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APPLICATION OF HYBRID INTELLIGENT MULTI-OBJECTIVE LIGHTING ALGORITHMS IN HOUSING DESIGN

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Abstract

Aiming at the defects of the traditional global illumination algorithm, such as high complexity, low efficiency, poor application effect in housing design, a global illumination algorithm model based on voxels and calculation methods under various lighting conditions has been proposed. In this study, a rasterisation method is designed to solve the defect that the current global illumination algorithm can only achieve the approximate global illumination effect on static objects. Also, a conical ray tracing calculation method is proposed to solve the ambient occlusion to improve the efficiency of lighting calculation. Finally, for the solution of indirect illumination, the integral hemisphere in the drawing equation is divided into several approximate conical regions, and the cumulative light radiation is weighted. The results show that the rendering time of the volume pixel-based global illumination algorithm model is 425.8 s, which is 67.4 s, 102.6 s, 182.9 s less than VXGI, LPV, and PM, respectively. And the MSE value of the volume pixel-based global illumination algorithm model is 0.0034, which are 0.0017, 0.0051, 0.0071 lower, respectively, than the other three algorithms. So, the global lighting algorithm based on body pixels is excellent in complex interior environments of houses, providing a more comprehensive and realistic performance for the interior design of houses.

Key Words

Global lighting algorithms; house residential design; body pixels; ray tracing

1. Introduction

In recent years, with the improvement of people's living standards, the demand for household equipment has become increasingly high, which has brought huge challenges to home design manufacturers [1]. The residential design has also become a focus of common concern for businesses and customers [2]. In addition to commercial marketing activities, 3D virtual scenes are widely used in education, medicine, industry, and other fields. The rendering of global illumination algorithms can improve the authenticity of 3D models to meet the actual needs of users [3], [4]. In recent years, with the improvement of computer technology and the increase in people's demand for entertainment, 3D animation, movies, and games have also been greatly developed. The application of global illumination algorithm to virtual scenes can effectively improve the authenticity of 3D images and meet the audience's entertainment needs [5], [6]. Therefore, the application of the global illumination algorithm is extremely extensive.

Meka *et al.* [7] proposed a real-time global illumination decomposition method for video to improve the performance authenticity of video. Prakash *et al.* [8] designed an interactive smooth probe projection based on the global illumination algorithm, which improved the rendering effect of the projection. Bae *et al.* [9] proposed a new method for detecting photoelectrochemical reactions on semiconductor surfaces using the global illumination, which solved the problem of poor detection performance of electrochemical microscopy on semiconductor surfaces. Tabata *et al.* [10] proposed a phase unwrapping method to handle the motion of target objects in real environments. This method was robust to global illumination and could project high-speed moving objects with high accuracy and resolution. Wawrzonowski *et al.* proposed applying global illumination algorithms to game rendering to improve the performance of game graphics. This method solved the lack of realistic visual effects in video games and simulation games [11]. Seyb *et al.* [12] applied global illumination to the design of the UberBake light baking system to promote optimisation. Jiang *et al.* [13] proposed applying the global illumination algorithm to measure the three-dimensional shape of semi-transparent objects in projection camera systems to increase the authenticity of the three-dimensional model. Zhu *et al.* [14] collected photons tracked by the light source and used the trained neural network to guide the path to achieve global illumination for each scene. Zhang *et al.* proposed an optical transmission strategy. This strategy allowed the network to learn complex material effects and global illumination,

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ensuring the physical correctness of diffuse reflection LT [15]. Zhu *et al.* proposed a lightweight neural network for path guidance to reduce the variance of path tracking. This method had a good global illumination effect in various optical transmission scenes [16]. Müller *et al.* [17] proposed a real-time neural radiation caching method for path tracking global illumination by implementing path tracking in various complex scenarios.

