Research Article

Vision Servo Motion Control and Error Analysis of a Coplanar XXY Stage for Image Alignment Motion

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In recent years, as there is demand for smart mobile phones with touch panels, the alignment/compensation system of alignment stage with vision servo control has also increased. Due to the fact that the traditional stacked-type $XY\theta$ stage has cumulative errors of assembly and it is heavy, it has been gradually replaced by the coplanar stage characterized by three actuators on the same plane with three degrees of freedom. The simplest image alignment mode uses two cameras as the equipments for feedback control, and the work piece is placed on the working stage. The work piece is usually engraved/marked. After the cameras capture images and when the position of the mark in the camera is obtained by image processing, the mark can be moved to the designated position in the camera by moving the stage and using alignment algorithm. This study used a coplanar XXY stage with $1\mu\text{m}$ positioning resolution. Due to the fact that the resolution of the camera is about $3.75\mu\text{m}$ per pixel, thus a subpixel technology is used, and the linear and angular alignment repeatability of the alignment system can achieve $1\mu\text{m}$ and 5 arcsec, respectively. The visual servo motion control for alignment motion is completed within 1 second using the coplanar XXY stage.

1. Introduction

Visual servo control with digital image processing for optical image alignment has been applied in many processes in recent years, such as MEMS, biochip, semiconductor, LED, LCD, and the popular touch panel. A basic alignment system contains two charge coupled device (CCD) cameras and a high-precision positioning/compensation stage. Kuo et al. presented a precision nanoalignment system using machine vision [1]. The alignment system used a stacked type of compensation stage, which is driven by piezoelectric ceramic motors. The system uses a circle to be the alignment mark and single camera to capture the image. The proposed system can compensate x and y axes' errors and the positional error can be in the range of 60 nm. For an image alignment system, another key point is the recognition of the mark. If the recognition of the mark is insufficient, there may be a misrecognition that influences the alignment quality, and the common mark is cross mark. It may be imagined that if the

mark is a circle, it is likely to be confused with the solder joint in the detection of PCB; if the mark is a straight line, the line of PCB may be misrecognized as the mark. Lin et al. develops a subpixel image matching method CPTRPT [2]. The results show that the translation and rotation mean errors are about 0.03 pixels and 0.1 pixels. Although, the proposed method shows good accuracy, the average run time is 20.5 ms which causes the method to be difficult to be applied on high-speed/real-time alignment. Lee et al. proposed a real time critical dimension measurement of TFT-LCD pattern [3]. The developed system can be used in the TFT-LCD manufacturing and repeatability is less than 30 nm. Pattern searching time is about 12 ms (for $XY\theta$, one time search). The study also proposes an edge detection method, which is simpler than Canny [4]. Huang and Lin used a camera and a stacked XY stage for alignment of XY direction in 2009 [5]. Cross symbol was used as the mark, and the alignment error in steady state was less than $1\mu\text{m}$. In the study, the alignment of $XY\theta$ direction can be finished using

FIGURE 1: Basic structure of coplanar XXY stage.

single camera; however the angular alignment accuracy was worse than two cameras alignment system due to low angular resolution.

The alignment was carried out by stacked XYθ stage in the past. However, the stacked stage usually has cumulative errors, such as flatness error, parallelism error, and orthogonally error between axes. These errors influence the alignment accuracy as the stacked stage has heavy weight and high gravitational center (compared with coplanar stage). If the acceleration and deceleration of alignment process are too large, it is likely to exceed the stroke because of the inertia (it can be regarded as an inverted pendulum system). In order to solve the above problems, the coplanar XYθ stage has been widely used in recent years. Using the piezoelectric actuators to construct the coplanar type of stage can be presented in many papers and they showed good positioning accuracy [6–9]. However, for manufacture industrial application like touch panel lamination, a piezoelectric based stage is too expensive and they do not need such an ultrahigh accuracy compensating stage. Yim et al. [10] proposed that a high precision stage for $370 \cdot 470 \text{ mm}^2$ size UV-NIL was modeled as flexible bodies. Both translational and rotational control for misalignment correction were performed using machine vision. Furthermore, each vertical motion of the three and four axis stages was analyzed and compared to each other. In this paper, a coplanar stage as shown in Figure 1 was used to implement visual servo motion control for alignment motion. The kinematic and error analysis were studied and the servo control and image processing were successfully integrated for precision visual servo control.

