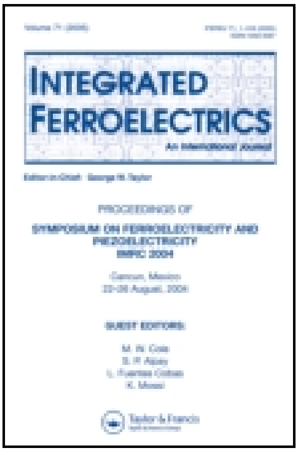

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Yan-Chun Li [a], Ji-Hong Dong [a], Wei Li [a], Quan-Feng Guo [a], Ke-Jun Wang [a], Hai-Ping Wang [a] & Wei-Guo Zhao [a]
[a] Changchun Institute of Optics, Fine Mechanics and Physic Chinese Academy of Sciences, Changchun, Jilin, 130033, China
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YAN-CHUN LI,* JI-HONG DONG, WEI LI, QUAN-FENG GUO, KE-JUN WANG, HAI-PING WANG, AND WEI-GUO ZHAO

Changchun Institute of Optics, Fine Mechanics and Physic Chinese Academy of Sciences, Changchun, Jilin 130033, China

The focal plane assembly is one of the most important components of Space camera, whose splicing accuracy the camera imaging quality. Through the analysis of CCD's splicing methods, the focal plane of space camera was staggered lap compact mechanical design, carried out high-precision splicing and testing. While splicing the image processing technology is used to CCD's pixel labeling's quantization processing. The ultimate purpose is to eliminate possible errors which due to human visual impact on the stitching accuracy and improve stitching accuracy based on the focal plane's character. The results show that the focal plane of CCD chip overlap error is less than 3 μm, the two rows of CCD in the parallel error is less than 3 μm, the coplanar error is less than 5 μm. Finally, according to the analysis of the image obtained from the imaging test on the ground, the camera image stitching results were coincided with the test results, which proved that the method is feasible and accurate. All the results show that the splicing and testing of the FPA for TDI CCD is achieved high-precision.

Keywords Focal plane assembly (FPA); TDI CCD; high-precision splicing; testing; image processing technology

1. Introduction

With the development of space remote sensing technology, especially with the rapid development of optical technology and electronics technology, the capabilities of space optical remote sensor is developed from low-resolution, single-spectrum, narrow coverage to high-resolution, multi-imaging spectral bands, wide coverage, real-time direction of transmission [1, 2]. In order to meet the needs of the imaging, those CCD (Charge Coupled Devices) with single-spectrum, low-pixel are gradually replaced by the CCD with multispectral and high-pixels. At present, the number of single-chip CCD pixel is preponderate over 10,000, still can not meet the requirements of high resolution and wide occupancy rate in the field of modern aerospace [3]. Subject to the limitations of the technical level and technological level, unrestrictedly increasing the single-chip CCD imaging pixel is very difficult [4]. In this case, the CCD-splicing techniques were emerged, and have been widely applied in optical remote reconnaissance system [5]. At present, high-precision splicing techniques were used in most of the remote sensing cameras in orbit. Therefore, the high-precision splicing and testing of the CCD is especially important.

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*Corresponding author. E-mail: feilong99031@yahoo.com.cn; feilong99031@163.com

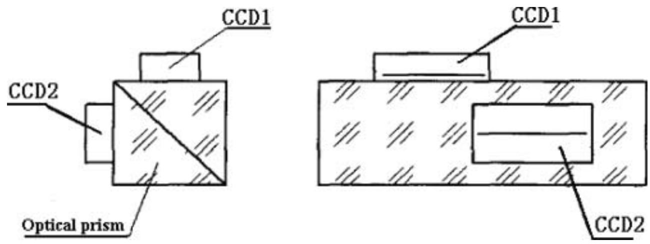

Figure 1. Optical splice schematic.

In this paper, a variety of splicing of the CCD were analyzed, finally the mechanical staggered lap stitching design of a space camera's focal plane was selected, high-precision splicing and testing were done. Based on the results, we did error analysis and experimental tests.

2. CCD Splicing Methods

CCD splicing is connected the multi-chip CCD imaging end to end, to form an equivalent field of view CCD detector in order to meet the requirements of the width of the camera field of view coverage. CCD splicing methods are concluded mechanical splicing, optical splicing machinery staggered stitching (also known as the electronics splice) etc [6, 7].

