Analysis of Scattering Media by High-Frequency Polarized Light Projection Using Polarizing Projector

Aigo Ohno, Fumihiko Sakaue and Jun Sato
Nagoya Institute of Technology, Nagoya, Japan

Keywords: Scattering Medium, Polarized Light, First-Order Scattering, Multiple Scattering, Specular Reflection, Diffuse Reflection.

Abstract: This paper proposes a special projection method called high-frequency polarized light projection using a polarizing projector to analyze scenes filled with scattering medium, and proposes a method to separate reflected lights and scattered lights by scattering medium in the observed image. In high-frequency polarized light projection, a high-frequency pattern is created by light with different polarization directions, projected onto a scattering medium, and the reflected light is observed. The light scattered by the medium and the reflected light from the object have different polarization properties, and we show that these two types of light can be easily separated.

1 INTRODUCTION

In recent years, due to the development of IoT and image information processing technologies, camera-based information analysis has been used in various scenes. In many cases, such technologies are based on the assumption that the scene is a clear scene in which light can travel straight ahead, such as in the air. However, when targeting outdoor scenes such as in-vehicle video analysis, scenes are often filled with medium called scattering medium such as fog or smoke. In such scenes, light emitted from objects is scattered before it reaches the camera. This results in an unclear observed image, making it difficult to use techniques that assume a clear image. Therefore, a method that can separate the effect of light scattering by the scattering medium from the observed image and obtain a clear image is required.

As a technique for this purpose, Nayar et al.(Nayar et al., 2006) propose the separation of scattered light using high-frequency projection. In this method, a controllable light source such as a projector is used to project and observe high-frequency patterns such as fine checker patterns on the object. This method enables the acquisition of images in which the effects of the scattering medium are suppressed and separated with only a simple calculation. However, this method requires multiple projection of images with large changes in brightness and darkness, making it difficult to use in driver assistance and other applications that require human observation with the naked eye. Mukaigawa et al.(Takatani et al., 2018) have proposed a method for finely separating primary scattered light, compound scattered light, specular reflected light, and diffuse reflected light by an object using a method called multiple weighted measurement. Although this method enables more detailed analysis than previous methods, it is time-consuming because it requires taking a variety of images under different conditions.

On the other hand, research has also been conducted to remove the effects of scattering from the image information alone. Kaiming et al.e(He et al., 2010) define a dark channel as the degree of whiteness, and use it to locally correct the captured image, thereby achieving processing that is unaffected by the shading of fog. However, such models approximate the scattering of light to some extent using a simple model, and therefore, when the density of the scattering medium is high, they are not able to perform proper separation. In recent years, there have been studies of using deep learning to remove the effects of scattering from image information alone(Cai et al., 2016; Ren et al., 2016; Gupta et al., 2015; Li et al., 2017; Zhang and Patel, 2018; Yang and Sun, 2018; Tang et al., 2014). These methods have been shown to be able to separate fog with very high accuracy compared to the physics-based methods described above. However, the estimation results of these methods are highly dependent on training data, making it difficult

Ohno, A., Sakaue, F. and Sato, J.
Analysis of Scattering Media by High-Frequency Polarized Light Projection Using Polarizing Projector.
DOI: 10.5220/0012473100003660

In *Proceedings of the 19th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2024) - Volume 3: VISAPP*, pages 772-778
ISBN: 978-989-758-679-8; ISSN: 2184-4321

to guarantee their performance for unknown scenes. This makes it difficult to use these methods in situations where high reliability is required, such as in driver assistance.

Therefore, this paper proposes a method of separating scattered light and reflected light from an object using a projection method called high-frequency polarized light projection. For this purpose, we show how to construct a polarized light projector to realize such described above high-frequency polarized light projection. Since the method proposed in this study is based on a physical model, it can be used independently of the scene conditions. It can be easily applied to various scenes because it can be estimated from a small number of images. High-frequency polarized light projection changes only the polarization state of the projected image, so there is almost no flicker when observed by the naked eye. This makes it possible to obtain an image that suppresses the effects of scattering without changing the results of human observation, even in situations such as in-vehicle image processing, where processing is performed simultaneously with human observation by the naked eye.