2. Design of a Coplanar XXY Stage

The coplanar XXY stage (following called XXY stage) is characterized by three actuators on the same plane, so that the gravity center is low. In other words, the moving speed of coplanar XXY stage can be faster than the stacked XYθ stage, and it is small and light. The main advantage of coplanar XXY stage is being smaller cumulative error of stage composition than the traditional stack-type stage.

2.1. Stage Composition. As shown in Figure 1, the XXY stage consists of four major components.

- (1) Base: the basic base fixes the XXY stage, the parallelism, and flatness verifying reference plane after system assembly.
- (2) Motors: the XXY stage is driven by three stepper motors which are installed on the same plane. The axial direction of Motor 1 and Motor 2 is parallel to the X-direction of the stage; Motor 3 is under the working stage (not displayed in the figure). The axial direction of Motor 3 is parallel to the Y-direction of the stage.
- (3) XYθ substage: XYθ substage consists of two small cross roller stages and small rotary stage to have three degrees of motion. The coplanar XXY stage consists of four small XYθ substages under the working platform. The main purpose of XYθ substage is to support and to provide constraint conditions for the movement of the XXY stage. In the XXY stage, three motors are connected to three adjacent XYθ substages by three ball screws, respectively, so each XYθ substage drives in only one direction (i.e. the others are free moving). There is a XYθ substage in the XXY stage unconnected to any actuator; the XYθ substage is called free body in this paper. This kind of component mechanism makes the working platform only with three degrees of motion.
- (4) Working stage: the stage carries work pieces or processed goods. Although each XYθ substage has cumulative error, when the four XYθ substages are combined with the stage, only the overall accuracy of the working stage should be considered, suggesting that the accuracy of XXY stage is free from the cumulative error of XYθ substage. Only the positioning repeatability of each XYθ substage is required to meet requirements during the stage verification.

2.2. Kinematic of Coplanar Stage. The XXY stage has three-dimensional motion, X, Y, and θ_z as shown in Figure 2. If the linear displacement of stage is represented as $\vec{s} = [\delta_x \ \delta_y]^T$ (unit: mm) and angular displacement of the stage is represented as δ_θ (unit: radius), the displacement of motors is $\vec{m} = [m_1 \ m_2 \ m_3]^T$ (unit: pulse); the basic linearized relation between the stage displacement and the motor displacement is

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \frac{R_m}{\ell_p} \begin{bmatrix} 1 & 0 & k_a \\ 1 & 0 & k_b \\ 0 & 1 & k_c \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_\theta \end{bmatrix}, \quad (1)$$

where R_m is the motor resolution (unit: pulse/rev); ℓ_p is the lead of the ball screw (unit: mm/rev); k_a , k_b , and k_c are the parameters for angle rotation. k_a , k_b , and k_c are related to the distance between the stage center and the XXY stage center connected to the coordinate systems of $\{m_1\}$, $\{m_2\}$, and $\{m_3\}$. For high precision motion control, the kinematic formula must take into account the center deviation of the XXY stage during the motion. If the position vectors between the stage

FIGURE 2: Three-dimensional motion, X, Y, and θ_z : (a) X motion; (b) Y motion; (c) θ_z motion.

FIGURE 3: Coordinate definition of kinematic analysis of XXY stage.

center and i th $XY\theta$ substages center is $\vec{r}_i = [r_{ix} \ r_{iy}]^T$, $i = 1, 2, 3$, and 4, shown in Figure 3, we have

$$m_i = \vec{t}_i (-\vec{r}_i + \vec{s} + \vec{r}_i'), \quad (2)$$

$$\vec{r}_i' = \mathbf{R} \cdot \vec{r}_i, \quad (3)$$

$$\mathbf{R} = \begin{bmatrix} \cos \delta_\theta & -\sin \delta_\theta \\ \sin \delta_\theta & \cos \delta_\theta \end{bmatrix}, \quad (4)$$

where $\vec{t}_1$ and $\vec{t}_2$ both are $[R_m/\ell_p \ 0]$ and $\vec{t}_3$ is $[0 \ R_m/\ell_p]$. After linearization of (2), (3), and (4), the parameters of (1) are $k_a = -r_{1y}$, $k_b = -r_{2y}$, and $k_c = r_{3x}$.