Traditional mechanical splicing is connected a CCD device in the mechanical from head to end, making them along the same line. This approach requires all CCD inclusive pixel must be valid .It prone to produce lapped joints in practice. The stitching accuracy is extremely difficult to ensure. In view of the above three reasons only some of the professional manufacturers or research units use this method [8].

The prism light effect is used in the Optical splice. The imagine plane was splitted into the spatial separation of a light-way equal to the conjugate surface, and CCD staggered distribution of this aplanatic conjugate surface, and each adjacent two CCD

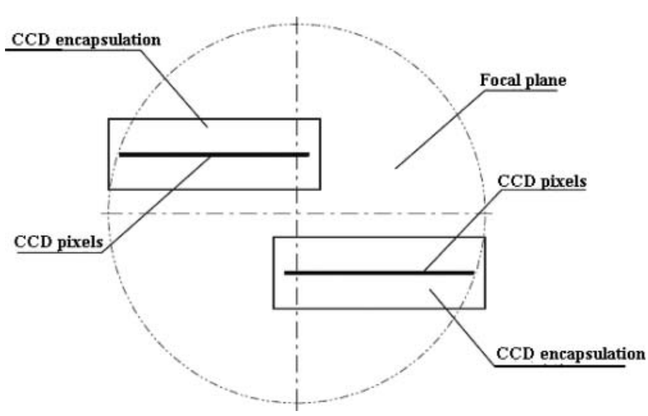

Figure 2. Mechanical interlaced splicing schematic.

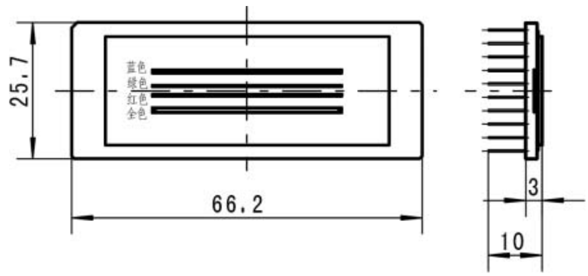

Figure 3. TDI CCD shape structure diagram.

inclusive pixel overlap to form a wide field of view like a square space, optical splicing schematic diagram shown in Fig. [6, 7]. Optical splicing prism has two types, the semi-anti-semi- permeably and the All through the reverse type prism. Anti-full through the prism can make use of the energy fully, but a rigorous relative position of the CCD and the prism is needed, and most of the CCD pixel are influence by the vignetting, so that the signal to noise ratio decreased; the semi-anti-semi- permeably prism is easy to assemble, but limited by the lower energy utilization rate, only widely used in the early optical systems. However, due to the optical splicing has chromatic aberration , not suitable for total reflection system, and general splice length is not easy to exceed 220 mm. All above led to limiting the splicing method's using in the remote sensor on the large field of view [9].

Mechanical staggered splicing is to assembly the CCD by dual row staggered focal plane forms, that is to say, the second line of the CCD in the same plane, just to fill up the gap formed by the first line of the CCD, the first adjacent CCD pixels aligned or overlapping a certain distance, in the remote sensor on the flight direction of two lines of CCD stagger a certain position.

By integrating the delay wide large field of image processing, the image processing of mechanical staggered splicing has made use of electronics docking methods. This method not only can produce a clear, simple structure of the splicing, but also does not produce chromatic aberration. Therefore it can meet the requirements of large field of view, in the

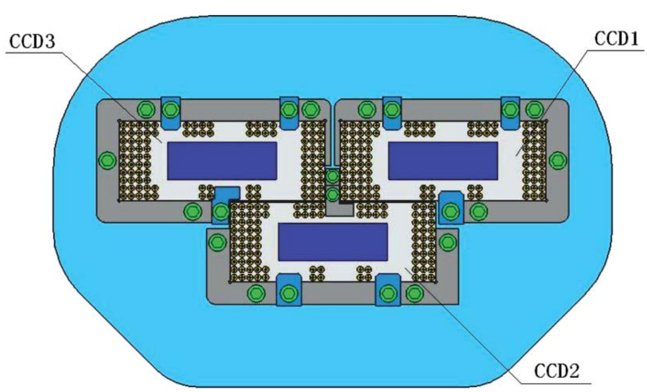

Figure 4. Layout of the focal plane assembly structure. (Figure available in color online)

