Design and analysis for a high-accuracy CCD*

WANG He-shun(王和顺)[1**], **ZHU Wei-bing**(朱维兵)[1], **WANG Qiang**(王强)[1], **and CHEN Ci-chang**(陈次昌)[2]

1. School of Mechanical Engineering and Automation, Xihua University, Chengdu 610039, China

2. School of Mechanical Engineering, Southwest Petroleum University, Chengdu 610500, China

(Received 29 October 2010)

In order to improve the test accuracy of CCD, a new type of CCD device is proposed. Several columns (rows) of photoelectric diodes (PDs) are combined together, and staggered with the distance of $H_1=H/N$, where H is the space between two adjacent PDs, and N is the number of columns (rows). The photoelectric signals are collected simultaneously by multi-channel A/D, and the accurate measurement result is obtained through appropriate signal processing. Without changing the size or space of PDs, more photographic pixels are arranged in the given direction within a finite length. Diameters of three standard poles are measured by a single CCD and two staggered CCDs, respectively with length of 30 mm and diameters of 5 mm, 8 mm and 12 mm, respectively. The results show that the accuracy of double staggered CCDs is two times of that of single CCD. The new type of CCDs can avoid the impact of PD space theoretically and higher measurement accuracy can be obtained.

Document code: A **Article ID:** 1673-1905(2011)03-0167-4

DOI 10.1007/s11801-011-0132-x

In recent years, CCD has been widely used in non-contact measurement and computer visual imaging. To enhance the measurement accuracy, the solution can be divided into two categories: (1) changing the CCD hardware structure[1-6]; (2) improving other parts of the measuring system and using the appropriate data processing method[7-10]. So far all of the methods have failed to break the impacts of the CCD pixel size and the pixel space, so it is difficult to make qualitative changes.

For a given CCD, its pixel size and pixel space are fixed, and the pixel space is one of the key factors affecting accuracy. This paper studies how to arrange more pixels in certain effective length and area without changing the manufacturing technique to improve the measurement accuracy of the CCD.

A dual-CCD was put forward in Ref.[2]. This imaging sensor can get twice PD numbers as the single CCD, and doesn't need smaller charge-transfer device (CTD). Ref.[3] put forward another dual-CCD structure that arrays two PD rows in an interlaced way, and it has twice PD numbers as the single CCD and doesn't need to manufacture small-size CTD. Compared with Ref.[2], larger PD can be used so as to ensure a high signal noise ratio and a wide dynamic range. Ref.[4] put forward a CCD that arrays many PD rows in an interlaced manner. The CCDs is arranged with higher density of PDs but unnecessary smaller CTD, and can modify the distortion in the process of charge transfer caused by the long length of the channel closely below the output gate. Fuji Company has introduced an image sensor called as super CCD. The PDs are arrayed with 45° in a honeycomb manner. This arrangement is compatible with the RGB three-color mode, and makes full use of the signal obtained by the adjacent PD. In data processing, though the number of PDs is unchanged, the pixel number after treatment is doubled. Super CCD has obvious advantages in digital color imaging, and has been widely used, but in high precision digital measurement it has no obvious advantages. A method to improve the CCD measurement accuracy by pixels interlacing is proposed in Refs.[1,6] (focused on linear measurement). The influence of pixel size and pixel space is avoided theoretically, and the measurement accuracy can be improved significantly.

On the basis of Refs.[1,6], a novel high-precision CCD is proposed in this paper. Under the existing technological condition (without smaller CCD pixels or pixel space), more CCD pixels in the certain direction are arranged, and higher accuracy is obtained.

At present, there are two kinds of CCDs, that is linear array CCD and area array CCD. A new type of area array CCD has been developed by Fuji Company recently, called as super CCD.

* This work has been supported by the National Natural Science Foundation of China (No.51005188), the Fund of Key Laboratory of Manufacturing and Automation of Xihua University (No.SZJJ2009-023), and the University Talent Foundation of Xihua University (No.R0720221).

