), or even in the early stages of civilization, as the detection of anomalies in accounts of commodities in Mesopotamia (3500BCE), signals and striking clocks in Greece, and the stethoscope by Laennec in 1816 [8]. Conveyance of sounds may be achieved through non-speech, but also through speech, for instance in warning signals as in [9], [10], [11].

Sonification is defined as “the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication and interpretation” [12], and it includes natural real-world sounds, that emerge from (i) natural phenomena or (ii) human-world interaction. The concept of synthesized audio is used for (i) increase the dimensionality of a display, (ii) provoke user engagement, or (iii) enhance realism. From the semiotic perspective [13], sonification is the use of sound to signify data or other information; therefore, the paradigms of its development and design are comparable to those of music and language [13], possessing along with them the main goal of meaning conveyance: sonification passed the breach from merely accompaniment to information conveyance.

Effective ways of sonifying data have been the use of left/right pan to show locations, or the use of combination of instruments to demonstrate thresholds [14] and more complex possibilities including a “sweeping sound” option to generate an overview [5]. These methods work in harmony with the users listening experience [15]. Recent developments in signal processing such as DSP, MIDI, HRTF, STFT and granular synthesis have made possible the development of advanced sonification approaches. Granular synthesis, for example, is a mathematical abstraction derived from Gabor's acoustic theory [16], where a quantum representation describes any sound [17].

Throughout sonification design, researchers have sought for intuitive languages, pleasant environments, and precise mappings, as well as the maintenance of accurate levels of redundancy and data relevancy in the sense of Shannon's information theory [18]. One of the common efforts in this task was to modify the signal parameters according to the image variables to represent. Some of these acoustic parameters that designers use to modify are pitch, panning, loudness, tempo, duration, spectral brightness and in complex scenarios, timbre [19]. In this matter, Barrass [20] proposed a rigorous approach to sound design for multimedia applications through his Timbre-Brightness-Pitch Information Sound Space (TBP ISS). Other option is the one-to-several image-to-acoustic mappings, which increases complexity level for the user. Taxonomy description of auditory displays had been purposed, as by de Campo in 2006 [21], where he offers a sonification design map that featured three broad categorizations of sonification approaches: (1) event-based; (2) model-based; and (3) continuous. From the point of view of functions of sonification; Buxton [22] and others [23]; [12]; [24] have described the function of auditory displays in terms of three categories: (1) alarms, alerts and warnings, (2) status, process and monitoring messages, (3) data explorations, and art and entertainment.

Visual impaired persons (VIP) usually have relied on the white-cane and the Seeing Eye dog for navigation; understanding navigation as the spatial awareness in the user's mind which can lead to subsequent mobility to reach determined targets with minimal number of collisions and acceptable time. Nevertheless, complica-

tions arise for the detection of farther or floating objects [25]. However, since the last century, efforts have made possible the development of Very Large Scale Integrated (VLSI) electronics which arose the possibility of complementary devices, known as ETAs (Electronic Travel Aids). Four main groups are recognized: (i) Obstacle detectors (echo-location devices) [26], [27] and (ii) Imaging devices (also known as SSD- Sensory Substitution Devices) [5], (iii) Devices to locate the blind in case he got lost, mainly through GPS [28], and (iv) Path-guidance devices via detecting land-marking clear near-infrared (IR), light or radio frequencies [29], [30]. Sensing inputs of ETAs are mainly classified into depth camera [31], [32], [33], [34], [35], [36], general camera, radio frequency identification (RFID), ultrasonic sensor, and infrared sensor.