2 SCATTERED MEDIUM AND LIGHT SCATTERING

At first, we will discuss the scattering of light and its classification. Light travels in a straight line in a material-free vacuum. However, in a real environment, light is reflected and attenuated in various directions due to collisions with various particles, such as oxygen and nitrogen molecules in the air, small water particles, dust, and dirt. This phenomenon is called light scattering, and it has a greater impact on the visibility of objects in medium with a large number of particles, such as fog, smoke, and water. Such a medium in which a large number of particles exist is called a scattering medium.

Scattering medium are classified according to the size of their constituent particles. Based on the ratio of particle size to wavelength, they can be classified into Rayleigh scattering, Mie scattering, and geometric scattering. Since the projector used in this study emits visible light and the scattering medium is fog with a particle size of $1 \sim 2\mu$m, the scattering phenomenon occurring in the scene is assumed to be described by Mie scattering.

Also, scattering medium are classified according to their optical thickness. Optical thickness is a measure of the opacity of a scattering medium, and the greater the optical thickness, the opaquer the scattering medium. For light incident on an optically thin scattering medium, the probability that the light will incident on a particle in the medium and be reflected in another direction is low, and is approximated by a scattering model in which the number of scattering events is limited to a single event. Such scattering is called first-order scattering or single scattering.

When multiple reflections occur in a medium, it is called complex scattering. Such scattering can be divided into cases that can be described above by scattering as few as $2 \sim 4$ times, and cases in which a sufficiently large number of reflections occur, called higher-order scattering. Low-order scattering is observed as light with some directionality because the number of times it is scattered in the medium is smaller than that of first-order scattering, although the number is larger. High-order scattering, on the other hand, is caused by collisions with many particles in the medium, resulting in countless scatterings. Higher-order scattering is represented as light spreading in all directions with no directionality, since it loses its directionality due to repeated reflections. In this study, we use these scattering characteristics to separate the light reflected from an object from the light scattered by the scattering medium.

3 POLARIZATION PROPERTIES

3.1 Polarization

Next, we will discuss the characteristics of polarized light used in this research. Although light is a transverse wave that oscillates in various directions, polarized light is light whose direction of oscillation is polarized in a specific direction. When polarized light is observed through a polarizer, the observed intensity changes as the polarizer is rotated. This intensity is explained as described above using the polarizer rotation angle ϕ, the maximum intensity of polarized light I_{max}, the minimum intensity I_{min}, and the angle ϕ_0 (polarization direction) of the polarizer that gives the maximum intensity.

$$I(\phi) = \frac{I_{max} + I_{min}}{2} + \frac{I_{max} - I_{min}}{2} \cos(2\phi - 2\phi_0) \quad (1)$$

This allows the intensity change of polarized light to be expressed as the addition of natural light I_{min} and polarized light with an intensity of $(I_{max} - I_{min})$ as shown in Fig 1

This polarization intensity is known to change with reflection and scattering.

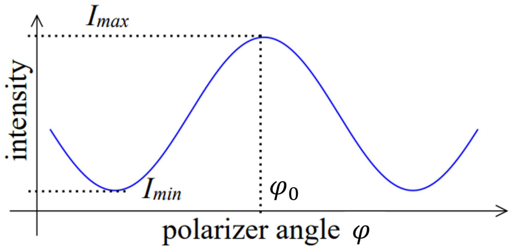

Figure 1: Intensity change of partially linearly polarized light.

