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Optical Butting of Plane Array Sensors for PA-LiDAR

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ABSTRACT In order to expand the field of view and improve the resolution, a method of optical butting was proposed for two plane array sensors using beam splitter prism in this paper. The principle of optical butting, the optical design, calibration and focusing technology, and alignment method were presented and analyzed. In addition, the gray image stitch and point cloud data registration were also realized. To prove the concept of the optical butting method, we built a prototype system for experiment. The splicing of two 320×240 sensors of plane array laser imaging detection and ranging (PA-LiDAR) was implemented. After optical butting, the total effective pixel number was 320×480, the total effective area was 6.4×4.8mm, and the field of view was $22^{\circ} \times 15^{\circ}$. Compared with the conventional laser radar system, the optical butting system can improve the field of view and resolution by a factor about 2×1. This method had the advantages of simple constitution, easy accomplishment, small space and high assembly precision which guaranteed the operating requirement of the PA-LIDAR sensor.

INDEX TERMS Laser radar, radar imaging, optical sensors, optical design, optical butting.

I. INTRODUCTION

In recent years, with the improvement of key devices and manufacturing technology, plane array laser imaging detection and ranging (PA-LiDAR), also named staring imaging lidar based on plane array detector has been developed rapidly. As a new active imaging method which can obtain three dimensional image of target instantaneously, it has many advantages such as high measurement accuracy, abundant information, good parallel real-time, low power consumption and small system volume, so it has become the main research direction of imaging laser radar [1]–[6]. The PA-LiDAR controls the emission of laser to form an illumination surface covering the whole target scene. The reflected echo is received by the array detector. The ranging is realized by measuring the time of flight (TOF) or modulation and demodulation, and finally the three-dimensional information of the target is obtained. The plane array detector is a kind of matrix sensor, which integrates a large number of independent pixels. Each pixel has complex structure, including modulation control unit, timing circuit, A/D (Analog/Digital) conversion unit, and data processing unit, which can measure both the flight time and the amplitude signal [7]–[13]. As the key component of the PA-LiDAR, the characteristic parameters of the plane array detector directly determine its FOV (field of view) and resolution.

In order to further improve the performance, expand the FOV of the optical system and improve the measurement resolution of PA-LiDAR, it is necessary to reduce the pixel size and increase the number of pixels. However, the process of large size or high resolution sensors is difficult to manufacture, has long manufacture cycle and high cost due to the restriction of semiconductor technology and technics. More importantly, it is difficult to balance the contradiction between sensor size and measuring distance. To cover these gaps, we extended the sensor's capabilities through the method of the optical butting. Many researchers have proposed various solutions, which can be divided into two categories: mechanical butting and optical butting. Mechanical butting is to arrange multiple sensors closely together to form a sensor array with large sensitive surface. The main advantage of this method is that it can achieve a larger sensor array, but it is impossible to achieve seamless splicing in any case. The main advantage of this stitching method is that it can achieve a large sensor array, but it is impossible to achieve seamless stitching in any case, and it becomes a blind area when imaging. This method needs complex circuit structure and auxiliary mechanism, and the cost is high. The basic principle of optical splicing is to use optical elements to divide the field of view of the optical system into several

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TABLE 1. Evaluation of several typical optical butting methods.

Butting method		Descriptions
Multi-system butting		The main feature of multi-system stitching is that the whole system is composed of several complete sub imaging systems, which include lens and corresponding sensors. The structure is redundant and loose, and there are parallax and dead zone in imaging.
Secondary imaging butting		Secondary imaging butting is composed of multiple imaging systems, including a main system and multiple secondary systems. The main system is used to image large scenes on the imaging surface, and then the secondary system is used to segment. The secondary system will cause aberrations, and the imaging quality is general.
Optical-path-splitting butting.	Refraction-type optical butting	A parallel plate is placed in different field of view, so that the deflection angle of light in different field of view is different. There are aberrations and the ability of field segmentation is limited.
	Reflection-type optical butting	Different sub fields of view are mapped to different planes by reflectors, and there is vignetting near the area of field of view segmentation.
	Semi-transparent and semi-reflective prism butting	The splitting prism is used to divide the beam into two uniform image planes. This method is simple, reliable and has no vignetting. The effective pixels of adjacent sensors can be overlapped completely without gap.

parts, and place a sensor on the imaging surface of these sub fields to receive the images of these sub fields. The image planes of these sub fields of view are either separated from each other by a certain distance or in different planes, so the sensors will not conflict with each other, and all the pixels of the whole image plane will fall on the sensitive surface of the sensor. The sub images received by these sensors are spliced together to achieve the purpose of large field of view imaging. Optical butting is divided into multi-system butting, secondary imaging butting and optical-path-splitting butting. Table 1 describes the characteristics of various butting methods. In this paper, we mainly discussed the butting method of optical-path-splitting.