In summary, global illumination algorithms meet the requirements of real-time rendering in various fields, achieving overall lighting effects in real-time environments and rendering effects in non-real-time environments. However, current global illumination algorithms still have issues such as high computational complexity in simulating real physical phenomena, and low efficiency when using computer-simulated lighting for rendering and segmentation. In addition, with the development of the economy and the improvement of income levels, people's requirements for living environment are also becoming higher. Residential buildings not only meet the most basic living needs but also have strong demands in terms of lighting, ventilation, and artistry. Therefore, the market pressure and challenges faced by housing and residential design manufacturers are increasing. More domestic and foreign scholars are turning their attention to the housing and residential design. In housing and residential design, it is necessary to quickly design different decorative styles and generate rendering images that are close to real effects to attract customer interest. Therefore, 3D scene rendering and graphic rendering are essential. Real-time global illumination can increase the realism of image rendering. In the interior design of residential buildings, a highly realistic rendering that reflects indoor lighting conditions is essential. To ensure the authenticity, the application of the global illumination algorithm in residential interior design is of great significance. In house design, three-dimensional modelling of the indoor environment provides a more intuitive observation of the design effects of the house, such as lighting, ventilation, *etc.* In 3D modelling and rendering, the application of global illumination algorithm is very important, but there is little relevant literature research at present. Therefore, the research applies the global illumination algorithm to the housing design work, which comprehensively shows the effectiveness of indoor design and providing data support for residential design. However, the current global illumination algorithm has high computational complexity, which leads to long time consumption and high cost in large-scale scenes. To improve rendering speed and reduce costs, the authenticity of scene rendering cannot be guaranteed. Aiming at the defect that the traditional global illumination algorithm cannot balance authenticity and timeliness, a global illumination algorithm based on volume pixels is proposed. The performance is verified by design experiments to find a high-performance global illumination algorithm, which provides a basis for housing design. There are two main innovations in the research: (1) To apply the global illumination algorithm to housing design to improve the efficiency and effect of housing design. (2) To propose a volume pixel-based global illumination algorithm to reduce the computational complexity of the traditional global illumination algorithm and improve the efficiency of the algorithm. There are two main contributions of the research: (1) To provide new ideas for the improvement, application and development of the current global illumination algorithm. (2) To provide a new way to improve the quality and efficiency of housing design, which has a promoting effect on the development of the housing design industry.

2. Construction of a Global Lighting Algorithm Model Based on Body Pixels

2.1 Application of Global Lighting Algorithms in Housing Design

Highly realistic renderings are essential in housing residential design work. Real-time global illumination is an important technique to improve the image realism and make the rendering more realistic. Therefore, in recent years, real-time global illumination algorithms have been widely used in housing design [18]–[20]. In computer graphics, the calculation of global illumination can be expressed by (1).

$$\langle S, f_r\left(\omega', \vec{x}, \omega\right), L^e\left(\vec{x}, \omega\right), W^e\left(\vec{x}, \omega\right)\rangle \tag{1}$$

In (1), $\vec{x}$ is the vector of illumination points on an object in the indoor environment. S is the geometric properties of the light point. f_r is the bi-directional reflectance distribution function (BRDF) optical material property of the light point. ω is the stereo angle of the outgoing light. ω' is the stereo angle of the incoming light. L^e is the light energy emitted by the light point. W^e is the interaction equation between the light and the surface of the object. In (1), global illumination can be expressed as an abstract quaternion. In the internal modelling of residential buildings, there are some models that contain only diffusely reflecting materials. Their global illumination models can be simplified and expressed by calculating radiance, as shown in (2).

$$B_i = E_i + \rho_i \sum_{j=0}^{n} B_j F_{j\to i} \tag{2}$$

In (2), B_i is the outgoing radiance of the light point on the surface of the object i. E_i is the spontaneous radiance of the light point on the surface of the object. ρ_i represents the reflectance of the light point on the diffuse reflective surface of the object. $F_{j\to i}$ represents the energy transfer relationship from the surface of the object j to i. The graphical rendering pipeline is an important structure for real-time rendering. The main function is to render and draw operations from the data of the 3D model to obtain a 2D image. Generally speaking, the graphics rendering pipeline is divided into three stages, namely, the application pipeline, the geometry pipeline, and the rasterisation pipeline [19]. The rendering performance of graphics rendering pipelines is influenced by the hardware and lighting conditions of the computer. In a graphics rendering pipeline, forward rendering is generally used to implement the lighting calculation. Based on the above, global lighting calculations can be implemented [20]. In fact, the vast majority of objects have rough surfaces. Therefore, reflection, refraction, scattering, and diffraction are considered when conducting lighting calculations [21]–[24]. The influence of specific lighting points on light, such as reflection and refraction, can be represented by BRDF reflection in (3).

$$l_0(v) = \int_\Omega f_r(l, v) \cdot L_i(l)(l \cdot n)\, d\overrightarrow{\omega'} \tag{3}$$

In (3), v represents the unit vector of reflected light at the point of illumination, that is, the line of sight. l represents the inverse unit vector of incident light at the point of illumination.