Probably the first electronic travel aid (ETA) for the blind was constructed by a Polish scientist Kazimierz Noiszewski [37], in 1897: the electrofalm, a device that used the photoelectric properties of Selenium cells to generate sounds (or tactile stimuli) of strength proportional to the average scene brightness. Ultrasound [38], [39], [40], [41], [42], [43], [44], [45], infrared [46], [47], [48] and Laser obstacle detectors rely on principles such as sonar or radar [26], [39], usually for the modification of guide canes [49], [50], [51], [52], [42], [53], [40], [41], [47], [54], [48]. One of the milestone implementations are the Sonic Glasses [55] developed in 1964. Among the ultrasonic devices, we may encounter the Guide Cane (a system using ten ultrasonic sensors for obstacle detection), the K-sonar [56], [57], the UltraSonic Torc, the Ultra cane [58], Miniguide [59], Palmsonar [60], Ultra-Body-Guard [61] and iSonic cane [62]. Laser-signal based devices examples are C-5 Lase Cane [63] and Teletact [64]. More recently, the SonicPathFinder [65], KASPA [66], EAV and Tyflos were developed on this conception. Obstacle detection is classified into three (3) categories: ETAs, electronic orientation aids (EOAs) and position locator devices (PLDs) [59]. Other classifications, as well as methods for detection are widely described in [67], [25]. However, even though technology has been progressed, there are still holes for vision disabled people, and weaknesses such as cost, low comfortability (some of the “smart canes” cannot be folded, or some use technology which require outer tags to be placed in the locality of execution, as RFID).

Modern systems make use of combination of some known technologies as GPS, ultrasound and voice-based audio [68], GPS and GSM [69], or ultrasound and voice-based audio in a Raspberry Pi-core embedded system [70]. GPS systems are robust enough for outdoor navigation but fail in indoors [71]. RFID bases systems, are used in the Smart Cane [72], in the RF guide [73], [74], and Navibelt [75], where PDA maps GIS (Geographic Information System) into the RFID grid. RFID are transponders where exchange of information is performed by the use of magnetic or electric fields [76]; drawback of this technology is the need for proximity between tag and reader [77]. Use of different sensor technology, as in [77], where ultrasonic sensor, water sensor, pit sensor, GPS receiver are combined, as well as on the side of the actuators (vibrator, voice synthesizer, speaker, and keypad), to conform the smart walking stick navigation tool for VIP.

The first SSD device was developed in 1914 by Fournier/D’Albe, named the optophonic [3]. SSD devices take the form of a wearable device [25], or smartphone applications [78], [31]. Wearable ETA devices generally consist of a camera set mounted on a headgear and an audio rendering device as [79], or a tactile array of actuators as [80]. Processing units are commonly worn in backpacks [80]. In the case of smartphone technology, the so-called screen readers are sonic user interfaces. An application [78] was developed as a navigation tool for the blind, as part of the Naviton project developed at Lodz in 2009 [27]. On the other hand, EdgeSonic [81] has been reported to be a significant improvement in image understanding. However, for smartphones, high-level (symbolic) sonification has been the focus (VoiceOver, JAWS) [81]. Some applications go beyond TTS and implement computer vision algorithms for object recognition (LookTel [82]), VizWiz [83]. Low level sonification has mainly been developed by the vOICe system [2] and Timbremap [84], and the sonification of Ivan and Radek [85], where color is mapped to a frequency oscillator.

Milestones of SSD have been the SonicGuide, NAVI [86], AudioMan [87], SoundView [88], the Navbelt [89], the Naviton [90], VIBE [91], seeColor, SonicGlasses (the Binaural Ultrasound Sensory Aid) [92], the Guidecane, Espacio Acústico Virtual (2006), the vOICe system (Meijer, 1992), PSVA (prosthesis for substitution of vision by audition) –developed by Capelle et al (1998), NAVIG [93] and the device developed by Cronly-Dillon (Cronly-Dillon et al 1999). The last three systems convert the vertical position of a luminous object in the video image into different audio frequencies, with high-pitched sounds corresponding to upper locations and low-pitched sounds to lower locations in the video image [26]. Brightness in the vOICe system is code to loudness. Ac-

According to Melara and O'Brien (1987), this scheme corresponds to a natural cross-modal correspondence [26]. An additional feature of the device developed by Cronly-Dillon is that it has a system for feature extraction for deconstruction of a complex optical image into a set of simpler representations [26]. Some applications (as the Naviton and the vOICe) have even had variants solely dedicated to mobile phones. A huge subset of SSD devices only use haptic feedback as it is the case of the VIDET [94], [95], which converts distance into haptic cues, and others like [96], [97], [98], [99], [100], [101].