2.3. Error Analysis. The XXY stage consists of four $XY\theta$ substages. The setup errors are usually contained when XXY stage is assembled. The setup errors include three straightness errors and three angular errors. As shown in Figure 4, the designed position of the $XY\theta$ substage which is linked with motor 1 is m_1 . However, the actual position of the $XY\theta$ substage is in the position of m_{e1} due to setup error. Let the vector of setup error is $\vec{e}_1 = [e_x \ e_y \ e_z]^T$; we have

$$\vec{r}_{e1} = \vec{r}_1 + \vec{e}_1. \quad (5)$$

According to (2), (3), and (5), we can write

$$\vec{p}_i = \mathbf{R}_{pi} [\mathbf{R}_{err} (-\vec{r}_i - \vec{e} + \vec{s} + \mathbf{R} \cdot \vec{r}_i)], \quad (6)$$

where

$$\mathbf{R}_{err} = \begin{bmatrix} \cos \beta \cos \gamma & \cos \gamma \sin \alpha \sin \beta - \cos \alpha \sin \gamma & \cos \alpha \cos \gamma \sin \beta + \sin \alpha \sin \gamma \\ \cos \beta \sin \gamma & \cos \alpha \cos \gamma + \sin \alpha \sin \beta \sin \gamma & \cos \alpha \sin \beta \sin \gamma - \cos \gamma \sin \alpha \\ -\sin \beta & \cos \beta \sin \alpha & \cos \alpha \cos \beta \end{bmatrix}, \quad (7)$$

$$\mathbf{R}_{pi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}. \quad (8)$$

Note that (7) shows the matrix of the angular setup errors of α , β , and γ . In order to expand the displacement vector $\vec{s}$ and distance vector $\vec{r}_i$ to three dimension space, we redefined both as $\vec{s} = [\delta_x \ \delta_y \ 0]^T$ and $\vec{r}_i = [r_{ix} \ r_{iy} \ 0]^T$. Positioning error caused from setup error can be estimated according to sensitivity as in the following equation:

$$\varepsilon(v) = \frac{\partial f_{err}}{\partial v}, \quad (9)$$

where f_{err} is the kinematic equation with setup error and v is the setup error source. The positioning error due to stage

FIGURE 4: Setup error of the XXY stage.

setup error can be estimated by the following equation:

$$E(v) = \varepsilon(v) \times \tau(v), \quad (10)$$

where $\tau(v)$ represents the evaluation value of the estimated error source. To resolve (6), the positioning error estimation result as shown in Table 1. In this estimation, we let $\vec{r}_1 = [-56 \ -74 \ 0]^T$, $\vec{r}_2 = [-56 \ 74 \ 0]^T$, $\vec{r}_3 = [56 \ 74 \ 0]^T$, $\vec{r}_4 = [56 \ -74 \ 0]^T$, $\vec{s} = [2 \ 2 \ 0]^T$, and $\delta_\theta = 2^\circ$. According to (2), we can get that the displacements from $\vec{s} = [0 \ 0 \ 0]$ and $\delta_\theta = 0^\circ$ to the desired position of each $XY\theta$ stage are $\vec{p}_1 = [3.617 \ -0.909]^T$, $\vec{p}_2 = [-1.548 \ -0.999]^T$, and $\vec{p}_3 = [-1.617 \ 2.909]^T$. The estimation results also showed that the setup error sources of e_{x1} , e_{x2} , e_{y3} , e_{z1} , α_i , and β_i do not obviously influence the positioning accuracy. Note that the setup error sources of e_{z1} , α_i , and β_i are related to the parallelism of the base board and the working board. The estimated error trend is as shown in Figure 5.

