Focal Plane Image Assembly of Subpixel

ZHONG Sidong MEI Tiancan SHI Zhongchao

1 Introduction

The measure system with CCD receiver has high demand on view field, resolution and in real time. The present CCD camera can not meet all above requirements simultaneously. While the single chip CCD meets the needs of speed, its total number of pixels is less than 107, and hard to reach high accuracy. On the other hand when it has enough number of pixels to meet the needs of accuracy, it runs into the problem of time lag. The assembly technique of CCD is an effective way to solve the problem. In the early 1980’s, the air force of United States has completed focal plane assembly of line array of CCD. Then assemblies of CCD develop from line array to area array[1]. The Chinese researcher has performed relevant study, finishing CCD assembly from 2 chips to 4, 10 chips[2,3,4]. The assembly error is less than 1. 5 μm. All the research work has overcome the difficulty to meet the practical needs of large view field, high resolution and real-time to some extent. However, at present, the assembly error is limited to about 1/5 pixel. How to improve the assembly accuracy to a high level is what this paper concerned.

2 Hardware system

The hardware system is composed of optical lens, CCD image sensor, x, y direction guide track, step motor and position measure system on both direction (x and y). When the system starts to run, the lens keeps still while the work stage can move in x, y direction. The slip board of guide track was driven by step motor with screw transmission. Then CCD is driven to the instructed position. The position accuracy is guaranteed by displacement sensor. The whole system is open loop control sys-
Table 1 Major Function Parameters

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Image device                     | 1/2 interline transfer CCD  |
| Image area                       | 2.94 mm × 6.45 mm          |
| Picture elements                 | 795(H) × 596(V)            |
| Resolution                       | 600 TV Line horizontal     |
| Electronic shutter               | 1/125-1/10000 sec         |
| Gain                             | AGC on/off                 |
| Vertical frequency               | 50 Hz                      |
| S/N ratio                        | Better than 48 dB          |
| Maximum responsive frequency     | 750 kHz                    |
| Step equivalent                  | 0.2 μm                     |
| Displacement                     |                            |
| Linear range                     | ± 20 mm                    |
| Linearity                        | 0.05                       |

Fig. 1 Control process

3 Principle of assembly and accuracy judging

Before the system completes the assembly process, we first perform assembly error correction. The calibration is completed in two steps. The first step is rough assembly, it is to control the assembly error in x, y direction less than 1/2 pixel. Although the displacement sensor of x, y direction can have this resolution, but the sensor can not detect the assembly error resulted from guide track linear error and vertical error between x, y direction. The second step is accurate assembly process. That is to precisely measuring the residual error after rough assembly. This is done through the moiré pattern generated from CCD moiré effect. Since the residual error is detected, we can adjust the number of steps of step motor to correct the residual error and record the data of displacement sensor at each assembly position. So far, the process of assembly is finished. The reason we limit the rough assembly error smaller than 1/2 pixel is to prevent the assembly process from making one pixel assembly error.

3.1 Rough assembly and judging

The whole target is separated into four areas (Fig. 2(a)), named 1, 2, 3, 4 related to the four imaging areas in the CCD assembly process. We set area 1 as reference and adjust the position of CCD according to the large receiver until the assembly error is small enough. We take areas 1 and 2 as example to explain how to adjust the error. When the error is not corrected the result is shown in Fig. 2(b). It indicates that CCD assembly has errors in x, y direction. At first we adjust the assembly error in y direction to make strips on the whole image align in y direction (Fig. 2(c)). At this time, CCD assembly error in y direction is small enough to meet the need of rough assembly. There still remains assembly error in x direction, we adjust the position of CCD until the image after assembly is as Fig. 2(d). In the same way, we set areas 2 and 3 as reference respectively to perform the CCD assembly of area 2-3 and area 3-4.

When the image after adjustment is as Fig. 2(d), we regard that the rough assembly error in x, y direction is controlled in 1/2 pixel.
3.2 Accurate assembly and judging

Since the assembly error is less than 1/2 pixel after rough assembly, it is hard to further improve the assembly accuracy with traditional precise measure instrument. In order to improve the assembly accuracy to a high level, we introduce the CCD moiré effect into the process of judging assembly error and take a new method - digital correlation filtering to locate the position of moiré fringe of CCD.

According to Reference [5], we know that expression of the light intensity of moiré fringe and displacement of CCD is

\[
I(x, y) = a\beta_0 + 2I_0 \sum_{n=1}^{\infty} A_n B_n H_n \cdot \left\{2\pi n \left[ (x\alpha_1 + y\nu_1) - x\alpha_2 \cos\theta_1 \right] \right\} \tag{1}
\]

The expression indicates that it represents the fundamental component when the factor \( n \) equals to 1, and that it represents the harmonic component when \( n \) equals to other value. In this expression, \( a, \beta \) is the space factor of main and slave grating, respectively; \( A_n, B_n \) is Fourier factor; \( \nu_1 \) is the spatial frequency of photosensitive cell; \( \nu_x, \nu_y \) is component of the spatial frequency of CCD light responsive function (\( x \) represents horizontal direction, \( y \) represents vertical direction); \( \theta_1 \) is the angle between the vertical grating of CCD and \( y \) axis; \( \theta_2 \) is the angle between the Ronchi grating and \( y \) axis.