### 3 | IMAGE ANALYSIS: HARALICK DESCRIPTORS

One step further in image analysis is the computation of high order statistics of the image and to obtain a correspondent sound representation to that set of descriptors. In a way, the challenge is to take into consideration features of one 2D image domain where color, depth, object-size, and texture are the relevant cues and in the other hand, a 1D sound domain (amplitude-time) is needed to map all these attributes, where pitch, frequency, and phase of the corresponding sound are the parameters to deliver the information.

The main advantage when deciding for the Haralick computation in this task, is that Haralick features correspond to an ordered set of texture-image attributes that may be numerically and systematically computed from the image. Previous sonification methods for SSD design lack of this systematization and this new approach may be promising from the rigor mathematical perspective. Other techniques, for example [102] uses multi-level approach revealing to the user, some image descriptors such as color, edges, and roughness with mid- and high-level information obtained from Machine Learning algorithms.

First order statistics computed from histograms of the grey-level values in images (mean, variance, skewness, and kurtosis) are commonly used in image analysis. Other methods use higher-order statistics as Wavelets [103], Gabor filters [104] and local binary patterns [105].

Haralick texture features are common texture descriptors in image analysis [106], [107]) proposed using a gray-level co-occurrence matrix (GLCM) as a method of quantifying the spatial relation of neighboring pixels in an image (Table I). Therefore, Haralick texture features are calculated from a Gray Level Co-occurrence Matrix (GLCM), a matrix that counts the co-occurrence of neighboring gray levels in the image.

Haralick descriptors have been applied successfully in analysis of skin [108], land-use and forest-type classification [109], automatic pollen detection [110], fabric defect detection [111], plant leaf classification [112], cutting tool monitoring [113] and electrophoresis [114].

The GLCM procedure enables a systematic approach to the image analysis stage as stated by [115] where specially for texture classification, the Haralick method is chosen.

Shortly, the element  $X(i, j)$  of the non-normalized GLCM counts how many times gray values  $I$  and  $j$  occur as neighbors in  $I$ , where  $i, j \in [1, N]$ . In this way, each pixel-position is compared to eight (8) neighbouring pixel-positions. If the pixel to be compared is at position (0,0), then the other positions would be: (1, 0), (-1, 0), (1, 1), (-1, -1), (0, 1), (0, -1), (-1, 1), (1, -1).

The next part describes the step-by-step procedure that is performed while obtaining the complete set of parameters used for sonification with the Haralick approach.

#### 3.1 | Pixelation/Gray-level partition

In this first step, pixelation of the image is carried on, to diminish the amount of data of the image. Here, the gray-levels of the original image are mapped into a quantized range, according to the function

$$\phi = [a, b]^{M \times K} \longrightarrow [1, N]^{M \times K}. \quad (1)$$

In this step, ADC maps set manual limits for the amplitude values of the image are set [116]. Here, appropriate levels of gray-scale values are adopted.

Leijenaar et al. [117] called this effect, the windowing method, i.e., how the images are quantized into gray

level bins, while GLCM processing. Leijenaar et al., entered deeply into the analysis of the effect of quantization methods.

### 3.2 | Adjacent calculation

GLCM textures considers relation between two (2) pixels at a time, called the reference and the neighbor pixel [118]. The calculation performed in this project involves not only one (1) pixel offset calculation, but also two (2) pixels offset, 3 and so on. This is performed to determine all Haralick values depending on all spatial differences in the image. Adjacency can be, therefore defined to occur in each of four directions in a 2D, as the Fig. 1 shows:



**FIG. 1** Directions for calculation of Haralick texture features. From left to right: horizontal, vertical, transverse and diagonal.