2.2 Global Illumination Algorithm Based on Body Pixels

There are three main factors that constrain the quality of image drawing in the interior image drawing of houses. They are the data perfection of the house and home scene model, the level of computer hardware and the observation dimension, and the performance of the lighting algorithm model. To this end, a global illumination algorithm model based on body pixel has been proposed and improvements have been made to address the shortcomings. The global illumination algorithm model based on volume pixels is to transform the object model of point coordinates into volume pixel data by using the raster method. The information of lighting calculation is stored in three-dimensional stereo pixels, arranged in a tree-like structure. Therefore, it has high efficiency in information retrieval, information localisation and information updating. The global illumination algorithm model based on body pixels constructed in this study consists of four steps: first, convert the indoor scene model into pixel data and store it; secondly, calculate the emission amplitudes of all body pixels; furthermore, directional body pixels are calculated and stored in the body pixel structure; finally, use the body pixel cone ray tracing algorithm to draw global illumination. Under a single light source, the radiance of an individual pixel can be expressed by (4).

$$V_r = L_i \frac{\rho}{\pi} \max\{N, \psi, 0\} \tag{4}$$

In (4), L_i indicates the light intensity. ρ indicates the albedo. N indicates the body pixel normal vector. ψ indicates the orientation of the light. Equation (4) cannot guarantee a high accuracy rate when averaging the geometric normal in a body pixel. There may be some error in obtaining the orientation of the average normal vector when calculating the normal declination using normal vectors $(N \cdot \psi)$. To address this issue, the normal-weighted declination method is used to obtain the normal declination for all faces of the body pixel, as shown in (5).

$$D_{x,y,z} = \left(\widehat{i} \cdot \psi, \widehat{j} \cdot \psi, \widehat{k} \cdot \psi\right) \tag{5}$$

In (5), $\widehat{i}, \widehat{j}, \widehat{k}$ are the three planes of the volume pixel, respectively. After obtaining the normal declination of all the faces, three dominant faces are selected using (6).

$$D_\omega = \begin{cases} \max\{D_\omega, 0\}, & N_\omega > 0 \\ \max\{-D_\omega, 0\}, & \text{otherwise} \end{cases} \tag{6}$$

In (6), D_ω is the dominant surface. The normal deviation angles of each dominant surface are multiplied to obtain the normal deviation angles of each surface of the voxel. The reflectance model is obtained by multiplying the normal deviation angle of each surface by the weight of the axis on which the average normal vector is located, as shown in (7).

$$\begin{cases} W = N^2 \\ V_r = L_i \frac{\rho}{\pi}\left(W_x D_x + W_y D_y + W_z D_z\right) \end{cases} \tag{7}$$

Within the housing dwelling model, the calculation of indirect illumination can be carried out according to the method shown in Fig. 1. The integral hemisphere in the plotting equation is divided into a number of approximate cone regions. These cone lights are weighted to calculate the cumulative light radiation.

To improve the efficiency of the light calculation, the same conical ray tracing is used for the diffuse reflection calculation. The ambient light shading parameter in a house is δ. When solving δ, a cumulative value α is set first. The cumulative valueα is accumulated and multiplied by the weighting function $f(r)$ at each accumulation to solve the ambient light obscuration parameter in the house. The weighting function is shown in (8).

$$f(r) = \frac{1}{1 + \lambda r} \tag{8}$$

In (8), r is the base radius of the cone of conical rays. λ is a user-set value, whose main function is to control the recession rate of $f(r)$.

The above is combined to complete the construction of a global lighting algorithm model based on body pixels. When applied to the design of residential buildings, it can improve the picture rendering effect and scene interaction experience, so as to achieve real-time global illumination is realistic image rendering, and help designers better complete the modelling and design of residential buildings under multi-level details and physical rendering based material and lighting algorithms.