3.2 Polarization in Reflection

Next, consider the polarization of light reflected from an object. Reflection of light is broadly classified into specular reflection and diffuse reflection. At first, we will discuss the change of polarization state in specular reflection. Specular reflection is represented as a one-time reflection, and the change in polarization state is expressed by Fresnel's equation. In this case, the direction of polarization and the intensity of the light change, but the polarization is preserved. As described above, the intensity reflectance R_p parallel to the plane of incidence and the intensity reflectance R_s perpendicular to the plane of incidence can be described as follows:

$$R_p = \left(\frac{\tan(\theta_t - \theta_i)}{\tan(\theta_t - \theta_i)}\right)^2, R_s = \left(\frac{\sin(\theta_t - \theta_i)}{\sin(\theta_t + \theta_i)}\right)^2 \quad (2)$$

where, θ_i and θ_t represent the angle of incidence and refraction, respectively, and the reflection angle is assumed to be equal to the angle of incidence assuming that the object plane is optically smooth. In addition, R_p and R_s are always $R_s \geq R_p$ regardless of the angle of incidence. At a certain angle of incidence, $R_p = 0$, and this angle of incidence is called the Brewster angle. As described above, in specular reflection, the polarization angle changes with the angle of incidence of the ray.

Next, we consider the change in polarization in diffuse reflection. In diffuse reflection, multiple reflections occur on the object surface or inside the object, irradiating light uniformly in all directions. In this case, even if the polarized light is incident, its characteristics change in various directions as the reflections are repeated. Therefore, the light observed by diffuse reflection is a superposition of light with various polarization directions, i.e., natural light. Thus, when diffuse reflection occurs, the light observed is natural light even when polarized light is incident.

3.3 Polarization in Scattering

Next, we discuss the change in the polarization of light due to scattering. When the medium is thin, scattering in a scene can be represented by a first-order scattering model in which light is scattered only once. This is because, if we focus on a single ray of light, the ray is considered to be reflected and refracted by a single fog droplet in the scene and scattered. Therefore, first-order scattering is considered to be similar to specular reflection in fog droplets. Let n_i and n_t be the refractive indices of air and water, respectively, and θ_i be the angle of incidence to the fog drop. As described above, the refraction angle θ_t is expressed by Snell's law as follows:

$$\theta_t = \arcsin\left(\frac{n_i}{n_t}\sin\theta_i\right) \quad (3)$$

Next, we consider the change in polarization state in complex scattering. Polarized light enters an optically thick scattering medium, and the first-order scattering described above is repeated multiple times. Although each scattering can be described by the aforementioned scattering model, the repetition of this process results in reflections in various directions, i.e., a mixture of various polarizations. This means that even if the incident light is polarized, the scattered light is a superposition of various polarizations, just like diffuse reflected light, so that the observed light becomes closer to natural light as the number of scatterings increases. Therefore, the light scattered by lower-order scattering becomes partially polarized light, while higher-order scattering becomes natural light. In this paper, the composite scattered light is assumed to be greatly affected by the higher-order scattering and is treated as natural light.

4 SEPARATION OF SCATTERED AND REFLECTED COMPONENTS USING POLARIZATION

4.1 Polarizing Projector

At first, we describe the polarizing projector used in this study. In general projectors, the intensity of light emitted from a light source is partially changed by using liquid crystals or micro-mirror arrays to project a variety of images. Let us consider liquid crystal displays (LCDs), which are used in many projectors. A typical LCD consists of a liquid crystal sandwiched between two orthogonally oriented polarizing plates.

When no voltage is applied to the LCD, polarized light incident from the back of the LCD is twisted in various directions by the discretely arranged liquid crystal molecules, resulting in a state close to unpolarized light. Therefore, a portion of the incident light changes its direction of polarization to a state that allows it to pass through the polarizer on the front surface. On the other hand, when voltage is applied, the orientation of the liquid crystal molecules is aligned, and as a result, polarized light incident from the back enters the front polarizer without changing its direction. Since the orientation of the two polarizers sandwiching the liquid crystal is orthogonal, light that has passed through the liquid crystal cannot pass through the polarizers. This makes it possible to control light passing through the entire liquid crystal display. In addition, by changing the voltage applied to the liquid crystal, the alignment of the liquid crystal changes, making it possible to observe light of various intensities.