**TABLE 1** Haralick texture features. Source: [125].

Feature	Equation
Autocorrelation	$\sum_{i=1}^N \sum_{j=1}^N (i \cdot j) p(i, j)$
Cluster Prominence	$\sum_{i=1}^N \sum_{j=1}^N (i + j - 2\mu)^3 p(i, j)$
Cluster shade	$\sum_{i=1}^N \sum_{j=1}^N (i + j - 2\mu)^4 p(i, j)$
Contrast	$\sum_{i=1}^N \sum_{j=1}^N (i - j)^2 p(i, j)$
Correlation	$\sum_{i=1}^N \sum_{j=1}^N \frac{(i \cdot j) p(i, j) - \mu_x \mu_y}{\sigma_x \sigma_y}$
Difference entropy	$-\sum_{k=0}^{N-1} p_{x-y}(k) \log p_{x-y}(k)$
Difference variance	$\sum_{k=0}^{N-1} (k - \mu_{x-y})^2 p_{x-y}(k)$
Dissimilarity	$\sum_{i=1}^N \sum_{j=1}^N  i - j  \cdot p(i, j)$
Energy	$\sum_{i=1}^N \sum_{j=1}^N p(i, j)^2$
Entropy	$-\sum_{i=1}^N \sum_{j=1}^N p(i, j) \log p(i, j)$
Homogeneity	$\sum_{i=1}^N \sum_{j=1}^N \frac{p(i, j)}{1 + (i - j)^2}$
Information measure of correlation 1	$\frac{HXY - HXY1}{\max(HX, HY)}$
Information measure of correlation 2	$\sqrt{1 - \exp[-2(HXY2 - HXY)]}$
Inverse difference	$\sum_{i=1}^N \sum_{j=1}^N \frac{p(i, j)}{1 +  i - j }$
Maximum probability	$\max_{i, j} p(i, j)$
Sum average, $\mu_{x+y}$	$\sum_{k=2}^{2N} k p_{x+y}(k)$
Sum entropy	$-\sum_{k=2}^{2N} p_{x+y}(k) \log p_{x+y}(k)$
Sum of squares	$\sum_{i=1}^N \sum_{j=1}^N (i - \mu)^2 p(i, j)$
Sum variance	$\sum_{k=2}^{2N} (k - \mu_{x+y})^2 p_{x+y}(k)$

The maximum likelihood estimator  $\chi^2$  is used to infer the distance between pixels with the most structure [119]. This parameter is defined as follows

$$X^2(d) = \sum_i \sum_j \frac{[N_d(i, j)]^2}{N_d(i)N_d(j)}, \quad N_d(i) = \sum_j N_d(i, j) \quad \text{and} \quad N_d(j) = \sum_i N_d(i, j) \quad (2)$$

with  $d$  the distance between pixels, and  $N_d(i)$ ,  $N_d(j)$  the sums of columns and rows in the adjacent matrix of grey levels of the image.

### 3.3 | Haralick Descriptors

Haralick values depend on basic statistics such as the mean, the variance and correlation (Table I). Co-occurrence of pixels reflects spatial relations between pixel values in an image. Those relations are calculated in any one of eight (8) directions (N, S, E, W, or the four diagonals). Frequently, only four of the eight directions are necessary to describe an image (see Fig. 1). In this work the diagonal directions are referred as “transverse” and “diagonal” according with the description showed in Fig. 1. The basis for the Haralick texture features is the gray-level co-occurrence matrix (G in Eq. (??)).

$$G = \begin{bmatrix} p(1, 1) & p(1, 2) & \dots & p(1, Ng) \\ p(2, 1) & p(2, 2) & \dots & p(2, Ng) \\ \vdots & \vdots & & \vdots \\ p(Ng, 1) & p(Ng, 2) & \dots & p(Ng, Ng) \end{bmatrix} \quad (3)$$

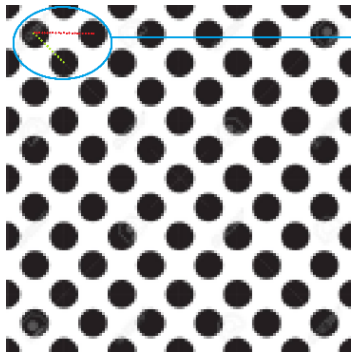
with  $Ng$  the number of gray levels in the image. Table 1 shows the complete calculation of Haralick texture features. From this set of values, we chose energy, entropy, homogeneity, and contrast. The reason for choosing the energy Haralick feature lies in the fact that in both domains (image and 1D sound), this attribute enables to calculate the overall amount of presence either in image or sound. For blind navigation and/or orientation this implies the possibility to actively evade obstacles with high levels of signal energy. This can be mapped comfortably to signal amplitude values in the sound excerpt which may be afterwards adopted by the user with training adequate procedures. The Haralick entropy values enable to predict patterns in the analyzed image, which in the navigation task could mean predictability of common or known travel paths. Finally, homogeneity and contrast are inversely related and the idea behind the render of both is to assure redundancy in the information deliverance.