3. Performance Analysis of a Body Pixel-Based Global Illumination Algorithm Model

In practical application, Light Meten is a reflective light meter with spotlight measurement and a light meter with incident light, which is exposed according to the sensitivity sensor of the mobile phone. It has accurately tested Gossen and Sekonic meters on most devices to verify the performance of the proposed global illumination algorithm based on body pixels. And compare the rendering effect under 3ds Max and path tracking drawing method.

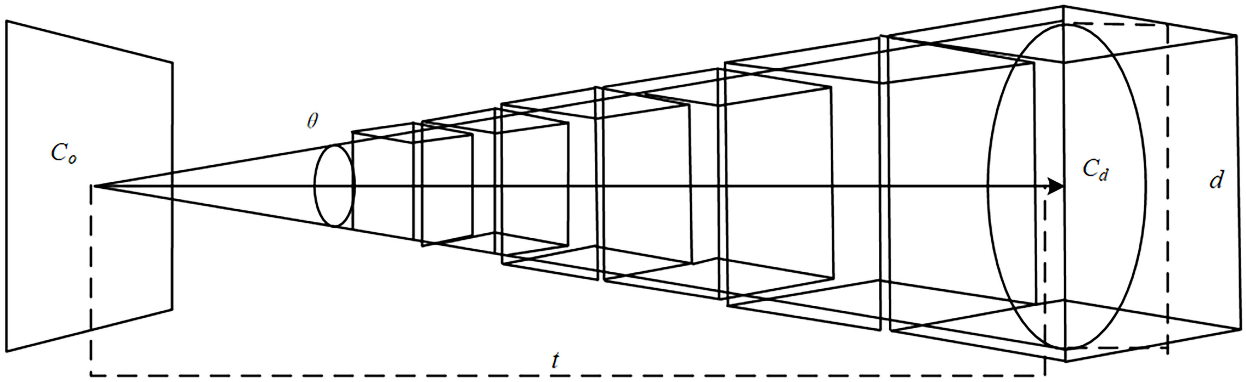

Figure 1. Schematic diagram of cone light.

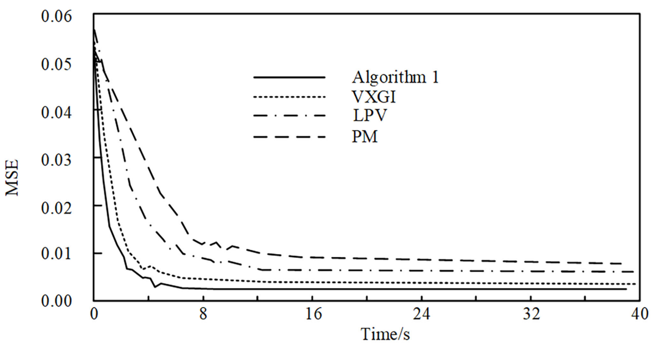

Figure 2. MSE of four global illumination algorithm models.

The experimental environment is set up for comparative experiments. The experimental environment is configured as follows. The primary configuration is Intel Core i7-6700K@4.00GHz 4-core processor, 16 GB of RAM, Nvidia GeForce GTX 950 graphics card. The PC operating system adopts the conventional Windows 7 system. Allocation 1 is an Intel Core i5-processor with 8GB of RAM, Nvidia GeForce GTX 950, with a Windows 7 PC operating system. Allocation 2 has the same PC configuration as Allocation 1. The experimental dataset is derived from residential scenarios in the public dataset provided by Stanford University. The voxel global illumination (VXGI), light propagation volumes (LPV) and photon mapping (PM) algorithms are common global illumination algorithms. The above three global illumination algorithms are compared with the proposed global illumination algorithm based on body pixels (Algorithm 1). The mean square error (MSE) between the scene result drawn by the global illumination algorithm and the reference scene is used as the evaluation index. The MSE of four global illumination algorithm models is shown in Fig. 2.

