Research of Light Field Technology

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Abstract: Light field technology is a relatively new theory and technical direction. At present, it has played a significant role in scientific research, production and life, national defense and military, but there are still many problems to be solved in terms of theoretical description, technical implementation, software and hardware processing capabilities, commercialization costs, and ease of use. Therefore, research the light field technology, explore the principle and application of light field imaging, and put forward some enlightenment for its application in industrial machine vision.

1. Introduction
Traditional imaging methods compress many optical field parameters, including transmission direction, wavelength, phase and other optical field information, which usually carry many important scene target information, and the limitations of down sampling methods to obtain information are becoming more and more prominent, so it is very important to study the optical field from various perspectives, such as basic theory, descriptive models and methods, or light field information acquisition and efficient utilization. Compared with traditional methods, optical field imaging technology can obtain more complete information than traditional imaging methods by controlling or recording multi-dimensional optical parameters including position and propagation direction simultaneously. The basic representation model of the optical field, various methods of optical field acquisition and control can significantly change the way of imaging, measurement, and display.

2. Geometric optical representation of the light field
According to the light assumption of geometric optics, the light field is the set of all light radiation functions in space, and each light ray carries two-dimensional position information as well as two-dimensional direction information (\(\theta\), \(\phi\)). The light field rendering theory proposed by Marc Levoy et al. states that all light rays in space with position and direction information can be parametrically represented by two mutually parallel planes. As shown in Figure 1, a light ray passes through two points on two parallel planes with coordinates (u, v) and (s, t), respectively, and the spacing between the two parallel planes is F. The two-dimensional angular information of the light ray can be obtained from the position coordinates of the two points, so the four-dimensional light field function \(L_F\) (s, t, u, v).
According to the four-dimensional light field function, the image radiance from the $u, v$ plane to a point on the $s, t$ plane can be expressed by the integral formula of light radiance as:

$$E_F(s, t) = \frac{1}{F^2} L_F(s, t, u, v) du dv$$

(1)

Figure 1 Parametric representation of the four-dimensional optical field

The relationship between the light field function defined by the lens plane and the sensor plane $L_F(s, t, u, v)$ and the light field function defined by the lens plane and the refocusing plane $L_F(s, t, u, v)$ can be obtained using a geometric transformation, as shown in Figure 2, where the propagation of the four-dimensional light field function in space is a tangential transformation.

$$L_F(s, t, u, v) = L_\alpha(s, t, u, v) = L_F(u + (s - u)/\alpha, v + (t - v)/\alpha, u, v) = L_F(u(1 - \alpha) + s/\alpha, v(1 - \alpha) + t/\alpha, u, v)$$

(2)

Figure 2 Schematic diagram of the propagation of the four-dimensional light field function in space

According to equation (1) and equation (2), the two-dimensional slice expression of the four-dimensional light field function at any position can be obtained. This method is simple and efficient, and the light field information can be described and processed digitally, so the four-dimensional light field expression with light as the basic assumption is more widely used in the field of computational imaging.

3. Acquisition of light field

The difference in interpretation and expression of the light field determines the difference in the acquisition form of the light field function, but regardless of the way of expression, the techniques that can achieve the differentiation and measurement of the four dimensions of light field parameter information belong to the category of light field acquisition techniques. The main technical means are the following three.

3.1 Microlens array

The huge size of the camera array limits its application. By reducing the baseline between each
imaging unit in the camera array, it is possible to achieve light field information acquisition based on a single camera frame using microlens arrays. Figure 3 shows the principle of acquiring light field information based on microlens arrays, in which microlens arrays are inserted at the primary image plane of a common imaging system, and each microlens unit and its corresponding sensor area record the light corresponding to the collection of the same part of the scene imaged under different propagation directions of the light, i.e., the four-dimensional light field data including position and propagation direction can be obtained through the two-dimensional lens array.