Optical-path-splitting butting method was widely used in linear array or strip satellite cameras. In general, the field of view of the optical system was divided into conjugate planes with equal optical paths by using a transparent-reflective prism. The linear array was placed alternately on these two conjugate surfaces, and the coverage of the whole linear array was extended. Fairchild company adopted this method to splice six (1024×64) TDI CCD into 6144 long linear CCD. This method was also applied in EFI camera, CBERS CCD camera, Pleiades camera and MLA camera [14]–[16]. In the application of area array CCD, Jain *et al.* put forward the concept of optical butting. They used the method of twice splitting by a transparent-reflective prism to realize the optical splicing of four area array CCD [17]. In order to realize megapixel HDTV, Kaneko proposed an optical butting method which uses a pyramid mirror to divide the field of view of the optical system into four parts [18]. The field of view of these four parts was reflected on different planes, each part wad equipped with a corresponding image sensor, and the four sub images were combined to form a complete large image. Rubin *et al.* also proposed a similar method, but the prism structure is more complex, which can divide the field of view of the optical system into 12 parts [19].

In this paper, we proposed an optical butting system of plane array sensors for PA-LiDAR for the first time. In the system, the transparent-reflective prism was used as the beam splitting element to realize the splicing of two plane array sensors of PA-LiDAR. This paper mainly discussed the optical butting principle, optical designs, structure design and data registration of sensors for PA-LiDAR, and proposed the results of two sensors butting prototype system. After optical butting, the total effective pixel number was 320×480, the total effective area was 6.4×4.8mm, and the field of view was $22\,^{\circ} \times 15\,^{\circ}$. Compared with the conventional laser radar system, the optical butting system can improve the field of view and resolution by a factor about 2×1. In Section 2, the basic theory of optical butting was introduced in detail, including model construction, lens design, calibration method and focusing technology. In Section 3, the experimental device, the results of gray image registration and point cloud depth data registration were proposed. Conclusions were present in section 4.

II. DESCRIPTION OF TECHNIQUE

A. WORKING PRINCIPLES OF PA-LiDAR SENSOR

In this PA-LiDAR system, CMOS-type built-in optical mixer is used, which is a kind of matrix depth sensor based on indirect Time-of-Flight (I-TOF) principle. Indirect time-of-flight method, also known as phase time-of-flight method, is a mature scheme of three-dimensional imaging. It has the advantages of moderate detection distance, good accuracy, low power consumption, high system integration and low cost. As shown in Figure 1, as the key device of the PA-LiDAR, the plane array sensor can realize the functions of ranging and imaging at the same time. TOF sensors measure the time it takes laser to travel a distance through a medium. Typically, this is the measurement of the time or phase delay between the emission of a wave pulse, which its reflection off of an object, and its return to the sensor. More to the point, the field of view and resolution of imaging function often depend on the performance of sensors. The size of a single pixel of the sensor chip determines its maximum resolution accuracy in two-dimensional distribution measurement, which also restricts the improvement of measurement accuracy to a certain extent. Certainly, smaller pixel size or more pixel numbers can be used to achieve higher resolution, but this is often limited by many other factors and the current

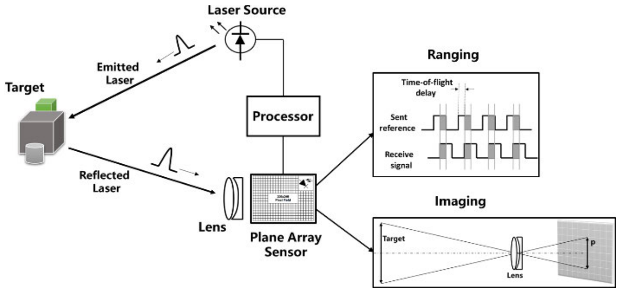

FIGURE 1. Operating principle of PA-LiDAR sensor.

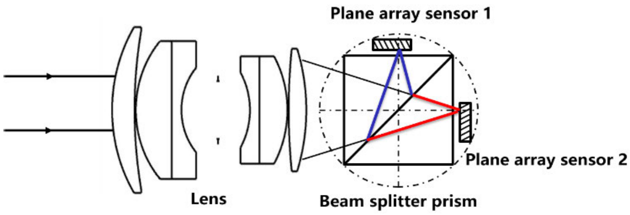

FIGURE 2. Schematic diagram of the optical butting system.

technology cannot meet this requirement. If we can further expand the ability of the sensors, that is, the use of multiple sensors together, then the indicators of FOV and resolution will have a qualitative leap.