In Fig. 2, after stabilisation, the MSE value of the global illumination algorithm model proposed in the study is 0.0034. The MSE value of the VXGI is 0.0051, which is 0.0017 higher than that of the proposed method. The MSE value of the LPV is 0.0085, which is 0.0051 higher than that of the proposed method. The MSE value of the PM model is 0.0105, which is 0.0071 higher than that of the body pixel-based global illumination algorithm model. The body pixel-based global illumination algorithm model proposed in the study has the lowest drawing error and the highest accuracy in the same scene. The four global illumination algorithms are used to draw six housing scenes. They are recorded as scene 1, scene 2, scene 3, scene 4, scene 5, and scene 6. The complexity of the scenes increases in order.

Table 1
Time Required for Four Global Illumination Algorithms to Draw Six Indoor Scenes

Scene	Time/s			
	Algorithm 1	VXGI	LPV	PM
Scenario 1	48.2	58.7	62.4	65.7
Scenario 2	97.5	114.3	124.5	136.7
Scenario 3	125.4	134.8	145.9	152.1
Scenario 4	225.8	246.7	266.3	274.0
Scenario 5	317.4	358.9	395.6	419.3
Scenario 6	425.8	493.2	528.4	608.7

In Table 1, as the complexity of the drawn scenes increases, the algorithms' drawing time for each scene also increases. For scene 1, the proposed global illumination algorithm model based on body pixels takes 48.2 s, which is 10.5 s, 14.2 s, and 17.5 s less than the VXGI, LPV, and PM, respectively. For scenes 1–6, the global lighting algorithm based on body pixels takes significantly less time than the other three algorithms, indicating that the global lighting algorithm based on body pixels can improve the efficiency of drawing and rendering. A comparison of the frame rates of the four global illumination algorithms at runtime is shown in Fig. 3.

In Fig. 3, the body pixel-based global lighting algorithm has the highest frame rate and is more stable. The average running frame rate is around 36FPS. It is 8FPS higher than the 28FPS of the VXGI global illumination algorithm. It is 13 FPS higher than the 23 FPS of LPV, and 29FPS higher than the 7FPS of PM. The rendering results of 3ds Max, path tracing rendering, and the global illumination algorithm proposed in this study were compared to verify the effectiveness of the global

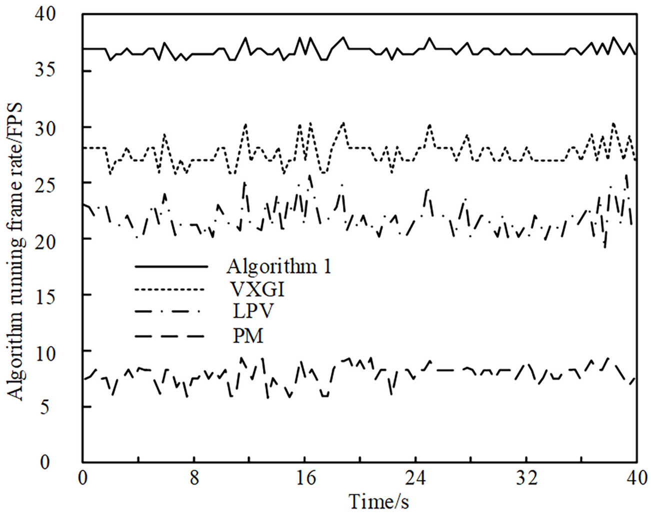

Figure 3. Comparison of frame rates of four global illumination algorithms at runtime.

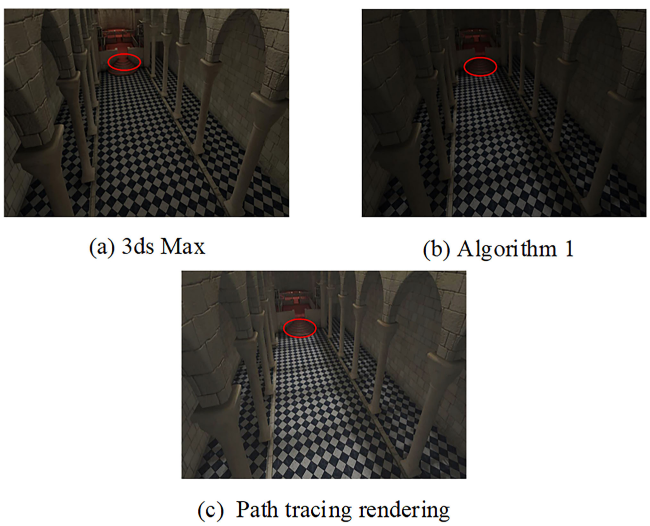

Figure 4. Rendering effect of global illumination algorithm based on volume pixel under sufficient illumination: (a) 3ds Max; (b) Algorithm 1; and (c) path tracing rending.