Figure 3 Microlens array imaging principle diagram

In 1992, Adelson et al. first proposed a light field camera model based on microlens arrays, and Ren Ng and others optimized the model to realize handheld light field camera products by compressing the volume through optical path optimization, and Lytro, established in 2010, has launched Lytro (Plenoptic 1.0) and Lytro Illum shown in Figure 4(a) and Figure 4(b). Lytro Illum, two commercial-grade cameras, feature a large depth-of-field reconstruction with “picture first, focus later,” which allows accurate focusing and clear pictures even in high-speed image movement and low-light conditions. Such cameras use a row of micro-lens arrays placed in front of the sensor, as shown in Figure 5. More commercial-grade products produced by Lytro, Germany’s Raytrix has been dedicated to the research and promotion of industrial-grade light field cameras. Figure 4(c) and Figure 4(d) show its Raytrix R5 and Raytrix R11 series of light field cameras, which can be used in automatic optical inspection, stereo microscopy and three-dimensional shape and feature detection in scientific research, in the industrial field, in traffic control, public safety such as face recognition and pupil scanning, and even in the military, aerospace and other defense fields also have related solutions and typical There are also related solutions and typical cases in the field of national defense such as military and aerospace.

Figure 4 Light field camera

Figure 5 Camera imaging schematic

The advantages of the method of obtaining light field information by using the light field camera with microlens array are stable relative position and angle relationship among imaging units [4], strong portability, small system size, and mature corresponding data processing method and supporting software, but the disadvantage is that the spatial resolution is sacrificed when obtaining the angular resolution, therefore, it cannot meet the requirements in applications requiring high spatial resolution.
3.2 Camera Array or Camera Scan

Camera array to obtain light field information refers to the specific distribution of multiple cameras in space to obtain different views of the scene image, each camera to obtain the four-dimensional light field in the camera relative to the scene direction of the two-dimensional projection [5], the camera image will be fused to obtain the complete four-dimensional light field data. The closely spaced camera arrays are mainly used to obtain high-performance dynamic scenes or scenes of three-dimensional distribution and structure and other information, while the large-scale spatial camera arrays are mainly used for synthetic aperture imaging to achieve "perspective" monitoring, or through the stitching to achieve a large perspective panoramic imaging. In the direction of camera arrays for light field measurement, there are more successful ones: MIT's 8×8 camera array, and the camera array-based light field microscope developed by Professor Qionghai Dai's team at Tsinghua University. In addition Marc Levoy, Aaron Isaksen and others use a single camera scanning system, moving the camera on a fixed guide, acquiring the scene images in different spatial perspectives in time, and finally fusion can also achieve the same function, using this method requires scanning, so the method is only applicable to the light field measurement of static scenes, and the accuracy of camera movement and positioning has an impact on its measurement accuracy. Figure 6 shows the case of obtaining light field information by camera array method, and Figure 7(a) and Figure 7(b) show the principle and case of obtaining light field information by single camera path scanning scheme, respectively.

Figure 6 Camera array light field information acquisition case

Figure 7 Single camera scanning light field information acquisition case
3.3 Mask and others

Microlens arrays acquire light field information at the expense of spatial resolution in exchange for angular resolution. Veeraraghavan Ashok's optical field camera, achieved by inserting a mask into the optical path of an ordinary camera, is a classic example. As shown in Figure 8, the images acquired by the mask-based light field acquisition system appear to be less different from those of ordinary cameras, but their frequency domain is regularly distributed, similar to the frequency domain characteristics of light field data, and four-dimensional light field information can be obtained through a series of processing. The advantages of such methods are as follows: the hardware system is simpler, the mask is a non-refractive element, the primary data processing is easier, and it is easier to implement compared to the microlens array structure. In addition, Antony Orth et al. proposed Light field moment Imaging (LMI), which uses two-dimensional images acquired at different out-of-focus locations to obtain four-dimensional light field data (imaging), which uses coherent light illumination samples with different propagation directions or scanning apertures to obtain four-dimensional light field data and achieve digital refocusing.