Let us consider the case where the polarizer installed on the front surface is removed. In this case, polarized light passing through the liquid crystal is projected directly to the front surface. In other words, the set of light rays whose intensity is adjusted by passing through the polarizer is projected as a set of light rays with different polarization directions. This makes it possible to project light of various polarizations with different directions in the same way as when projecting light of different intensities using an ordinary projector. Regardless of the state of the liquid crystal, the amplitude of the polarization, i.e., the brightness of the observed image, remains almost unchanged. Therefore, when observed by the naked eye, an image with almost the same brightness is observed regardless of the state of polarization. This makes it possible to change the light source status of a scene without significantly disturbing human observation. In this paper, we call such a projector a polarizing projector and show how to use it to separate scattered light from reflected light.

Note that polarizing projectors do not directly control the direction of polarization, but rather control the degree of polarization of the light that passes through them, i.e., how close to perfect polarization or how close to natural light the light is. Therefore, it is not possible to directly project perfectly polarized light that is orthogonal to the polarizer mounted on the back of the liquid crystal. However, considering that partial polarization and natural light can be expressed as a linear combination of orthogonal perfect polarizations, the partial polarization obtained through the LCD can be expressed as a linear combination of a perfect polarization with an orientation equal to that of the polarizer on the back and an orthogonal perfect polarization. Considering the linearity of light, multiple images taken with varying partial polarization can easily be linearly combined to produce an image when irradiated with perfect polarization.

Furthermore, polarization can be adjusted for each pixel in a polarizing projector. This allows for the synthesis of various polarizing projections, such as the synthesis of polarization stripe patterns.

By using this to project various polarization patterns, scattered light in an observed image can be separated.

4.2 Separation of Reflected and Scattered Light Based on Polarization

At first, we consider the case where polarized light is projected with the same orientation to the scene using a polarizing projector, as shown in Fig 2.

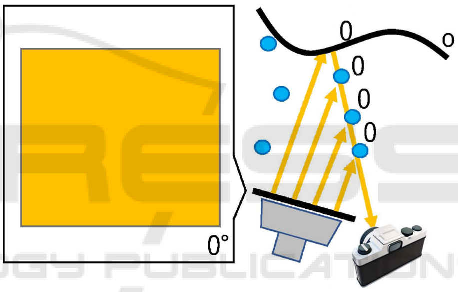

Figure 2: Single polarized light projection.

As mentioned previously, the first-order scattered light from the scattering medium and the mirror reflection light from the object retain the polarization property. On the other hand, the compound scattered light and the diffuse reflected light from the object surface are natural light. Let us consider the case where such light is observed by a polarization camera. In this case, the observed light is partially polarized light that is a combination of natural light and perfectly polarized light. Let us assume that the diffuse reflected light and the composite scattered light are perfect natural light. In this case, the natural light indicated by the equation Eq.(1) is a combination of diffuse reflection and complex scattered light. On the other hand, perfectly polarized light is a composite of first-order scattered light and specular reflected light.

Both of these two components contain both reflected and scattered light from the object. If all light reflected from an object is diffuse reflected light or if there is no compound scattered light, it is possible to separate reflected and scattered light by this method.

However, in general scenes, such assumptions do not hold, and it is difficult to separate them by simple polarization alone.

4.3 Separation of Specular Reflection by High-Frequency Polarized Light Projection

In this study, we propose a method for separating object specular reflection light by high-frequency polarized light projection using a polarizing projector. To separate the first-order scattered light from fog and the specular reflection light from the object surface, this study takes advantage of the fact that fog has a spatial thickness. In other words, we propose a light separation method that takes advantage of the difference between fog, in which a first-order scattered light is integrated in the depth direction of the camera, and an object, in which specular reflection occurs only on its surface.

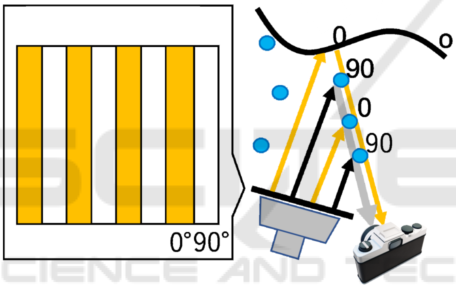

Figure 3: High-frequency polarized light projection.