In order to solve the above gaps, the optical butting technology used splitting prism was applied to PA-LiDAR for the first time, which can make the seamless butting of two plane array sensors, and the imaging range of the clear field of view increased by one time.

B. BUTTING PRINCIPLE AND SYSTEM CONSTRUCTION

The basic concept of optical butting system is to separate the field of view of the imaging system into two parts by using a beam splitter prism. Because of the method of beam splitting, we can not only splice the pixel in any position of the sensor according to the need, but also the illumination of all pixels after butting is uniform without vignetting. The beam splitter prism is placed between the lens and the focal plane, but close to the focal plane. The optical image is divided into two image parts by the prism. Two image sensors are located in the mapped focal plane to receive those image parts. Figure 2 shows the systematic configuration of the optical butting system.

Because the beam splitter prism is an important device to realize the optical butting, there are certain requirements for the material, angle tolerance and splitting ratio of. The beam splitter prism in our system is composed of two 45° right angle prisms. The cementing surface is coated with 50% reflection and 50% transmission neutral film.

Depth sensor with a single pixel size of 0.02mm and an area of 1/2 inches (6.4mm∗4.8mm) was used in the experiment. This sensor is ESPROS epc660 series, with a resolution of 320×240 pixels. There are two kinds of splicing functions: 640 × 240 pixels or 320 × 480 pixels. In contrast, the two edge length of 320 × 480 is closer, the image plane size is

TABLE 2. Optical butting lens design parameter.

Parameters	Index
Sensor size	9.6mm∗6.4mm
Focal length	25mm
F- Number	2
FOV (H∗V∗D)	14.59°∗21.74°∗25.99°
Wavelength	400-700nm, 850nm
Total system length	≤ 60mm
Distortion	<3%
Relative illumination	Edge relative illuminance>30%,
Working distance	0.2m-∞
MTF@50lp/mm	≥ 0.6.
Working temperature	−20°C∼70°C

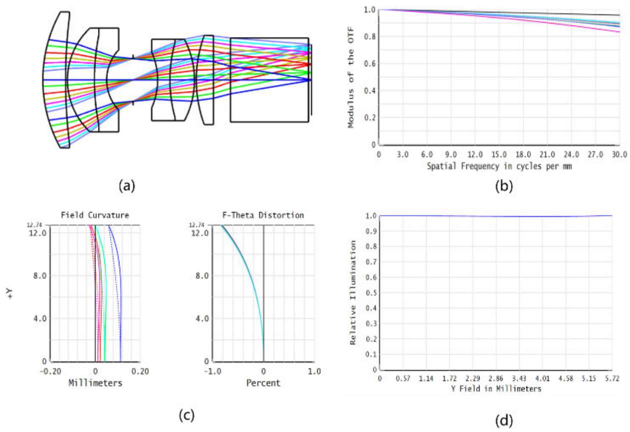

FIGURE 3. (a) Structure of imaging optical system (b) MTF analytical diagram (c) Field curvature and distortion (d) Relative illumination curve.

smaller, and the edge of sensor is closer to the central field of view of lens after optical butting, so this function is selected.

After selecting the splicing function, the parameters of lens for optical butting should be designed. Two points should be considered in the determination of lens parameters. One is to establish a suitable lens structure according to the optical beam path, prism parameters and sensor parameters. The other is to propose the appropriate lens resolution according to the size of the butted sensors. The design parameters of optical butting system are shown in Table 2.

The structure of the optimized optical system is shown in Figure 3(a). Figure 3(b) shows the relative illuminance of the optical system. It can be seen that the relative illumination is greater than 80% when the half image height is 5.72. Figure 3(c) shows the field curve and distortion of the optical system. It can be seen that the system distortion is less than 1%. Figure 3(d) shows that the MTF of all fields of view is greater than 0.5 at the spatial frequency of 30lp / mm, which meets the performance requirements. The main parameters of optical butting lens are listed in Table 3.

C. CALIBRATION AND FOCUS FIXING

After the design of optical path and lens, it is necessary to calibrate the optical system consist of lens and beam

TABLE 3. Main parameters of optical butting lens.