![Figure 8 Schematic diagram of the mask light field acquisition system](image)

4. Results

Automation is the key to producing high-quality products, and if the products produced are required to be more flexible, then their automation processes become increasingly complex. At the same time, high demands are placed on the processing of integrated images. However, existing machine vision solutions fall far short of expectations. These demanding tasks can be solved quickly, easily and reliably using light field technology.

Light field technology provides additional solutions for difficult tasks in industrial machine vision. For example, with light field cameras it is possible to capture complex materials, even if they are shiny or even sparkling. Light field technology can also be used well in industrial production plants where active illumination is not required. When using phase arrays, even ordinary ambient light is sufficient for object capture, as accurate results can be obtained using light field technology. At the same time, light field images can provide depth information: distances and intervals can be calculated by slight displacement and combined with the corresponding algorithms. This makes the light field technique a means to obtain accurate object sizes with an accuracy of up to 0.1 mm. at the same time, the geometry of the object can be measured not only in the light field, but also information such as surface texture and glossiness can be obtained. Even detailed point clouds, quantified surface features, and 3D models can be easily implemented. The generated data can be used in various industrial fields, such as object recognition, object classification or quality inspection [6].

When processing images in automated production, the special properties of light field technology enable the reliable identification of complex workpieces consisting of metal with stains or bright spots as well as non-glossy plastic or translucent parts. In contrast to many existing machine vision solutions,
it can be implemented not only without complex light sources, additional cameras, etc., but only requires a compact light field sensor to be installed over the industrial production site, which is especially well-suited for extensive production facilities.

5. Conclusions
In general, the means for obtaining light field information is relatively complete, but its application direction still needs to be further developed and expanded. Currently, digital refocusing and 3D reconstruction are the two most important light field application directions. The digital refocusing concept has been relatively mature since it was proposed by Ng Ren and has been applied in Lytro products. Most 3D reconstructions are carried out on the theoretical basis of traditional multi-eye stereo vision. Due to the small size of the light field camera and the short baseline between the sub-fields, the acquisition of high-precision disparity maps is limited \(^{(7)}\). Therefore, current research in this area relatively slow. In view of this situation, the use of deep learning methods and making full use of light field information to obtain the disparity map of the multi-eye stereo vision system is a direction that can be further tried. In addition, the use of light field technology can obtain a wealth of information. Light field technology has the potential to be used in many fields such as super-resolution imaging, defogging imaging, and three-dimensional object recognition \(^{(8)}\). New research direction. Light field technology can replace the existing machine vision technology to do some difficult tasks, and light field technology can be used in industrial automation production.

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References
[1] Peter, Hartmann, István, Donkó, Zoltán, & Donkó. (2013). Single exposure three-dimensional imaging of dusty plasma clusters. Review of Scientific Instruments.
[2] Ng, & Ren. (2005). Fourier slice photography. ACM Transactions on Graphics (TOG).
[3] Zhou, P., Kong, L., Sun, X., & Xu, M. (2020). Three-dimensional measurement of specular surfaces based on the light field. IEEE Photonics Journal, 12(5), 6901613.
[4] Tian-Jiao, Li, Su-Ning, Li, Yuan, & Yuan, et al. (2018). Light field imaging analysis of flame radiative properties based on monte carlo method. International Journal of Heat & Mass Transfer.
[5] Li, S. N., Yuan, Y., Liu, B., Wang, F. Q., & Tan, H. P. (2018). Influence of microlens array manufacturing errors on light-field imaging. Optics Communications, 410, 40-52.
[6] Garbe, C., & Schindler-Kotscha, M. (2021). A new dimension for machine vision. PhotonicsViews, 18(5).
[7] Qian, W., Li, H., & Wu, Y. (2020). Improvements of resolution of light field imaging based on four-dimensional optical framing via a semi-transparent mirror. Optics Express, 28(9).
[8] Shen, S., Yuan, Y., Ruan, Z., & Tan, H. (2018). Optimizing the design of an embedded grating polarizer for infrared polarization light field imaging. Results in Physics, 12, 21-31.