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Image enhancement via lateral inhibition: An analysis under illumination changes

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ABSTRACT

Image enhancement is a fundamental issue in digital image processing. Image enhancement via lateral inhibition is a relatively new method inspired by the phenomenon that the optic nerves in illuminatingly light regions inhibit those in darkness. However, it is common that the observed images incorporate illumination noises. This potentially limits the utilization of an image enhancement method because amplifying the noises would make the situation even worse. In this study, performance of lateral inhibition to handle illumination changes is investigated through theoretical analyses and simulations on a few transportation cases. Specifically, uniform, linearly varying and stochastic illumination changes are considered. Experimental results confirm that lateral inhibition can enhance the original image without amplifying the illumination noises in the aforementioned three scenarios.

1. Introduction

Image enhancement refers to a change in the image appearance such that an observer can extract certain desired information more readily after the change [1]. Image enhancement is commonly regarded as a preliminary image-processing step in a vast of real-world applications, e.g., degraded document scanning [2,3], automated fingerprint identification [4–6], atmospheric correction [7–9], underwater photography [10,11], medical diagnosis [12], color transfer [13] and autonomous navigation [14–17]. Through image enhancement, attributes of the original image are modified according to observer-specific demands, wherein subjectivity commonly exists [18] and thus rendering the scheme difficult.

Image enhancement methods can be broadly classified into two categories, namely the spatial domain methods and the frequency domain methods. Spatial-based domain methods operate directly on pixels whereas frequency-based domain methods transfer the original image into frequency domain before operating on the transform coefficients. Spatial methods are computationally cheap and thus are suitable for real-time processing. Frequency methods are featured by satisfactory robustness. Interesting reviews regarding image enhancement can be found in Refs. [19–25].

Image enhancement via lateral inhibition is inspired by the phenomenon that the optic nerves in illuminatingly light region inhibit those in dark region. That phenomenon was first observed when limulus vision was investigated in 1932 [26]. Following this, similar discoveries have been made in the vision systems of other animals [27–30] since the 1940s. Well-known mathematical models that aim to describe the biological lateral inhibition phenomenon include Refs. [31–35]. Broadly speaking, when processed via lateral inhibition, contours in an original image will be stabilized. This may be a promising solution to illumination disturbances in the original image. Till now, lateral inhibition has been a well-known image enhancement method [27,36–48].

In spite of the bright side, lateral inhibition is sensitive to noises. That is, background noises may be amplified as well when useful contours are enhanced. Ref. [44] indicated that lateral inhibition was utilized in image enhancement missions with almost none noises. This study investigates the scenarios wherein the original image is involved in illumination disturbances, aiming to provide a thorough understanding of lateral inhibition.

The remainder of this paper is organized as follows. In Section 2, principle of lateral inhibition is introduced. Section 3 holds theoretical analyses of our proposal. Simulations are conducted in Section 4. Conclusions are drawn in the last section.

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2. Principle of lateral inhibition

The phenomenon of lateral inhibition was first discovered by Hartline and Graham in an electrophysiology experiment on limulus vision [26]. According to their observation, each ommateum of a limulus is inhibited by the neighboring ommatea if the neighbors are excited [27]. Here, an excited ommateum refers to one that is with illumination whereas an unexcited ommateum refers to one that is in darkness. It should be emphasized that whether an ommateum is excited or unexcited is not absolute. In other words, an ommateum that absorbs light with intensity index 10 inhibits one that with intensity index 5 but can be simultaneously inhibited by another with intensity index 20. When inhibition takes effect on a specific ommateum, it perceives less illumination than it actually absorbs. Such inhibition effect exists between every two ommatea and can be accumulated spatially. In this way, the light and shade contrast in the eyeshot of limulus is enhanced. In fact, lateral inhibition exists in a wide array of animals, including human. An interesting demonstration is given in Fig. 1 [49].

In the lateral inhibition model, the original gray-level image is denoted as $\mathbf{I_0}$ and the enhanced one is denoted as $\mathbf{R}$. Lateral inhibition is implemented according to Eq. (1) [39]:

$$\mathbf{R}(x, y) = \mathbf{I_0}(x, y) + \sum_{i=-M}^{M}\sum_{j=-N}^{N}\alpha_{ij} \cdot \mathbf{I_0}(x+i, y+j), \quad (1)$$

where $\mathbf{I_0}(x, y)$ refers to the original pixel gray level at (x, y), $\mathbf{R}(x, y)$ denotes the enhanced pixel gray level, α_{ij} is an inhibition weight parameter, M and N determine the inhibition scale. A schematic example is shown under the condition that $M = N = 2$ in Fig. 2. There are various ways to select α_{ij}, but a common requirement is