illumination algorithm in housing and residential design. When the light is sufficient, the results of the 3ds Max rendering, the proposed global lighting algorithm based on the body pixels, and the effect under the path tracking rendering, are shown in Fig. 4.

In Fig. 4, under more light conditions, the lighting effect in the area marked by the red line in Fig. 4(a) is more heavily smeared, resulting in a strong sense of unnaturalness. The area marked by the red line in Fig. 4(b) shows the light and shadow details very well, with a much stronger sense of realism. The area marked by the red line in Fig. 4(c) shows the brightness details well, fully presenting the optical effect, but the light and shadow effects are poor. The above illustrates that the global lighting algorithm based on body pixels performs better in rendering when there is more light. In summary, the performance of the global lighting algorithm based on body pixels is better than the traditional global lighting algorithm, which is more suitable for housing residential design work.

4. Conclusion

Global lighting algorithm plays a key role in the design of houses at, where a high degree of realism is essential. To this end, therefore, this study proposes a global illumination algorithm based on body pixels for illumination calculation schemes in diffuse reflection, ambient shadow, and other lighting situations. The experimental results show that when the drawing time exceeds a certain time, the MSE value of the body pixel-based global illumination algorithm model proposed in the study is 0.0034. The VXGI algorithm is 0.0051, the LPV is 0.0085, and the PM is 0.0105. When rendering scene 1, the rendering time of the global illumination algorithm model is 48.2 s, which is 10.5 s, 14.2 s, and 17.5 s less than that of the VXGI, LPV, and PM algorithms, respectively. In summary, the performance of the body pixel-based global illumination algorithm is superior to that of the traditional global illumination algorithm, which is more suitable for housing residential design work. Therefore, the global illumination algorithm proposed in the study has a certain role in promoting the development of the housing design industry. To some extent, it also points out the direction for the development of the global illumination algorithm. However, there are still certain shortcomings in the research. There is a risk of light leakage during voxelisation under specific circumstances. Therefore, further improvements are needed in the future to address this deficiency.

Availability of data and materials: The data used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

[1] F. Bianconi, M. Filippucci, and A. Buffi, Automated design and modelling for mass-customized housing. A web-based design space catalogue for timber structures, *Automation in Construction, 103*, 2019, 13–25.

[2] C. Pérez, P. Arroyo, C. Richards, and C. Mourgues, Residential curbside waste collection programs design: A multicriteria and participatory approach using choosing by advantages, *Waste Management, 119*, 2021, 267–274.

[3] H.M. Hu, H. Zhang, Z. Zhao, B. Li, and J. Zheng, Adaptive single image dehazing using joint local-global illumination adjustment, *IEEE Transactions on Multimedia, 22*(6), 2019, 1485–1495.

[4] T. Liu, J. Gao, and Z. Lei, An Approach to global illumination calculation based on hybrid cone tracing, *IEEE Access*, *8*, 2020, 92061–92071.

[5] H. Sa'Dyah, K. Fathoni, D.K. Basuki, and A. Basofi, The fundamental topics of static global illumination algorithms for 3D games, *Proc. 2018 IEEE 3rd International Conf. on Communication and Information Systems (ICCIS)*, Singapore, 2019, 237–241.

[6] J. Deng, Y. Liu, and X. Xie, Performance characterization of illumination algorithms for reconfigurable graphics processor, *The Journal of China Universities of Posts and Telecommunications, 26*(05), 2019, 64–75.

[7] A. Meka, M. Shafiei, M. Zollhfer, C. Richardt, and C. Theobalt, Real-time global illumination decomposition of videos, *ACM Transactions on Graphics, 22*, 2021, 1–16.