## 4 | RESULTS

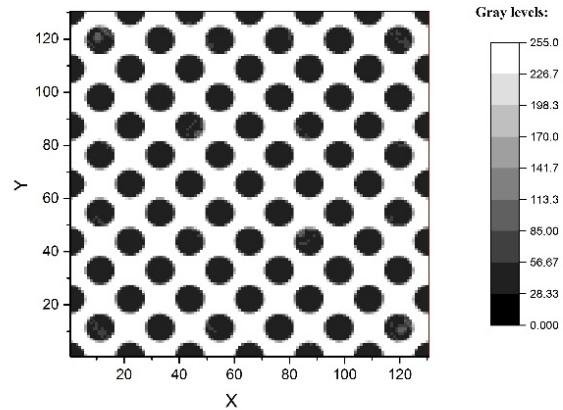
In order to show the basic properties of the Haralick descriptors, the Fig. 2 was analyzed. This figure was selected because of the regular interaction between black and white colors, especially the fading effect which may be interesting while analyzing Haralick descriptors. In the first step, the figure was pixelated showing a regular pattern each 11 pixels in the diagonal and transverse directions, and each 22 pixels in the vertical and horizontal directions. Second step in the calculation enables us to set definite subsets of gray values in pixels (Fig. 3), in this step the possible number of different gray levels was reduced to 9 (originally from 0 to 255).

Then, the maximum likelihood estimator  $\chi^2$  and four of the most important Haralick descriptors (energy, entropy, homogeneity, and contrast), were calculated for the image showed in Fig. 3 and for different distance between pixels (from 1 to 44). The results for the horizontal and diagonal directions are presented in Figs. 4 and Fig. 5. By the symmetry of the image analyzed, vertical and transverse directions present similar values for the descriptors. For comparison purposes between different Haralick descriptors, the value of each Haralick

descriptor was divided by the sum of the values of the same Haralick descriptor in the 44 distances between pixels.

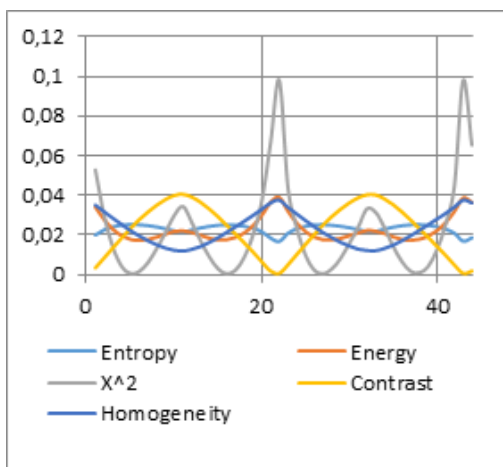


**FIG. 2** Pixelated image showing the regular pattern in the horizontal and the diagonal directions (22 and 11 pixels respectively).