$$\sum_{i=-M}^{M}\sum_{j=-N}^{N}\alpha_{ij} = 0, \quad (2)$$

which implies balanced inhibition energy. For example, the inhibition weight matrix $\left[\alpha_{ij}\right]_{5\times5}$ can be selected as

$$\begin{bmatrix} -0.025 & -0.025 & -0.025 & -0.025 & -0.025 \\ -0.025 & -0.075 & -0.075 & -0.075 & -0.025 \\ -0.025 & -0.075 & 1 & -0.075 & -0.025 \\ -0.025 & -0.075 & -0.075 & -0.075 & -0.025 \\ -0.025 & -0.025 & -0.025 & -0.025 & -0.025 \end{bmatrix}.$$

In Section 3, in-depth analyses regarding the lateral inhibition model are proposed.

Fig. 1. A simultaneous contrast concerning visual illusion due to lateral inhibition. Note that two objects are identical but the left one looks lighter when placed in darker backgrounds.

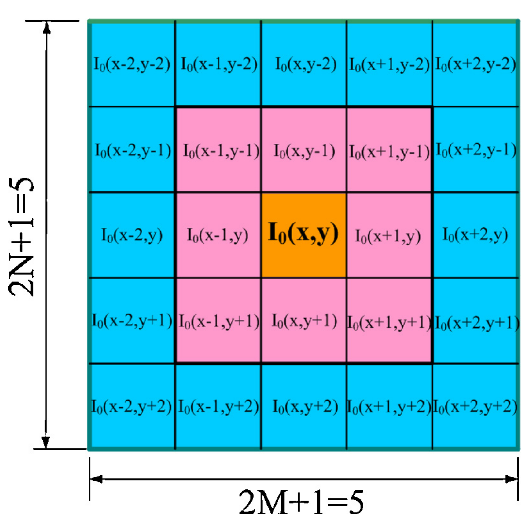

Fig. 2. Schematic diagram of lateral inhibition model when $\mathbf{R}(x, y)$ is computed under the condition that M = N = 2. Here, $\mathbf{I_0}(x, y)$ stands for the original gray level of central pixel (x, y) and all the surrounding pixels have influences on the computation of $\mathbf{R}(x, y)$.

3. Theoretical analyses of lateral inhibition under illumination changes

The performance of lateral inhibition model to handle illumination changes is analyzed theoretically in this section. For the convenience of analyze, it is presumed that the inhibition weight parameters in the matrix $\left[\alpha_{ij}\right]_{M\times N}$ form rings (like that in Fig. 2). Suppose that matrix $\mathbf{I_o}$ contains pixel gray levels of the original pure image, matrix $\mathbf{I_r}$ represents the one incorporated with illumination changes, matrix $\mathbf{F_{illus}}$ represents the illumination changes and $\mathbf{R}$ represents the enhanced image. According to these definitions, we have

$$\mathbf{I_o}(x, y) + \mathbf{F_{illus}}(x, y) = \mathbf{I_r}(x, y), \quad (3)$$

$$\mathbf{R}(x, y) = \mathbf{I_r}(x, y) + \sum_{i=-M}^{M}\sum_{j=-N}^{N}\alpha_{ij} \cdot \mathbf{I_r}(x+i, y+j), \quad (4)$$

where (x, y) denotes the location of any existing pixel in those matrixes. Eqs. (3) and (4) indicates that

$$\mathbf{R}(x, y) = \mathbf{I_r}(x, y) + \left[\sum_{i=-M}^{M}\sum_{j=-N}^{N}\alpha_{ij} \cdot \mathbf{I_o}(x+i, y+j)\right] + \left[\sum_{i=-M}^{M}\sum_{j=-N}^{N}\alpha_{ij} \cdot \mathbf{F_{illus}}(x+i, y+j)\right]. \quad (5)$$

Ideally, we expect that $\mathbf{R}(x, y) = \mathbf{I_r}(x, y) + \left[\sum_{i=-M}^{M}\sum_{j=-N}^{N}\alpha_{ij} \cdot \mathbf{I_o}(x+i, y+j)\right]$, i.e., illumination changes do not affect the lateral inhibition performance at all:

$$\sum_{i=-M}^{M}\sum_{j=-N}^{N}\alpha_{ij} \cdot \mathbf{F_{illus}}(x+i, y+j) = 0. \quad (6)$$

In the remaindering of this section, whether some types of illumination changes satisfy Eq. (6) or not are analyzed.