Let us now consider the case where a polarization pattern is projected onto the scene such that the direction of polarization changes horizontally to 0° and 90° at a high-frequency polarized light projection, as shown in Fig 3. When the scene is observed by a polarization camera from a different direction from that of the projector, as shown in Fig 3, there will be different polarizations on the observed light path. Therefore, the scattered light observed by the camera is a combination of the first-order scattered light with a polarization of 0 degrees and the first-order scattered light with a polarization of 90 degrees, i.e., natural light. On the other hand, the light reflected from the specular surface of an object is generated only on the surface of the object, and thus is observed with perfect polarization. This makes it possible to easily separate the perfectly polarized light from the specularly reflected light, since the only perfectly polarized light in the observed light is the specularly reflected light.

4.4 Separation of First-Order Scattered Light

Finally, we describe a method for separating first-order scattered light from fog. The diffuse reflection component from objects and the combined scattered light from the medium are components that change to natural light in the scene. Therefore, they are considered to have the same intensity in both cases of high-frequency polarized light projection and single-directional polarized light projection. Therefore, by subtracting the natural light image obtained by single polarized light projection from the natural light image obtained by high-frequency polarized light projection, the first-order scattered light from the fog can be easily separated. This makes it possible to obtain an image containing only scattered light from fog and an image containing only reflected light from objects with only two projection/photographing steps.

Note that it is difficult to completely separate the complex scattered light by the medium and the diffuse reflected light by this method alone because of their close polarization characteristics. However, since the complex scattered light are weaker than the first-order scattering, their effect is small in scenes with low fog density. Furthermore, by combination with the usual high-frequency projection with varying brightness, it is possible to separate these components as well.

5 EXPERIMENTAL RESULTS

5.1 Environment

The results of the separation of reflected light and scattered light using the proposed method are presented. In this experiment, fog was generated in a plastic greenhouse in which observation targets were set up. High-frequency polarized light projection patterns and single polarized light projection patterns were projected onto the scene, which was photographed by a polarization camera. Fig 4 shows the scene.

Figure 4: Experimental environment.

Fig 5 shows an image taken under high-frequency

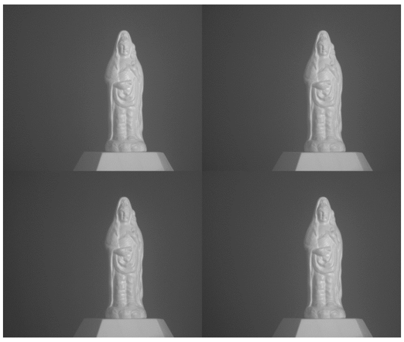

Figure 5: Images under high-frequency polarized light projection.

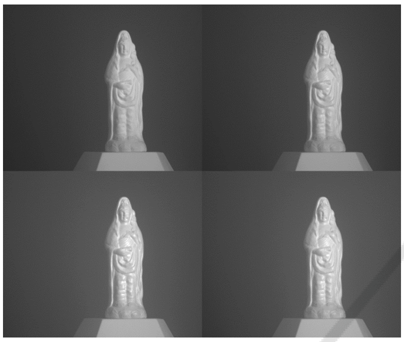

Figure 6: Images under single polarized light projection.

polarization, and Fig 6 shows an image taken under single polarization, respectively. These four images were taken simultaneously by the polarization camera through filters with polarization angles of 0° (upper left), 45° (upper right), 90° (lower left), and 135° (lower right), respectively. The results of these two types of images show that the brightness of the fog only around the object in the images taken under single polarization is different for each polarization angle. This is thought to be due to the fact that the scattered light from the fog is strongly partially polarized, resulting in a large change in the intensity observed at each angle. On the other hand, when high-frequency polarized light projection is used, the fog is observed to be almost equally bright in all polarized light images. This is considered to be a result of the fact that the first-order scattered light from the fog is observed as natural light due to the high-frequency polarization.

5.2 Results of Separation

Next, we show the results of separating the observed light using the proposed method. At first, the results of separating natural light and polarization components for each captured image are shown in Fig 7 and Fig 8. The results show that almost no polarized light is observed outside of the object surface at the base of the high-frequency polarized light projection.

