Regeneration of Orbital Angular Momentum Beam Against Arbitrary Occlusions in Free-Space Optical Systems

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FSO 시스템에서 임의 차단된 궤도각운동량 광선의 재생

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Abstract

Orbital Angular Momentum is a property of optical vortex beams, where one topological charge from an infinite range of states is orthogonal to another. However, when the beam is partially obstructed by the presence of living organisms or thrown objects, detection will fail, and its accuracy will be compromised. To resolve this realistic problem, this paper proposes a convolutional neural network to regenerate OAM intensity images from partially obstructed ones. We then compare our results with existing results in similar studies.

Ⅰ. Introduction

Optical beams, such as Laguerre-Gaussian beams, intrinsically have a property used to increase optical communication capacity with orbital angular momentum (OAM) orthogonal states [1]. However, when the Laguerre-Gaussian (LG) beams are in a free-space optical (FSO) field, the mode independence is distorted when exposed to turbulence, lowering the capacity of the communication system [2].

Channel occlusion is another way to distort the original figure of the beam, as the optical device's inherent trait, when the optical link is blocked. Several experiments have been conducted by controlling one or several portions of the OAM intensity figures [3][4], but there were fewer results where they considered real-life objects. Therefore, we propose a regeneration system with a convolutional neural network.

The paper is organized as follows. The second section demonstrates the required background knowledge, and the third section discusses the simulation procedures. Finally, we conclude our proposal in Section 4.

Ⅱ. Background Knowledge

The angular momentum of the electromagnetic (EM) field can be divided into spin-orbital angular momentum (SAM) and orbital angular momentum (OAM). Derived from the phase singularity of EM waves, the wavefront will perform a helical phase front described by the phase term $\exp(il\theta)$, where θ is the transverse azimuthal angle and l is the topological charge (TC) or OAM mode set to real number. These TCs are inherently independent of one another and is shown

$$\int_0^{2\pi} e^{il_1\theta}(e^{il_2\theta})^* d\theta = \begin{cases} 0 & l_1 \neq l_2 \\ 2\pi & l_1 = l_2 \end{cases} \tag{1}$$

Beams that show this characteristic vary, but LG beams are most prominent because they are paraxial solutions of the wave equation in FSO communication. In cylindrical coordinates, the complex amplitude distribution of the LG beam along the z-axis is given by [5]

$$E_{lp}(r,z) = E(r,z)\exp[-i(\frac{kr^2}{2q(z)}+kz+l\phi-\psi_{pl}(z))] \tag{2}$$

where $E(r,z)$ can be expressed as

$$E(r,z) = E_0\frac{\omega_0}{\omega(z)}\left(\frac{\sqrt{2}r}{\omega(z)}\right)^{|l|+2} L_p^{|l|} \tag{3}$$

E_0 is the nominal light magnitude, k is the wave number, ω_0 is the beam waist radius, z_R is the Rayleigh range, $\omega(z)$ is the beam size from the waist, $q(z)$ is the complex beam parameter, $\psi_{pl}(z)$ is the Gouy phase, and $L_p^l(\cdot)$ is associated Laguerre polynomials with TC l and transverse mode number p.

The convolutional neural network topology used for occlusion simulation is called U-Net, named from its shape with contracting paths and expansive paths. The contracting path is a repeated network with convolutional layer followed by rectified linear unit (ReLU) and max-pooling layers. The expansive pathway combines the information of the contracting path throughout a sequence of up-convolutions and concatenations. The U-Net is commonly used in image segmentation and reconstruction.

Ⅲ. Simulation

In order to simulate a realistic environment where an object or person is trespassing between the channel transmitter and the receiver in an incontinuous moment, we generate OAM input with a single

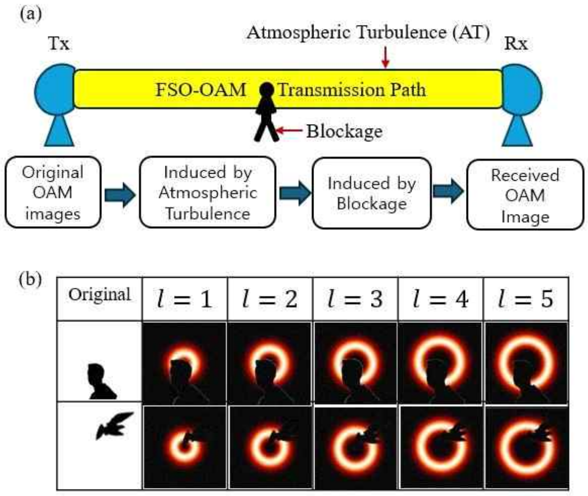

Figure 1. (a) Proposed simulation environment process. (b) Resulted intensity figures where TC is from 1 to 5. Original image accessed from [6] and [7].

mode where topological charge ranges from 1 to 5. Subsequently, we apply Gaussian noise along the transmitted figures to visualize the atmospheric turbulence (AT). Additionally, we add adjusted images of a flying pigeon, the upper part of a human as a path blockage. The total process and the resulting intensity figures are given in Fig. 1, when the wavelength is 623.8nm and beam waist is 350 micrometers.

We used processed intensity figures as an input for de-occlusion model U-Net. The topology for image regeneration algorithm is presented in Fig. 2. As an evaluation tool, we mark confusion matrix, algorithm train rate, and accuracy graphs. As a result, we compare the results with others validating our algorithm proposal.

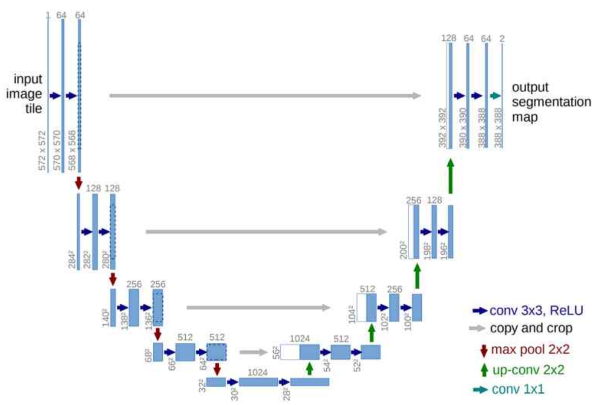

Figure 2. U-Net architecture topology used in de-occulsion algorithm.

Ⅳ. Conclusion

In this paper, we have proposed a U-Net regeneration system that can heal from obstructed OAM intensity figures. These figures came from an AT-induced channel with occlusive objects trespassing optical transmission paths. Our proposed algorithm leverages convolutional neural networks to effectively heal these obstructed figures, hindering signal integrity. This novel solution offers a promising moment for enhancing the reliability of OAM-based communication systems in real-world environments.

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