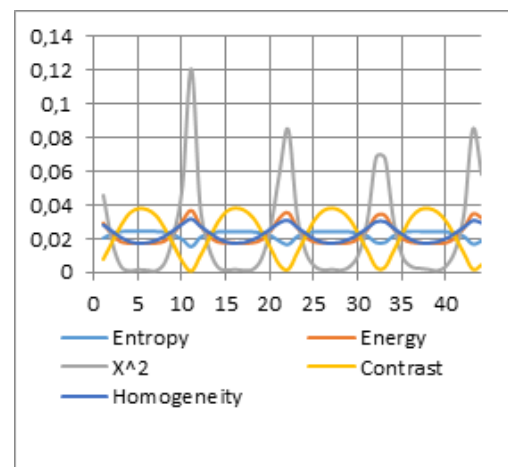


**FIG. 3** Pixelation and gray levels partition of the image.

For the parameter  $\chi^2$ , Fig. 4 shows the largest picks at distances between pixels multiples of 22. This result is coherent with the repetitions patterns for the horizontal direction. As expected, for the parameter  $\chi^2$  measured in the diagonal direction, the most important repetition pattern is found at multiples of 11. For this parameter, an interesting result is presented in Fig. 4 in the sense that some picks of lower high are found for distances of 11 and 33 pixels. This regularity can be associated with the black-white regular pattern generated between the inside parts of the black circles and the outside parts of them, this conclusion is reinforced analyzing the contrast, which for the same distances (11 and 33 pixels) presents the highest picks. The contrast measures the difference between the gray level, given more weight to large differences.



**FIG. 4** Pixelated image showing the regular pattern in the horizontal and the diagonal directions (22 and 11 pixels respectively).



**FIG. 5** Pixelation and gray levels partition of the image.

In Fig. 4, this parameter presents maximums at 11 and 33 pixels, corresponding to largest changes in the gray level, and minimums at multiples of 22, corresponding to regularity patterns of the same grey level (see red points in Fig. 4). For Fig. 5, the contrast presents minimums at multiples of 11, indicating that the

regular pattern corresponds to the same gray level. As in the case of the horizontal direction, for the diagonal direction, some patterns of different gray levels appear at distances: 5-6, 16-17, 26-27, and 37-38. These patterns are easy to identify from the contrast parameter, because in the parameter  $\chi^2$  these peaks are almost imperceptible. Entropy is a parameter that can be associated to the disorder of the system, for example, in Figs. 4 and 5, this quantity presents minimums at distances with regularity patterns (ordered patterns), notice that a maximum of  $\chi^2$  corresponds to minimums of entropy. Homogeneity can be understood as the contrary of contrast, in the sense that this quantity gives more weight to pixels of similar gray level. As expected, in Figs. 4 and 5, the homogeneity has the opposite behavior of contrast. Finally, energy presents the opposite behavior of entropy, indicating that this parameter gives more weight to pixels with similar gray levels in the image. Notice that energy presents a similar behavior than the parameter  $\chi^2$ , but with less sensibility.

Correlating these results with the ones found in [120], orientation maps and micro-textures can convey a huge amount of information to the visually impaired people. Two possible sonification paths follow, one dedicating synthetic sound to the image-to-sound mapping and the other “real-world” sounds. The aim is to train the user to this texture-type sonification so that an intuitive approach to colors and texture can be achieved by the user.

## 5 | CONCLUSIONS

The originality of this work lies in the use of a new descriptor for delivering information about the image-to-sound mapping mechanism. The search for an image-to-sound sonification method is encouraged by a rigorous image processing method such as the Haralick texture features extraction. The proper sonification of these values may result in an innovative non-invasive sensory substitution scheme for the guidance of the visually impaired population. Recent works [121], [122] have applied the Haralick method for medical imaging purposes, mainly, for the diagnosis, classification and treatment response assessment of cancer. Other works deal with color texture classification using Haralick descriptors [123], but the use of Haralick for the visually impaired population navigation is here proposed for the first time.

### Next steps

#### | Sonification of Haralick Descriptors

Next step, which is intended to be finished for mid-2022, is the sonification of some of the Haralick descriptors for different images, and according to some defined criterion. Some ideas are related to crystal water sounds, based on physically modeled sounds, or, the sound of sea, or other water related phenomenon.

The four (4) Haralick descriptors analyzed in this work (Entropy, Energy, Contrast, Homogeneity) can be calculated for different distance between pixels, the determination of the ideal distance for the sonification could be inferred from structure parameter  $\chi^2$ . Continuation of the present study is focused on the sonification of these four (4) Haralick descriptors for different distances selected according to the value of  $\chi^2$ .

#### | Testing

Testing to a definite sample corpus of blind-folded population in order to acquire results of the impact of this sonification is planned for the second half of 2022.

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