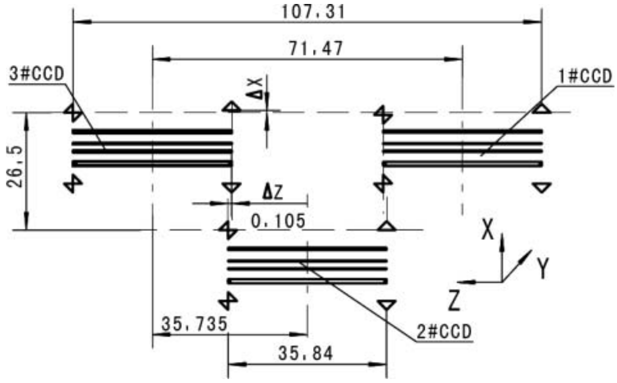

Figure 5. Measurement of the FPA.

large field of view it has been widely used in space optical remote sensor. Mechanical interleaving the splice principle is as shown in Fig. 2.

3. Splicing and Testing of the FPA

According to the actual situation of the optical designing, through the comprehensive analysis of the varieties of splicing characteristics, we choose the method of mechanical staggered joint to mosaic the focal plane.

3.1 Design of the FPA

The focal plane assembly is consist of three TDI CCD. Each CCD is fixed in the focal plane on the substrate of the long strip by the way of mechanical staggered joint, whose three-dimensional structure as shown in fig. 3. According to the requirements of space

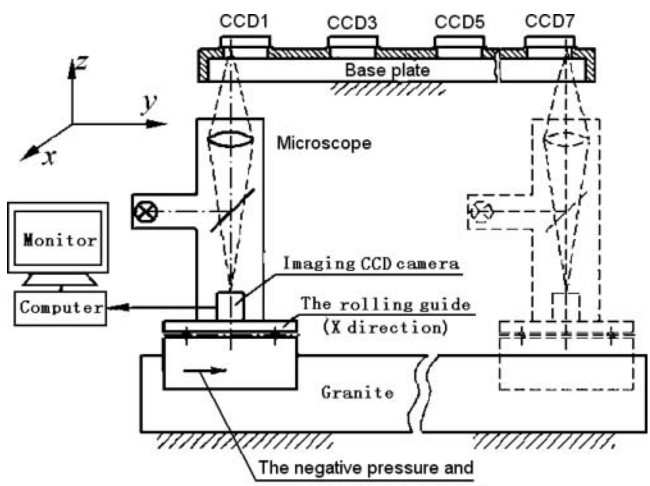

Figure 6. Sketch of TDI CCD measuring instrument.

optical remote sensor to remote sensing images, combined with the optical design of the actual situation, the TDI CCD pixel that has full color for more than 4096 spectra has been chosen eventually. The selected CCD full-color pixel's size is 8.75 μm $\times$ 8.75 μm, single-line has 4096 pixels. The size of the color pixel is 35 μm $\times$ 35 μm, each single line has 1024 pixels. The outline dimensions of CCD as shown in Fig. 3.

According to the optical designing specifications, the focal plane assembly is consist of three pieces of TDI CCD through the way of staggered joint. That is to say, the three pieces of TDI CCD is fixed in the focal plane of the substrate by the way of staggered joint, as shown in Figure 4.

In order to ensure the structural stability of the components of the FPA, the CCD pedestal is designed, and the CCD is fixed on the CCD pedestal at the same time, both of them as a whole structure involved in splicing. Namely, CCD high-precision testing is achieved by adjusting the CCD pedestal's position in the process of splicing. At the same time, the material's reasonable selection of substrate of the focal plane and CCD pedestal is done. It can promise the focal plane components meet the requirements of splicing accuracy under certain temperature.

Having completed the designing, the designed focal plane assembly's system stability has been validated by analyzing the finite element modal and uniform and calculating the even rising temperature. Structure display, the first natural frequency of the system is larger than 200 Hz, higher than the frequency of the outside, which proved that it has the ability of anti-vibration, shock and overload. The analysis of the even temperature rise is showed that when the temperature rise of the FPA changes between at room temperature (20°) $\pm$ 30°, the changes in the lap of the components of the FPA and coplanar less than $\pm$ 1.5 um, all meet the requirements.