** E-mail: wangheshun@sohu.com

Optoelectron. Lett. Vol.7 No.3

Fig.1 is the structure of linear array CCD pixels, and there are many pixels evenly distributed in a straight line. General linear CCD has thousands of pixels, such as the Toshiba TCD103C formed by 2673 pixels, and linear array CCD is used to measure the linear sizes of many objects, such as the diameter of the cigarette, gear parameters and so on. The linear array CCD is also widely used in digital products, such as scanners, digital cameras, copiers and others.

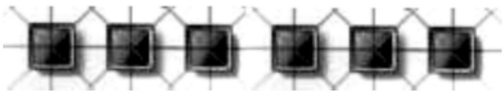

Fig.1 Structure of linear array CCD pixels

Fig.2 shows the pixel arrangement of the ordinary area array CCD, and all the pixels are distributed in matrix form and arranged evenly in rows and columns ultimately. Nowadays most area array CCD pixels have reached the millions, some even tens of millions. Because of the structural characteristic of area array CCD pixels, the area array CCD is widely used in digital cameras, medical devices, computer vision imaging system and other areas.

Fig.2 Structure of area array CCD pixels

The super CCD is actually a kind of area array CCD, which is put forward mainly to improve the resolution of digital products. The difference between super CCD and ordinary area array CCD is that two adjacent pixels are equidistantly staggered along the column (row) direction. There is no change in the total number of pixels compared with the general area array CCD, and wasn't affected a lot when dealing with black and white imaging. It is based on RGB color imaging, and the adjacent RGB three-color pixels are staggered. Each pixel can be combined into a colorful pixel point with 2 of the 6 adjacent pixels, thereby composing 6 image points, so every 3 adjacent pixels form a colorful pixel, and each pixel will be used for six times and the resolution of CCD can be doubled. For example, a 200 mega-pixel super CCD is theoretically equivalent to a 400 mega-pixel ordinary CCD. Theory and experiment have verified the super CCD design ideas and the effect is found to be significant. At present the super CCD has been used in digital cameras[4].

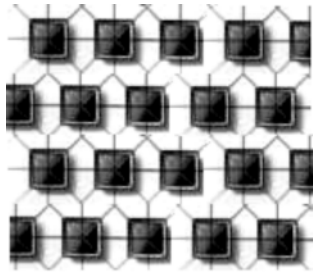

Fig.3 Structure of super CCD pixels

A new CCD device is brought up here based on the existing CCD pixel arrangement structure and the requirement in practice. It's mainly focused on high-accuracy measurement of linear dimension without the influence of CCD pixel size and pixel space, and greatly improving the accuracy theoretically.

Fig.4 shows the pixel arrangement of the new CCD, whose feature is that pixels in all columns (rows) of the area array CCD are equidistantly staggered to get a new arrangement structure without changing pixel space or pixel size of the same column (row). Fig.4 shows the situation of 6-pixel columns arranged in the staggered way along the vertical direction.

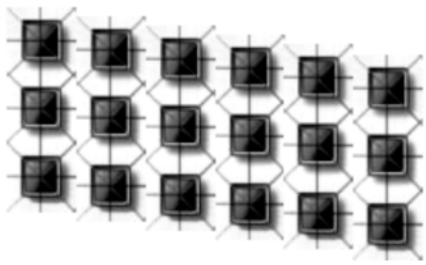

Fig.4 Structure of the new type CCD pixels

The new type of high-accuracy CCD is analyzed theoretically based on the measurement of linear dimensions.