Parameters	Value
Focal length	26mm
F- Number	1.98
Total system length	43.76mm
Distortion	$<$1%
Relative illuminance	$>$90%
MTF	@50lp/mm $\geq$ 0.6 @25lp/mm $\geq$ 0.8

splitter prism. The process of calibration is to establish the geometric model of the imaging system and express it in mathematical forms. The parameters of the imaging geometric model are solved, including the internal optical parameters (internal parameters), such as focal length, optical center coordinates, etc. The parameters of the imaging geometric model are solved, including the internal optical parameters (internal parameters), such as focal length, optical center coordinates, etc. It also includes the position data of the system relative to the world coordinate system, also known as the external parameter, which describes the coordinate position and attitude data of the camera in the world coordinate system. The calibration results are used to obtain the internal and external parameter matrix of the system, and the pixel coordinates are converted to physical coordinates, and then the corresponding calculation is carried out.

There are many algorithms to estimate the system response function. We adopt the method introduced by Zhang *et al.* [20] The proposed procedure consists of a closed-form solution, followed by a nonlinear refinement based on the maximum likelihood criterion. See Eq. (1) for parameter matrix equation:

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \frac{1}{Z}\begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{Z}KP \tag{1}$$

where K is the parameter matrix, $P(X, Y, Z)$ is the coordinate of the actual object in the observation coordinate system, f_x and f_y are the focal length in the x-axis and y-axis directions respectively, and c_x and c_y are the coordinates of the main point in the image plane. Mathematically, the distortion can be expressed by polynomial function. K_1, K_2 and K_3 describe radial distortion, p_1 and p_2 describe tangential distortion.

$$\begin{cases} x_d = x\left(1+k_1r^2+k_2r^4+k_3r^6\right)+2p_1xy+p_2\left(r^2+2x^2\right) \\ y_d = y\left(1+k_1r^2+k_2r^4+k_3r^6\right)+p_1\left(r^2+2y^2\right)+2p_2xy \end{cases} \tag{2}$$

where (x, y) is the coordinate point before distortion, (x,y) is the coordinate point after distortion, and R is the distance from the image center. The distortion parameters are suitable for both gray and depth images.

In optical butting system, it is necessary to ensure that each sensor focuses accurately at the same time, that is to say, four image sensors must be on the same imaging conjugate surface. In order to achieve this goal, we used auto-focus technology. Specifically, the focus evaluation function was used to describe the whole focusing process, so as to find the best focus position. What we used was Laplacian gradient function. In each sub image, a small area in the four corners and the center of the image is selected, and the definition evaluation algorithm is used to evaluate the image definition of these five regions. By continuously adjusting the position of the lens, the relationship between the definition evaluation value and the focusing position is obtained. The lens is fixed and the sensor is adjusted so that the evaluation value of image clarity of these five regions is within a threshold range of the maximum value. The first two steps are performed for each image sensor. When all five areas of each image are focused accurately, each sensor can be considered to be in focus accurately.

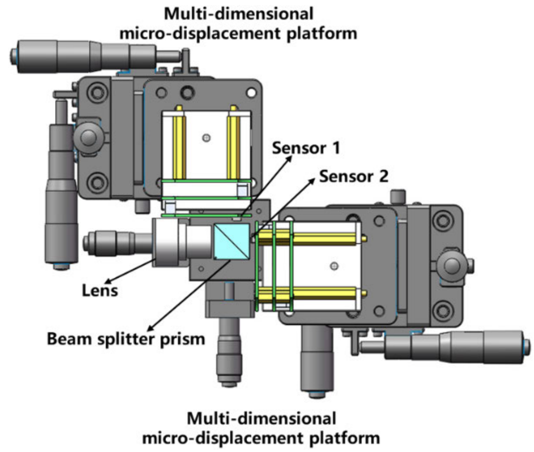

FIGURE 4. Schematic diagram of optical splicing device.

III. EXPERIMENT AND DISCUSSION

A. ADJUSTMENT DEVICE

The optical butting system consists of lens, beam splitter prism, two plane array sensors, precise adjusting mechanism and circuit boards. The structure is shown in the Figure 4. In order to ensure the image quality of sub images, we use a micro adjusting frame based on thread adjustment to control the tilt, defocus and overlap area of sub image plane.

The technical requirements of optical butting are mainly the requirements of spatial relative position of each device and irradiance, as shown in Table 4.

B. DATA REGISTRATION

In the optical stitching system, after obtaining the data of two area array lidar sensors respectively, the most important step is to combine these data to form a complete result. Gray image registration is a pixel based image registration algorithm proposed by Lucas [21]. A result after gray image stitching process is shown in Figure 5.

For the PA-LiDAR, the more practical value is the three-dimensional information, that is, the point cloud data, so we registered the point cloud obtained by the optical splicing system. The most classical ICP (Iterative closest

TABLE 4. Requirements for optical butting.