[8] S. Prakash, C. Wyman, P. Shirley, S. Rodriguez, T. Leimkühler, and G. Drettakis, Glossy probe reprojection for interactive global illumination, *ACM Transactions on Graphics,39*(6), 2020, 237–242.

[9] J.H. Bae, A.B. Nepomnyashchii, X. Wang, D.V. Potapenko, and M.V. Mirkin, Photo-SECM on the nanoscale with through-tip illumination, *Analytical Chemistry, 91*(20), 2019, 12601–12605.

[10] S. Tabata, M. Maruyama, Y. Watanabe, and M. Ishikawa, Pixelwise phase unwrapping based on ordered periods phase shift, *Sensors, 19*(2), 2019, 377–377.

[11] M. Wawrzonowski and D. Szajerman, Optimization of screen-space directional occlusion algorithms, *Open Physics, 17*(1), 2019, 519–526.

[12] D. Seyb, P.P. Sloan, A. Silvennoinen, M. Iwanicki, and W. Jarosz, The design and evolution of the UberBake light baking system, *ACM Transactions on Graphics, 39*(4), 2020, 150–162.

[13] H. Jiang, H. Zhai, Y. Xu, X. Li, and H. Zhao, 3D shape measurement of translucent objects based on Fourier single-pixel imaging in projector-camera system, *Optics Express, 27*(23), 2019, 33564–33574.

[14] S. Zhu, Z. Xu, T. Sun, A. Kuznetsov, M. Meyer, H. Wann Jensen, H. Su, and R. Ramamoorthi, Photon-driven neural reconstruction for path guiding, *ACM Transactions on Graphics, 31*(1), 2021, 1–15.

[15] X. Zhang, S. Fanello, Y.T. Tsai, T. Sun, T. Xue, R. Pandey, and S. Orts-Escolano, Neural light transport for relighting and view synthesis, *ACM Transactions on Graphics, 40*(1), 2021, 1–17.

[16] S. Zhu, Z. Xu, T. Sun, A. Kuznetsov, M. Meyer, H. Wann Jensen, H. Su, and R. Ramamoorthi, Hierarchical neural reconstruction for path guiding using hybrid path and photon samples, *ACM Transactions on Graphics, 40*(4), 2021, 1–16.

[17] Tmüller, F. Rousselle, J. Novák, and A. Keller, Real-time neural radiance caching for path tracing, *ACM Transactions on Graphics, 40*(4), 2021, 1–16.

[18] L. Ruppert, S. Herholz, and H. Lensch, Robust fitting of parallax-aware mixtures for path guiding, *ACM Transactions on Graphics, 39*(4), 2020, 147 –161.

[19] M. Nimier-David, S. Speierer, B. Ruiz, and W. Jakob, Radiative backpropagation: An adjoint method for lightning-fast differentiable rendering, *ACM Transactions on Graphics, 39*(4), 2020, 146–160.

[20] J. Deng, J. Li, H. Feng, S. Ding, Y. Xiao, W. Han, and Z. Zeng, Efficient intensity-based fringe projection profilometry method resistant to global illumination, *Optics Express, 28*(24), 2020, 36346–36360.

[21] K. Ullah, G. Hafeez, I. Khan, S. Jan, and N. Javaid, A multi-objective energy optimization in smart grid with high penetration of renewable energy sources, *Applied Energy, 299*, 2021, 117104.

[22] S. Ali, K. Ullah, G. Hafeez, I. Khan, and F.R. Albogamy, Solving day-ahead scheduling problem with multi-objective energy optimization for demand side management in smart grid, *Engineering Science and Technology, an International Journal, 36*, 2022, 101135.

[23] K. Ullah, T.A. Khan, G. Hafeez, I. Khan, S. Murawwat, B. Alamri, F. Ali, and S. Ali, Demand side management strategy for multi-objective day-ahead scheduling considering wind energy in smart grid, *Energies, 15*(19), 2022, 6900.

[24] S. Hoseinzadeh, D. Groppi, A.S. Sferra, U. Di Matteo, and D. Astiaso Garcia, The PRISMI plus toolkit application to a grid-connected Mediterranean Island, *Energies, 15*(22), 2022, 8652.

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