3. Image Vision Alignment

3.1. Image Alignment. The basic concept of image alignment is shown in Figure 6. The main purpose is to eliminate the spacing distance between the mark and the camera target position, assumed to be $\vec{e}_1 = [x_1 \ y_1]^T$ and $\vec{e}_2 = [x_2 \ y_2]^T$. In an ideal state, the distance D_p between two camera target positions is identical with the distance D_c between two marks. The alignment equation can be derived from Figure 7. Thus, the alignment equation can be obtained similar to (2) to (4) as follows:

$$\begin{aligned} m_i &= \vec{t}_i \left(-\vec{r}_{ai} + \vec{s} + \mathbf{R} \cdot \vec{r}_{ai} \right), \\ \vec{r}_{ai} &= \vec{r}_i - \vec{v} - \vec{s}, \end{aligned} \quad (11)$$

where $\vec{v}$ is the distance vector from $\{O\}$ to the camera target position. As shown, when the XXY stage is used as the alignment stage, the procedure of image alignment is very simple. It is unnecessary to use the stage center as reference point for alignment anymore but to use the position of mark center as the reference point to calculate the displacement of stage. This method is the floating reference point method.

TABLE 1: Estimated glass position error when the camera setup error is existed. (unit: mm, degrees).

v	$\tau(v)$	Estimated error		
		E_x	E_y	E_θ
m_1				
e_x	± 1	0	0	0
e_y	± 1	∓ 0.017	± 0.013	∓ 0.013
e_z	± 1	0	0	0
α	± 1	0	0	0
β	± 1	0	0	0
γ	± 1	∓ 2.608	± 1.973	± 2.020
m_2	± 1			
e_x	± 1	0	0	0°
e_y	± 1	∓ 0.018	∓ 0.013	± 0.014
e_z	± 1	0	0	0
α	± 1	0	0	0
β	± 1	0	0	0
γ	± 1	0	∓ 0.02	∓ 0.02
m_3	± 1			
e_x	± 1	0	± 0.035	0
e_y	± 1	0	0	0
e_z	± 1	0	0	0
α	± 1	0	0	0
β	± 1	0	0	0
γ	± 1	0	∓ 0.029	0

3.2. Floating Reference Point. Besides the above advantage in alignment, the location mode of floating reference point has its advantage in the replacement of production line. As shown in Figure 8(a), when the traditional fixed stage reference point is used, the work piece center of the next production line should be put on the stage reference point before the production line is changed. In other words, more products represent more replacements. If there is error between the center of work piece and the relative position of stage reference point, the processing quality will be influenced. If the floating center is used, as shown in Figure 8(b), the production line can be changed by keeping to the side; only one replacement is enough for the work pieces in different sizes. As the floating reference point technology can set any position as the reference point, even if there is large offset between the work piece and the center of XXY stage, the alignment function of the stage will not be influenced.

3.3. Mark Recognition. For the image alignment, besides the alignment stage and alignment algorithm, another key point is the mark recognition capability. If the mark recognition is not stable and robust enough, alignment accuracy will decline. In practical application, the changes in external environment and the accuracy of mark recognition are considered. Figure 9 shows different cases: 001 to 004 are general cases, 005 is underexposure, 006 to 009 are overexposure, 0010 to 0013 are incomplete mark, 0014 represents the image without mark, 0015 represents a half of mark out of picture, and 0016 and 0019 represent the photo with noise

(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 5: Positioning error estimation results: (a) ex_3 ; (b) ey_1 ; (c) ey_2 ; (d) γ_1 ; (e) γ_2 ; (f) γ_3 .

FIGURE 6: Basic concept of image alignment.

FIGURE 7: Conceptual graph of analysis of image alignment.

images. The above phenomena are probable cases, which have discussed in many studies. Generally, the pattern image must be clear enough, complete, and small orientation angle for high precision alignment. The image processing procedure in this study is described below: during image processing, the actual image (Figure 10(a)) and pattern image (Figure 10(b)) are binarized. The captured image is binarized as shown in Figure 10(c), and then the binary image is smoothed and morphologically processed to obtain a cleaner binary image as shown in Figure 10(d). The binarized image is compared with the pattern image. If they match, the region of interest (ROI) is set, and then the ROI image is subtracted from the pattern image (Figure 10(e)).

