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Underwater Communication Enhancement using Cellular Automata and Image Processing

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1. Introduction

The scope of underwater communication systems has extended far beyond their initial military applications, such as submarine communication and underwater target tracking. These systems now play a pivotal role in diverse domains, including marine resource development, ocean exploration, marine environment monitoring, and the operations of autonomous underwater vehicles (AUVs). The evolution of digital communication has led to the emergence of underwater communication systems employing various modulation methods.

In stark contrast to land-based communication, underwater communication uniquely relies on sound waves for transmission. However, the propagation speed of sound waves through water is considerably slower, approximately 1500 m/s. The intricacies of underwater communication are compounded by dynamic variables such as water temperature, salinity, barometric pressure fluctuations, ocean currents, and complex underwater topography, all contributing to signal distortion. [1–2)]

Numerous research efforts have aimed to enhance underwater communication systems, yet the ever-changing underwater environment and its dynamic fading channels necessitate context-specific improvements. Notably, underwater multipath phenomena exhibit time-varying characteristics due to factors like reflection from the sea surface and seabed, sound speed variations attributed to water temperature disparities, and suspended particles. The resultant delay-spread in received signals induces inter-symbol interference and frequency selectivity, significantly impacting system performance. [3–5)]

This paper introduces a novel approach for denoising distorted image data stemming from underwater multipath effects, utilizing cellular automata image processing. The proposed method seeks to enhance data accuracy, mitigating the inherent noise induced by time variance through sophisticated image processing techniques.

2. Cellular automata

Cellular automata are computational models operating on a cell grid, each with finite states. Cells evolve at discrete time steps through predefined rules, with behavior emerging from neighbor interactions. This simplicity belies their power in simulating complex systems. Grid structures vary from one to multi-dimensional. At each step, a cell's new state derives from its current state and neighbor states, following defined rules—ranging from binary conditions to intricate math. Based on this principle, the Cellular Automata algorithm can be used as a spatial domain image processing technique. [6–8)]

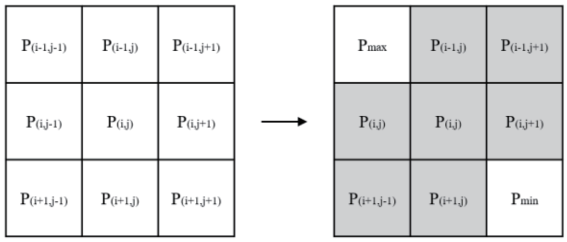

Fig. 1 Cellular automata 3*3 filter

$$f_{CA}(x,y)\begin{cases} mean\left(\sum_{j=-1}^{1}\sum_{i=-1}^{1}P_{(i,j)}\right), \\ \quad except\ P_{max,min} \\ median\left(\sum_{j=-1}^{1}\sum_{i=-1}^{1}P_{(i,j)}\right), \\ \quad except\ P_{max,min} \end{cases} \quad (1)$$

Here is the cellular automata denoising algorithm in Eq. (1). Image distortion caused by underwater multipath exhibits similarities to salt and pepper noise, often referred to as impulse or shot noise. In underwater communication, data perturbation frequently involves transitions between 0 and 1, or vice versa, leading to potential bit-level noise within the 8-bit RGB color scale. To mitigate this, a strategy is adopted where the extreme values, often the most heterogeneous among the 8 neighboring cells, are excluded by Fig. 1. This prudent measure safeguards against undue influence on subsequent states, ensuring effective noise suppression in the image data.

The mean filter is advantageous in noise reduction, as it substitutes the current pixel with the mean of adjacent values. However, if residual heterogeneity persists even after excluding minimum and maximum pixels, employing a median filter becomes essential to preserve edge integrity and

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avert blurring in those areas. This paper harnesses cellular automata technology for underwater video communication, coupling it with two distinct filters. Anomalies beyond the range of 2 standard deviations from the mean of all neighboring data were identified as heterogeneity and addressed using a median filter. Conversely, an average filter was employed for other instances, forming a comprehensive strategy for effective image enhancement.

3. Experimental conditions and results

The model was constructed most similar to the underwater multipath channel. The channel impulse responses when the signal is received are shown as Eq. (4). Based on this expression, we assumed that the channel impulse responses had only 7 signals – direct, bottom, surface, bottom-surface, surface-bottom, bottom-surface-bottom and surface-bottom-surface paths. In this case, α_i denotes the magnitude of the i th multipath signal and τ_i denotes the delay time of the ith multipath signal.

$$h(t) = \sum_{i=0}^{N} \alpha_i \delta(t - \tau_i) \qquad (2)$$

The range between the transmitter and receiver is set to be 100m and the depths of transmitter and receiver are set to be 10m and 12m. The carrier frequency is respectively chosen as 16 kHz. The transmitted rgb color 64*64 image is consisting of 98,304 bits of data. Table 2 shows the results of noisy images caused by underwater multipath and applying them to cellular automata image processing techniques.

Table 2. Experiment result

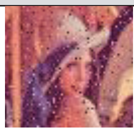
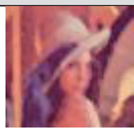
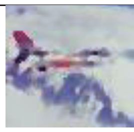
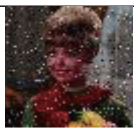
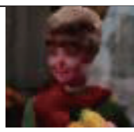
Image	Noised	With CA
Lena		
Airplane		
Female		
Peppers		

Table 2. Peak Signal-to-Noise Ratio

Image	PSNR[dB]	
	Noised	With CA
Lena	23.05	28.14
Airplane	20.90	21.95
Female	21.53	26.11
Peppers	23.05	22.31

Table 3. Structural Similarity Index

Image	SSIM	
	Noisd	With CA
Lena	0.7968	0.9253
Airplane	0.6733	0.8201
Female	0.6809	0.8906
Peppers	0.8459	0.8619

4. Conclusion

To ascertain the objective enhancement of image quality, the evaluation metrics of Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index (SSIM) are employed. A PSNR index approximating 50dB or an SSIM index nearing 1 signifies quantitative likeness to the original image, providing a rigorous benchmark for assessment.

As a result of the comparative analysis, after the application of cellular automata, all SSIMs were improved, and the PSNR values were improved except for the Peppers image. It is expected that entities that are not noise-canceled within the scope of existing underwater acoustic communication technologies will benefit significantly from the synergistic integration of cellular automata.

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