Fig.5 is the schematic diagram of the new high-accuracy CCD (single side measurement). Pixel columns (rows) of the general area array CCD are uniformly staggered, and the distance between adjacent columns (rows) equals that between two adjacent pixel centers in the column (row) direction di-

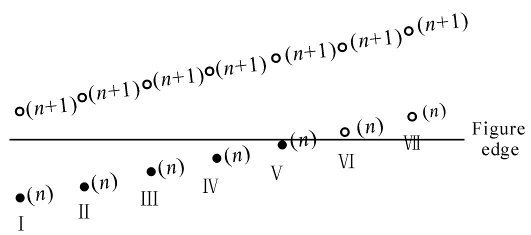

Fig.5 Principle of the new type CCD

vided by the number of columns (rows) of the CCD.

In Fig.5, the horizontal line represents the edge of the measured object, and the dots represent pixels of the CCD. The black dots represent unobvious sensitization while the hollow dots represent the opposite. The Roman numbers represent the column numbers of the CCD device. (n) and (n +1) are the pixel numbers of each column.

Firstly, column Ⅰ is analyzed. The edge of the measured object lies between the nth and (n +1)th pixels. It is hard to find the exact position between the two adjacent pixels in this column. Moving to the column Ⅱ, if the measured object edge just falls between the nth and (n +1)th pixels, continue to the next column, until both pixels are light-sensitized. Here is column Ⅵ.

Supposing that the measured value of the nth CCD pixel in column Ⅰ is a, the number of columns with pixels n and n +1 obviously photosensitive is m, the CCD pixel vertical space is H, the total number of CCD columns is N, and the measurement value is L, we can get

$$L= a + (H/N)(m-1) \quad , \tag{1}$$

$$\text{or } L= a + (H/N)(m-2) \quad . \tag{2}$$

If the edge lies exactly between the (n+1)th pixel of column Ⅰ and the nth pixel of the last column, there isn't a column with both pixels sensitized. Based on the special position of the measured subject, the following equation is obtained:

$$m = N+1 \quad . \tag{3}$$

Then the measurement value can still be calculated by Eq.(1) or (2).

Fig.6 shows the measurement process.

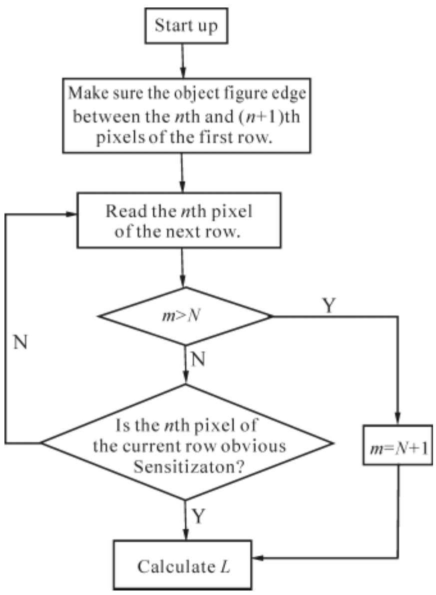

Fig.6 Flow chart of measurement

As there is no product at present, we conduct experiments to simulate the CCD by using multiple linear CCD staggered equidistantly along the linear length direction. Here a combination of two linear array CCDs is used.

Diameters of three standard poles are measured by a single CCD and two staggered CCDs respectively, with length of 30 mm and diameters of 5 mm, 8 mm and 12 mm respectively. During the double-CCD measurement, the microspindle with a resolution less than 1 μm is used to calibrate the two CCD staggered distance. The binary method and fuzzy image method are used in data processing, and the measurement results are shown in Tab.1. The pixel space is 14 μm, the image distance is 10 cm, the light fence diameter is 0.3 cm, and the white light with the imaging ratio of 1:1 is used. The diameters of three standard rods to be measured are within the precision of micron.