Let the image to be searched be denoted by I , the pattern image denoted by T , and the matched score denoted by R . The matched score is evaluated by the following equation:

$$R(x, y) = \sum_x \sum_y [T(x', y') - I(x + x', y + y')]^2. \quad (12)$$

The method above is called square difference matching method. For the case of perfect match, R is zero; otherwise,

R is large when bad matches. If the number of R is smaller than the preset threshold, the sample matching is completed (Figure 10(f)). In order to fasten the mark recognition speed, the image pyramid is used in this study. The original image is denoted by I_0 and the pattern image is denoted by T_0 . The first level image pyramid of original image and pattern image are denoted by I_1 and T_1 , respectively, and the second level are denoted by I_2 and T_2 . The width and height of I_1 and T_1 are half of T_0 and I_0 . The image size of I_2 and T_2 are quadrant of I_0 and T_0 . Thus, the mark recognition time of I_2 is 16 times faster than I_0 . Let the searched mark position be (x_2, y_2) . However, the position is not real mark position on the original image. So, we do mark recognition for I_1 . Now, we do not need to search full image this time. We set a range of interesting (ROI), which is a rectangle area, and the mark recognition is done in the ROI. The ROI starts from the point of $(2x_2 - 0.5W_{T_1} - 1, 2y_2 - 0.5H_{T_1} - 1)$ to the point of $(2x_2 + 0.5W_{T_1} + 1, 2y_2 + 0.5H_{T_1} + 1)$, where W_{T_1} and H_{T_1} are the width and height of T_1 , which means that the area of second mark recognition remains 3×3 . If the position of the second mark recognition is (x_1, y_1) , similarly, we set a ROI for I_0 . The left-top point of the ROI is $(2x_1 - 0.5W_{T_0} - 1, 2y_1 - 0.5H_{T_0} - 1)$ and the width and height of the ROI is $W_{T_0} + 1$ and $H_{T_0} + 1$, respectively. Here, the area of mark recognition for T_0 is still 3×3 . After mark recognition, the mark position (x_0, y_0) can be determined. Image pyramid not only makes the image small but also makes the image large. If we do the procedure above one time, when the processed image size now is the double of the original image, we can get the mark position (x'_1, y'_1) . To transfer the mark position to the original, the mark position is $(0.5x'_1, 0.5y'_1)$. In other words, when we large the image N times by image pyramid method; the mark recognition resolution can be increased N times to achieve subpixel resolution. However, large N makes long mark recognition time.

4. System Verification

In this paper, the coplanar XXY stage for system verification is produced by Chiu Yan Technology. The motion control card is NI PCI-7390. The industrial camera is Basler ace1300-30 gm equipped with 1X low distortion telecentric lens. The optical resolution is about $3.75 \mu\text{m}$; the field of view (F.O.V) is $9.6 \text{ mm} \times 7.2 \text{ mm}$. The image is processed by OpenCV. The stage is measured by Keyence GT2-H12K. When the optical system is in alignment, the resolution of optical system is increased by four times by using subpixel; namely, the subpixel processed image resolution is less than $1 \mu\text{m}$, theoretically.

4.1. Synchronism of Stage Location. As the movement of XXY stage in X -direction is resulted from the movement of m_1 and m_2 , when m_1 and m_2 are asynchronous, the stage will have θ displacement. As shown in Figure 11, when the XXY stage moves in X -direction (from 0 mm to 10 mm), the positioning repeatability is about $\pm 1 \mu\text{m}$. The angular error is very small (less than 5 arcsec), and the repeatability is good. The interference in Y -direction is about 0.13%. From

FIGURE 8: Comparison between floating reference point and fixed reference point: (a) fixed reference point; (b) floating reference point.

FIGURE 9: Different alignment pattern image with different quality.

FIGURE 10: Pattern image processing steps. (a) Origin image; (b) pattern image; (c) binarization of origin image; (d) smoothly of the binary image; (e) difference after pattern matched; (f) searched pattern position.

FIGURE 11: The positioning repeatability of X -axial motion of XXY stage: (a) X starting point; (b) X end point; (c) position of Y -axis when X is at starting point; (d) position of y -axis when x is at end point; (e) position of θ -axis when X is at starting point; (f) position of θ -axis when X is at end point.

Figures 11(e) and 11(f) we can see that m_1 and m_2 have good parallelism performance.

The movement of XXY stage in Y -direction is resulted from the movement of m_3 . As shown in Figure 12, when the stage moves in Y -direction (from 0 mm to 10 mm), the positioning repeatability is about ± 2 mm. When Y is at the stroke end, the angular error is about -109 arcsec. The repeatability is still good, and the interference in X -direction is about 0.35%. We conjecture that large positioning error of X -direction is not because of setup error, but because of friction force. As shown in Figure 14, assumption of the desired displacement is δ_y ; Y -direction displacement of motor 2 is less than δ_y due to friction force. The phenomenon is similar to the gantry type of stage. Figure 13 shows the

positioning repeatability of rotation motion; the stage was rotated from 0 degrees to 3 degrees. The angular positioning repeatability is $\pm 0.001^\circ$ (about ± 3 arcsec).