3.2 Splicing of the FPA

Having combined with the advantages and disadvantages of the several splicing methods and the actual spatial distribution and the mechanical characteristics of the FPA and the image processing technology, we spliced the FPA.

3.2.1 Splicing Accuracy Requirements. As shown in Fig. 5, the CCD splicing precision requirements are as follows:

a) The lapping accuracy requirements ($\triangle$Z): Overlapping 12 pixels, and the tolerance is $\pm$ 0.005 mm. That is to say the lap length is 0.105 mm $\pm$ 0.005 mm;
b) The requirements of the linearity and parallelism (Z direction): the first line of the CCD marks must be along the same line, the non-linear error ($\triangle$X) is less than $\pm$ 2 μm; The second line of the CCD marks and the first line of the CCD marks must be parallel, the distance is 40 mm, the non- parallelism to the error is less than $\pm$ 2 μm;
c) Coplanar requirements (Y direction): 3 CCD pixel tag must be on the same focal plane, and the non-coplanar error is less than $\pm$ 5μm.

3.2.2 Splicing of the FPA. CCD splicing is to ensure the relative position among each CCD. When splicing, one piece of the CCD should be as the base, adjust the other six pieces of CCD to this one's relative position relationship, so as to reach the splicing index requirements. CCD stitching must be done on the special splicing apparatus. The splicing apparatus we developed is composed of the following components: high-powered display

Table 1
Non-linear error data of checking results

	Pixel mark 1				Pixel mark 2			
Number	First	Second	Third	Average	First	Second	Third	Average
CCD1	0	0	0	0	0.5	0.5	0.5	0.5
CCD3	0.5	0.5	0	0.33	0	−0.5	0	−0.16
CCD2	−0.5	0	0.5	0	0.5	0.5	1	0.67

of long focal length lens, coaxial optical illumination system, CCD cameras, monitors, computers and high-precision two-dimensional mobile platforms and so on. The schematic is shown in fig. 6. [10]

At first, the substrate of the focal plane was fixed together with the splice tooling, both of them were fixed on the corresponding position of the splicing apparatus. Then leveling the focal plane substrate, so that the relative error of the splicing benchmark in the focal plane on the substrate is no more than 0.001 mm. Three CCD components were assembled to the corresponding position of the focal plane substrate in turn. After that adjusting each CCD substrate's position to ensure error of the overlap between the various CCD is no more than ± 0.005 mm.Then each CCD component were fixed to the adjust position of the focal plane substrate using the torque wrench. Just now we have completed the Pre-splicing. After that the coplanar splicing was done.

In the process of coplanar splicing, in order to eliminate the reading error by the human eyes and maintain the consistency of test results, we used the imaging processing technology to obtain the testing data in the direction of the focal depth. Having obtained the data of depth for focus values from the position of the four corners of each CCD pixel mark, the data that measured depths of three CCD focus was inputted special software. Through the special software, a CCD mosaic surface was fitted bench mark parallel to the surface closest to the plane of the CCD imaging surface, the data of the 3 CCD block grinding pad corner should be scratched was calculated in order to repair to the amount. Then by grinding corresponding grinding pad, we make them to achieve the computing requirements. After that each CCD component was re-stitched to adjust the substrate of the focal plane. First of all we must ensure that the overlap accuracy was less than ± 0.005 mm. If the error is within ± 2 um, did retest the focal depth of each pixel point tag. Otherwise, according to the testing data, scratching the CCD grinding pad again to make it meet the requirements.