Requirements	Descriptions
Pixel overlap	For sensor splicing by prism method, the coplanar error after optical butting shall not be greater than 0.02mm, and the overlapping pixels shall not be greater than 10 lines.
Straightness	Pixels in the same column of sensor1 and sensor2 must be on the same line.
Coplanarity	Each sensor is required to be on the imaging surface of the optical system, that is to say, all sensors must be in the focal depth range of the optical system.
Vignetting and distortion	There is no distortion and vignetting in each field of view.
Uniform illumination	The illumination of each imaging surface is uniform

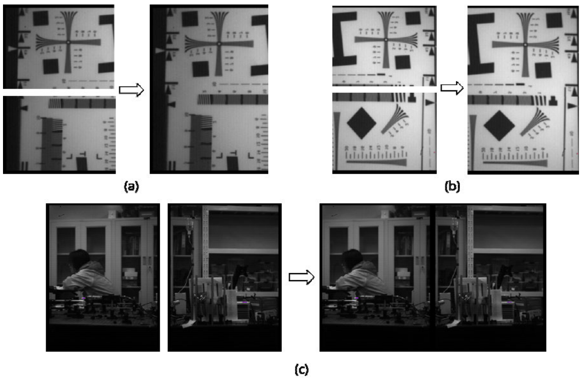

FIGURE 5. The results of gray image registration.

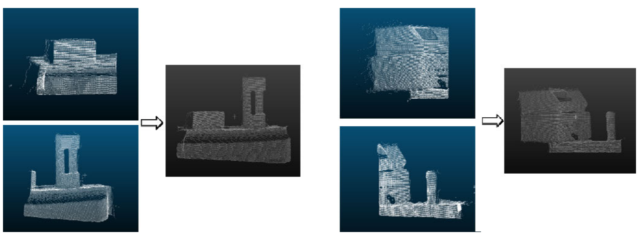

FIGURE 6. Registration results of point cloud.

point) algorithm was adopted [22]. ICP algorithm is essentially an optimal registration method based on least square method. The algorithm repeats the process of selecting the corresponding point pairs to calculate the optimal rigid body transformation until the convergence accuracy requirements of correct registration are met. The main purpose is to find the parameters of rotation and translation. One of the point clouds in two different coordinate systems is taken as the global coordinate system. After the other point cloud is rotated and translated, the overlapped part of the two sets of point clouds completely overlaps Figure 6 shows the registration results of two sets of point cloud data. In the experiment, the number of iterations was 20, the threshold of RMS difference was 0.00001, and the theoretical overlap was 100%. The registration result showed that the RMS difference value is 0.00065

TABLE 5. Spatial coordinates of point cloud registration results.

Point Number	Sensor1 coordinate (x, y, z)(mm)	Optical butting system coordinate (x, y, z)	Sensor2 coordinate (x, y, z)	Optical butting system coordinate (x, y, z)
1	(75.9, 33.7, 2000.7)	(75.3, 33.3,2000.7)	(78.7, 61.3, 2123.7)	(78.7, 64.7, 2123.7)
2	(59.8, 22.4, 1801.5)	(59.5, 23.1, 1801.5)	(162.8, 99.1,1910.6)	(165.5, 99.1,1910.6)
3	(71.4, 42.3, 1710.3)	(71.1, 42.3, 1710.3)	(39.3, 180.2, 1821.2)	(39.3, 180.2, 1821.2)
4	(196.2, 158.6,1788.1)	(196.2, 158.6,1788.1)	(67.9, 87.7, 1887.4)	(67.9, 87.7, 1887.4)

(38999 points are calculated), and the overlap degree is 85%. Table 5 shows the (x, y, z) spatial coordinates of a group of selected point cloud registration results, that is, three-dimensional information. On the basis of each PA-LiDAR sensor realizing the ranging and imaging functions respectively, the optical butting system can effectively combine them to improve the performance.

IV. CONCLUSION

Optical butting is a solution to extending the FOV and resolution of optical system whose are limited by the parameter of the sensor. It is done by dividing the optical image into several parts and then compositing them to form a large image. In this paper, combining with the characteristics of PA-LiDAR and the structure of sensors, a prism beam splitting method was proposed for optical butting. On the basis of theoretical analysis, experiments were carried out to realize the butting of two plane array sensors with the field of view of $22^\circ \times 15^\circ$. Compared with the single-chip sensor system, the field of view of clear imaging will be doubled. The experimental results showed that the optical butting system can realize seamless splicing without vignetting and moving parts for large field of view. The optical butting method is a possible approach to extend the FOV of imaging systems who's FOV are limited by the resolution (format size) of the sensor. Moreover, the method is not affected by the size and type of sensor, so it can be developed synchronously with the improvement of sensor technology. It can be used for reference in the research and practice of other laser radar sensors.

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