The moiré effect of CCD generates vertical fringe when \( \theta_1 = \theta_2 = 0; \nu_1 = \cos\theta_1 (c \epsilon positive fraction) \). The moiré effect of CCD generates horizontal fringe when \( \theta_1 = \theta_2 = (1/2)\theta_1; \nu_1 = \cos2\theta_1 (c \epsilon 1, 2, 3\ldots) \). The moiré effect of CCD generates slope fringe when \( \theta_1\neq\theta_2; \nu_1 = \cos2\theta_1 (c \epsilon positive fraction) \).

In the accurate assembly process, the target is a Ronchi grating. We can obtain moiré fringe of different behavior by adjusting the position and object distance of Ronchi grating. Then we can determine the assembly error by making a correlating operation between the moiré fringe light intensity at both sides of assembly boundary.

In the signal detection, the correlation function of \( x(t) \) and \( y(t) \) is defined as follows:

\[
y_{xy}(\tau) = \sum_{n=-\infty}^{\infty} x(n)y(n-\tau) \tag{2}
\]

It can be used to measure the similarity between two signals. It is said that two signals are similar except they have different initial phase, which is caused by time delay or space offset, the time delay or space offset between the two signals can be obtained through the correlation processing. When they are identical to each other, the maximum correlation value is acquired when \( \tau \) equals to zero. When they just have different phases, the maximum correlation value is acquired when \( \tau \) equals to the offset between the two signals.

In the CCD assembly process, the moiré fringe signals on each side of assembly boundary have the same cycle, frequency and different phases. The different phases are caused by the assembly error (the offset between the two assembly areas). Then the maximum correlation value is acquired when \( \tau \) equals to the offset between the signals. Thus the offset (assembly error) can be obtained through the correlation operation. The graph of the correlation function is shown in Fig 3.

The steps to get the assembly error are as follows:

1) Make the digitalization of moiré fringe signal \( z(n) \) at the assembly boundary of CCD at area 1 and conduct self-correlation; record the position \( (n_0) \) of the center of main peak.
2) Make the digitalization of moiré signal at the assembly boundary of CCD at area 2, conduct cross correlation of \( x(n) \) and \( y(n) \) and obtain the position \( (n'0) \) of the maximum value of cross correlation.

The assembly area 1 and area 2 are shown in Fig. 4.

By expression:
\[
\delta y = n'0 - n0
\]  
we can determine the assembly error in \( y \) direction, in this way we can also determine the assembly error in \( x \) direction.

As for general condition, when both directions have assembly error, we determine the assembly error by the following steps:

1) Determine the assembly error (\( \delta y \)) in \( y \) direction with vertical moiré fringe following the method mentioned above.

2) Determine the displacement (\( \delta z \)) of slope moiré fringe at the position of assembly boundary with the same method. The displacement of slope moiré fringe is caused by the assembly error in both directions. Then we can use formula
\[
\delta x = \sqrt{\delta z^2 - \delta y^2}
\] to calculate the assembly error in \( x \) direction. Finally, we record the data of assembly position after accurate adjustment with displacement sensor.

4 Experiments

According to the assemble method mentioned above, an experimental CCD assembly system is designed. In the assembly process, the first step is to perform the rough assembly, and the second step is to perform precise assembly. The process of precise assembly is in the following steps:

1) Get CCD moiré fringe signals (Fig. 5, Fig. 6). Determine the assembly error of assembly area 1-2. When the error is obtained, area 1 is set as datum to adjust the assembly area 2 until the error is small enough.

2) Determine the assembly error of assembly area 2-3, and then area 2 is set as datum to adjust the assembly area 3 with the assembly error between them.

3) Determine the assembly error of assembly area 1-4, and then area 1 is set as datum to adjust the assembly area 4 with the assembly error between them.

After the adjustment is finished, the final assembly errors are obtained and shown in Table 2. The data shows the relative assembly error of the area 1-2, 2-3, 3-4, 1-4. Some among them are zero in Table 2. This is because the error obtained through
the correlation filter is less than one unit. In the experiment, the width of Moiré fringe is about 50 pixels, so one unit represents 1/50 pixel. When assembly error is less than 1/50, the error is too small to be worth considering. The arrangement of assembly area is shown in Fig. 5. The data in Table 2 also shows that the assembly error of area 1-2, 2-3, 1-4 is relatively small; nevertheless the error of area 3-4 is relatively big. Through the assembly process, it can be explained and it represents the residual assembly error. Since the error is obtained, it can be compensated in practical CCD assembly. Fig. 7 is the assembly result of a real picture.

| Table 2 Errors of assembly |
|----------------------------|
|                           |
| \( x \) direction \( y \) direction |           |
| 1-2                       | 0         |
| 2-3                       | 0         |
| 3-4                       | -0.88     |
| 1-4                       | 0.02      |

Fig. 7 A picture after assembly

5 Conclusion

The assembly technique of CCD is an effective way to solve the problem of large view field and high resolution of observatory measuring. Through the analysis of present assembly technique of CCD, this paper raises a new technique of assembly to overcome the shortcoming of current CCD assembly: focal plane scanning assembly technique. Similar to the human vision, this technique can obtain and process the part of a large view field we concern in real time. And we introduce the CCD moiré effect into appraising the assembly accuracy. The experiment results show that the position accuracy of the assembly system is less than 1/20 pixel when we adopt error compensation.

References

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