Tab.1 Experimental results

Measurement order	Single CCD (mm)		Double-CCD (mm)		Accurate value (mm)
	Binary method	Fuzzy image method	Binary method	Fuzzy image method	
1	4.998	5.003	4.998	5.000	5.000
	7.994	7.998	8.001	7.999	8.000
	11.998	12.003	11.998	12.000	12.000
2	4.998	5.002	4.998	5.000	5.000
	8.008	8.004	8.001	8.000	8.000
	11.998	12.001	11.998	12.001	12.000
3	5.012	5.003	4.998	5.000	5.000
	7.994	8.001	8.001	8.000	8.000
	12.012	12.002	11.998	12.000	12.000

Tab.1 shows that by using the binary method, the measured value always varies between both sides of the actual value. When measured by a single CCD, the maximum measurement error is a pixel space; when measured by double-CCD, the maximum measurement error is half of a pixel space. It can be concluded that by using N combined CCDs, the error of quadratic interpolation will be $1/N$ of the pixel space. And by using fuzzy image method, when measured with a single CCD, the measurement error is within 5 μm and when measured by double-CCD, the error is within 2−3 μm, very close to the actual value.

In the experiment, the whole measurement and data processing theory won't change if part of the linear array CCD is changed into columns of the new high-accuracy CCD.

When the total column (row) number of CCD pixels is N, the theoretical value of the maximum error is:

$$e = H / N \, , \tag{4}$$

where H is seen as a fixed value since it's mainly influenced by manufacturing process, and then e will depend on the number of the CCD pixel columns (rows) N. Subtract the error under condition of N columns (rows) by that with $N+1$ columns (rows):

$$e_s = H(\frac{1}{N} - \frac{1}{N+1}) \quad . \tag{5}$$

From Eqs.(4) and (5), we can see that the maximum error increases as N decreases, while the theoretical minimum error approximates to zero. The smaller the N is, the more obviously the error decreases as the pixel columns (rows) increase. So the measurement error can be reduced significantly when CCD pixel columns (rows) are increased by a small number, but when N is comparatively large, the impact on accuracy improvement will be slight.

In summary, we can get the following conclusions:

1) Limited by the level of technology, pixel size and pixel space of CCD cannot be made too small, which will largely affect the measurement accuracy of CCD.

2) A new CCD is proposed, which is characterized by N equidistant row (column) CCD pixels staggered by the distance of H / N. In theory, the measurement error will not exceed H / N, and thus a substantial increase in the CCD accuracy is got.

3) With the proposed high-accuracy CCD, it's unnecessary to reduce the size of the pixels or the distance between centers of adjacent pixels.

4) In application, it's favorable to adopt fewer rows (columns) of CCD pixels staggered equidistantly according to the accuracy requirement, so as to obtain the higher measuring accuracy without changing the single column (row) CCD structure.

References

[1] WANG He-shun, CHEN Ci-chang and HUANG Wei-gong, Journal of Optoelectronics • Laser **21**, 63 (2010). (in Chinese)

[2] Hirama Masahide, Watanabe Yasuomi and Koike Seiichi, IEEE Transactions on Consumer Electronics **36**, 473 (1990).

[3] Kuno Yoshinori, Matsushita Tadashi and Higuchi Takayoshi, IEEE Transactions on Consumer Electronics **41**, 436 (1995).

[4] Mutoh Nobuhiko, Morimoto Michihiro and Nishimura Miyo, IEEE Transactions on Electron Devices **38**, 1048 (1991).

[5] DAI Jing-min, LIU Ying and YU Tian-he, Journal of Optoelectronics • Laser **19**, 1507 (2008). (in Chinese)

[6] WANG He-shun, CHEN Ci-chang and HUANG Wei-gong, Acta Optica Sinica **25**, 1148 (2005). (in Chinese)

[7] WANG He-shun and CHEN Hua, Journal of Sichuan University **33**, 63 (2001). (in Chinese)

[8] GONG Hua-ping, LU Zhi-wei and LIN Dian-yang, Journal of Optoelectronics • Laser **18**, 125 (2007). (in Chinese)

[9] WANG Qing-You, Image Sensor Application Technology, Beijing: Publishing House of Electronics Industry, 1 (2003). (in Chinese)

[10] WANG He-shun, CHEN Ci-chang and HUANG Wei-gong, Optical Technique **35**, 402 (2009). (in Chinese)