Figure 7: Polarized light (left) and natural light (right) in high-frequency polarized light projection.

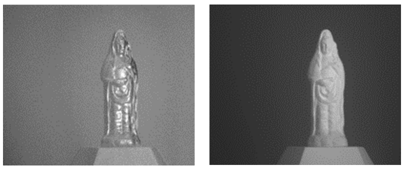

Figure 8: Polarized light (left) and natural light (right) in single polarized light projection.

This may be due to the fact that the high-frequency polarized light projection allows the thicker parts of the object to be observed as natural light. On the other hand, in the case of single polarized light projection, polarization is also observed in the fog area, indicating that first-order scattering from the fog is observed as polarized light.

The results of the separation of the scattering and reflection components based on these images are shown in Fig 9. The results show that the brightness of the fog first-order scattering image decreases in the area where the object is placed. This is thought to be due to a decrease in the fog thickness caused by the placement of the object. In the specular reflection component, the brightness increases in areas where the normal direction is the same, indicating that it is observed as a specular reflection. In the composite image of diffuse reflection and composite scattering, diffuse reflection from the entire object surface is observed. The brightness of the areas where there are no objects is suppressed, confirming that composite scattering was not strong in this environment. These results confirm that the combination of single-frequency polarized light projection and high-frequency polarized light projection can achieve separation according to the characteristics of the observed image with only two projection and imaging.

Figure 9: Results of separation of reflection and scattering components: fog first-order scattering (left), specular reflection (center), diffuse reflection + complex scattering (right).

6 CONCLUSION

In this paper, we propose a method for separating various components in an observed image, such as reflected and scattered components, by means of high-frequency polarized light projection and high-frequency projection using a polarizing projector. We also show how to configure a polarizing projector to realize this method. In the future, a method to completely separate the scattering and reflection components by separating diffuse and composite scattering will be investigated.

REFERENCES

Cai, B., Xu, X., Jia, K., Qing, C., and Tao, D. (2016). Dehazenet: An end-to-end system for single image haze removal. *IEEE transactions on image processing*, 25(11):5187–5198.

Gupta, M., Nayar, S. K., Hullin, M. B., and Martin, J. (2015). Phasor imaging: A generalization of correlation-based time-of-flight imaging. *ACM Transactions on Graphics (ToG)*, 34(5):1–18.

He, K., Sun, J., and Tang, X. (2010). Single image haze removal using dark channel prior. *IEEE transactions on pattern analysis and machine intelligence*, 33(12):2341–2353.

Li, B., Peng, X., Wang, Z., Xu, J., and Feng, D. (2017). Aod-net: All-in-one dehazing network. In *Proceedings of the IEEE international conference on computer vision*, pages 4770–4778.

Nayar, S. K., Krishnan, G., Grossberg, M. D., and Raskar, R. (2006). Fast separation of direct and global components of a scene using high frequency illumination. In *ACM SIGGRAPH 2006 Papers*, pages 935–944.

Ren, W., Liu, S., Zhang, H., Pan, J., Cao, X., and Yang, M.-H. (2016). Single image dehazing via multi-scale convolutional neural networks. In *Computer Vision–ECCV 2016: 14th European Conference, Amsterdam, The Netherlands, October 11-14, 2016, Proceedings, Part II 14*, pages 154–169. Springer.

Takatani, T., Mukaigawa, Y., Matsushita, Y., and Yagi, Y. (2018). Decomposition of reflection and scattering by multiple-weighted measurements. *IPSJ Transactions on Computer Vision and Applications*, 10(1):1–13.

Tang, K., Yang, J., and Wang, J. (2014). Investigating haze-relevant features in a learning framework for image dehazing. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 2995–3000.

Yang, D. and Sun, J. (2018). Proximal dehaze-net: A prior learning-based deep network for single image dehazing. In *Proceedings of the european conference on computer vision (ECCV)*, pages 702–717.

Zhang, H. and Patel, V. M. (2018). Densely connected pyramid dehazing network. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 3194–3203.