Table 2
Splicing length error data of checking results

	Splicing length			
Number	First	Second	Third	Average
CCD1-CCD2	100.5	100	101	100.5
CCD2-CCD3	101	102	101	101.33
Error	−0.5	−2	0	−0.83

Table 3
Error analysis of measuring instrument

Number	Error types	X direction (um)	Y direction (um)	Z direction (um)
1	Straightness error	0.5	0.5	0.5
2	Guide plane error	1	1	1
3	Substrate flatness error	0.5	0.5	1
4	Substrate alignment error of the FPA	0.5	0.5	1
5	Microscope alignment limit error	0.2	0.2	0.2
6	Display resolution error	0.1	0.1	0.1
7	Electric reticle scale error	0.2	0.2	0.2
8	Grating positioning error	0.5	1	0.5
9	Microscope focusing error	0.2	0.2	1
10	Total system error	1.53	1.76	2.14

After scratched twice, the coplanar error of measured numerical value was within ± 0.75 um

After completion of the coplanar splicing, did the parallel and straight stitching. By fine-tuning the position of each CCD components, we make it meet the following requirements: a) the lap length between 1 # CCD and 2 # CCD is 0.105 mm ± 0.001 mm, 2 # CCD # CCD lap length is 0.105 mm ± 0.001 mm; b) The pixel marks of 1 # CCD and 3 # CCD panchromatic imaging area side must be on the same line, their unfair line error is no more than ± 0.001 mm; c) The second line of the CCD marks and the first line of the CCD marks must be parallel ,the distance is 40 mm, none- parallel to the error is less than ± 2 μm.

4. Precision of Detection and Analysis of the PFA

After the splicing is completed, in order to eliminate the stress of assembly between the structures of the FPA and make the FPA in a stress-free steady state, we did the vibration mechanics experiments and atmospheric high and low temperature experiments on the PFA. This stress relieving way can avoid the precision change of FPA due to the slow release of the assembly stresses and can increase the image quality in space.

After the splicing is completed, we tested the stitching precision of the FPA on the special stitching instrument. In the process of testing, we maintain the FPA and splicing instrument's fixed mode consistency with the splicing, to eliminate the error caused by changes in the technical state. The test results were given in Table 1 and 2.

According to the above testing results, the actual detection precisions of splicing of the FPA are as follows. a) Odd linear limit of error is no more than 1 um; b) Parallel error is no more than 1.5 um; c) Overlap length limit of error is no more than 2 um; d) Coplanarity error is no more than 2.3 um.

Figure 7. Photo of image testing.

5. Errors Analysis and Verification

In the process of detection, it is inevitable that there will be a variety of factors led to the detection errors. The analysis of the system errors of detection device is shown in Table 3. Among them, the errors of guide line tolerance, the rail flatness and the focal plane substrate datum are shape error, which can be measured directly. The focal plane mosaic benchmark height error, the focal plane of the substrate and two-dimensional adjustment of the position error are error-free system, which can be controlled and measured through the alignment. The remaining errors are the constant errors of the stitching instrument system, and the size of those errors numerical value should be calculated [10].

The different direction errors in the form were done by the formula of $\Delta H = \sqrt{\sum_{i=1}^{9} \Delta H_i^2}$, Among them, ΔH_i substituted the error of the system in each directions for Δx_i, Δy_i, Δz_i. Thus, we can calculate the systematic errors of the TDI CCD device in each detection. When the errors were synthesized, we get the total splicing errors as follows: a) Odd linear limit error is no more than 1.83 um; b) Parallel error is no more than1.5 um; c) Coplanarity error is no more than 3.14 um.

Since then, a series of environmental testing were done, including vibration testing, impact testing, and thermal vacuum testing. After each experiment, the accuracy of the surface components of the splicing was re-examined, and the error change is no more than 1um. Subsequently, the FPA was involved in the whole assembly. An outdoor photo-quality image testing to the moon was done, the test data is consistent with the images of the moon. It proved the validity of the mode of this spicing and testing once again. The photo of image testing is given in Fig. 7.

6. Conclusions

Based on the comparative analysis of CCD's various splicing methods, the method of mechanical staggered joint was chosen to design of stitching the focal plane assembly of some space camera, high-precision splicing and testing were carried out at the same time. We did the splicing testing based on the specific requirements for an engineering model of the FPA. Through using the image analysis techniques, we got a substantial increase in the splicing precision. The testing results showed that, the CCD between the overlap errors is less than 3 μm, two rows of the CCD parallel error is less than 3 μm, and coplanarity error is less than 5 μm. All this meet the imaging requirements of space remote sensing. It proved that the splicing and testing's methods are feasibility and precision. High-precision splicing and testing of the FPA for TDI CCD is achieved.

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