4.2. Floating Reference Point Test. In order to validate the feasibility of floating reference point, the pattern image center captured from CCD1 (mark1) is set as the reference point for movement, as shown in Figure 15. Ideally, the reference center should be not changed when we rotated the stage around the reference center. The top part of Table 2 shows the result of rotation of the stage at negative angles (0.05° each time) when the mark1 is in the initial center position (-319.8 mm, 127.9 mm). The bottom part of Table 2 shows the result of

FIGURE 12: The positioning repeatability of Y-axis motion of XXY stage: (a) position of x-axis when Y is at starting point; (b) position of x-axis when Y is at end point; (c) Y starting point; (d) Y end point; (e) position of θ -axis when Y is at starting point; (b) position of θ -axis when Y is at end point.

FIGURE 13: The positioning repeatability of rotation motion: (a) θ starting point; (b) θ end point.

FIGURE 14: Illustration of positioning error due to friction force.

FIGURE 15: Take sample center on CCD1 as reference center.

rotation of the stage at positive angles ($+0.05^\circ$ each time) when mark1 is in the initial center position (0 mm, 0 mm). The results show that the reference center difference amount in X- and Y-directions are about $10 \mu\text{m}$ and $20 \mu\text{m}$.

4.3. Alignment Repeatability Test. The practical optical alignment uses a touch panel tester (capacitive test) produced by Chiuan Yan Technology as the testing machine as shown in Figure 16. The object for alignment was a capacitive type of touch panel glass ($10.5''$, $232 \text{ mm(L)} \times 135 \text{ mm(W)}$). During the test, the stage was randomly moved, in order to move the glass to leave the alignment target point (or alignment reference point), and then started alignment procedure. The preset alignment accuracy was $\pm 1 \mu\text{m}$, and the maximum alignment times were three for each alignment motion. The experimental results are shown in Figures 17 and 18. Each alignment motion of this system was shorter than one second, and each alignment motion could be completed within three times of correction. The alignment accuracy of the system was $\pm 1 \mu\text{m}$ and $\pm 5 \text{ arcsec}$.

5. Conclusions

The paper proposed a visual servo control and image alignment system using a special design coplanar XXY stage. The kinematic analysis and setup error influence were also

FIGURE 16: Optical alignment system structure.

TABLE 2: Result of floating reference point movement centered on CCD1 sample center.

Rotation angle (degree)	Center position (μm)	
	x	y
-0.5	-326.7	113.7
-0.45	-326.0	116.0
-0.4	-326.7	113.7
-0.35	-326.7	114.4
-0.3	-325.2	119.2
-0.25	-323.3	123.9
-0.2	-322.9	130.2
-0.15	-323.7	130.2
-0.1	-322.9	128.6
-0.05	-321.4	124.7
0	-319.8	127.9
0	0	0
0.05	1.5	0.8
0.1	1.5	1.6
0.15	2.3	3.9
0.2	3.8	2.4
0.25	5.4	2.4
0.3	6.1	6.3
0.35	6.9	4.7
0.4	7.7	7.9
0.45	9.2	14.2
0.5	10.7	17.4

discussed in the paper. A floating reference point based image alignment method was presented for decreasing the influence on each alignment process between the change of the work piece center and the stage reference point. It has better adaptability when the work piece is changed; provided with a stable coplanar XXY stage system, high-precision image alignment can be implemented. Thus, this system also shows good stability. Each alignment motion of this system was shorter than one second, and each alignment motion could

FIGURE 17: Experimental result 1 of positioning repeatability of image alignment (4,000 times of alignment). (a) Alignment completion time; (b) times of alignment completed.

FIGURE 18: Experimental result 2 of positioning repeatability of image alignment (4,000 times of alignment) (a) X-direction; (b) Y-direction; (c) θ -direction.

be completed within three times of correction. The alignment accuracy of the system was $\pm 1 \mu\text{m}$ and $\pm 5 \text{ arcsec}$.

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