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A Leveling Measurement Method and Its Application in Robotic Systems

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***Abstract*—Leveling error is critical for final alignment accuracy in accurate assembly tasks, which needs to be sensed and further compensated. In this paper, we propose an easy and cost-saving leveling measurement method. The parameter sensitivity is studied, and the leveling compensation approach in robotic systems is stated. We conduct experiments to examine its accuracy performance, and show its effectiveness in a demonstration assembly case.**

***Index Terms*—leveling measurement; robotic system; accurate assembly**

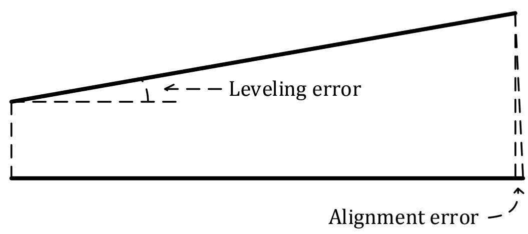

Fig. 1. Leveling error will cause final alignment error.

I. INTRODUCTION

Automatic manufacturing in 3C (computer, communication, and consumer electronics) industry, in particular, the small part assembly operation, has become a booming application for industrial robots. Different from the automobile industry, small part assembly requires higher geometry alignment accuracy, which can be up to 0.02 mm.

In a robotic assembly system, *fixture* (or *pallet*) is normally provided for holding the parts so that they can be disposed in the desired place and orientation. Conventionally, robots are programmed by teaching with the *golden* fixture, which is the most representative fixture available. The same robot targets and movements are repeated in real production with lots of (e.g. 100+) pallets running along the assembly line. This solution works fine as long as all the pallets are consistent. However, it asks for high manufacturing quality and cost. Alternatively, we can lower the pallet manufacturing requirement and teach different robot targets for each pallet, or each group of pallets. Such approach is obviously tedious and time-consuming. Therefore, we want a convenient way to deal with the pallet deviations.

Vision systems are often used to detect errors of translations in $\mathbf{x}$ and $\mathbf{y}$ directions ($T_\mathbf{x}, T_\mathbf{y}$) and rotation about $\mathbf{z}$ axis ($R_\mathbf{z}$). Besides this, a small leveling error can also cause the final alignment error, as illustrated in Fig. 1. Leveling describes the amount of tilt of the current part from its expected configuration. In other words, it can be interpreted as the error of rotations about $\mathbf{x}$ and $\mathbf{y}$ axes ($R_\mathbf{x}, R_\mathbf{y}$). For example, when assembling a 100 mm × 100 mm sheet, leveling error at 1° would cause about 0.015 mm alignment error, which really matters for accurate assembly.

Traditionally, engineers detect the leveling by mounting 3 displacement sensors on robot end-effector and measuring the heights of 3 points on the plane. It is a very intuitive approach. However, this setup is expensive and bulky in robot station, and brings high requirement on sensor installation.

Autocollimator is a precise optical instrument for non-contact measurement of angles [1]–[3]. Light beam is projected from the autocollimator, reflected back into the instrument by an external reflector, and focused onto a photo detector. Leveling of the external reflector is computed based on the shift of reflected beams. Since the reflected beams have to be converged by the lens, autocollimator has a relatively small measurement range (usually about $0.5°$) and short distance between autocollimator and external reflector. This, together with the high cost, limits its application in robotic assembly systems.

Angle measurement based on interferometry is a very popular kind of method. Rotation will result in the optical path difference of two interfered light beams, which will further lead to change in the interference pattern. Measurement based on interferometry usually requires continuous detection of phase change for large angles. Equipment using the Michelson interferometer has been proposed [4]–[6], and Sasaki *et al.* came up with a setup using Twyman-Green interferometer for small rotation angles [7]. Dai *et al.* took the advantage of a parallel interference pattern [8]. An angle measurement method combining interferometry and fringe analysis was reported in [9], which used Fourier transformation and phase-shift technique.

Another widely used method is the total internal reflection effect, which was firstly proposed by Huang *et al.* [10], [11]. In this method, two prisms are arranged orthogonally on a rotary stage in which internal reflections occur. Small angle of the rotary stage is estimated by measuring the reflectance difference between the prisms. The total internal reflection method can only detect the rotation angle in 1-dimension. A compact design of prism assembly was presented in [12] that can always parallel retro-reflect the incoming light beams and improve the method's linearity. Instead of measuring the intensity, Chiu *et al.* put forward the approach of measuring the phase difference between s and p polarization states at total internal reflection [13].

Surface plasmon resonance (SPR) is highly sensitive to optical and structural properties of the metal interface, which can also be used for angle measurement. Using this phenomenon, several methods have been developed [14]–[16].

The aforementioned approaches can precisely measure small rotation angles. However, the instruments are complex in structure and not easy to use in robot work stations. In this paper, we propose a leveling measurement method which takes advantage of a reflective surface and vision system. It is cost-saving yet has good accuracy performance. Moreover, we can easily implement this method with robotic systems.

This paper is organized as follows. In Section II we describe the working principle of the proposed leveling measurement system, and conduct sensitivity analysis. In Section III the leveling compensation approach in robotic assembly system is presented. We use experiment to verify the accuracy of proposed method in Section IV, and demonstrate its effectiveness by applying it in a USB disk assembly case in Section V. Finally, Section VI concludes this paper.

II. Proposed Leveling Measurement System

A. Leveling Parameterization

We can visualize leveling as the parallelism of two planes. Any rigid body has 3 spatial rotation degrees of freedom. However, leveling measurement has only 2 degrees of freedom: any rotation about plane's normal vector does not alter its leveling situation. As a consequence, we can obtain the tilted plane by directly rotating the reference plane about an axis in it.

If we setup a frame with $\mathbf{z}$ axis normal to the plane, as illustrated in Fig. 2, the leveling can then be naturally parameterized by angle α and β, where

- α is the angle between $\mathbf{z}$ and $\mathbf{z}'$;
- β is the angle between rotation axis and $\mathbf{x}$ axis;

Normal vector $\mathbf{z}'$ of the tilted plane is

$$\mathbf{z}' = \begin{pmatrix} \sin\alpha\sin\beta \\ -\sin\alpha\cos\beta \\ \cos\alpha \end{pmatrix}. \quad (1)$$

B. Basic System and Leveling Calculation

The proposed leveling measurement method applies the idea of reflection. As illustrated in Fig. 3, we apply a planar reflective surface on the fixture by attaching a piece of mirror or fine polishing the fixture's surface, and observe a marker's image via camera. Any feature point or pattern distinguishable from its surrounding environment can be used as the marker, and to ease the system setup we can always select the camera lens itself to be our marker in the system.

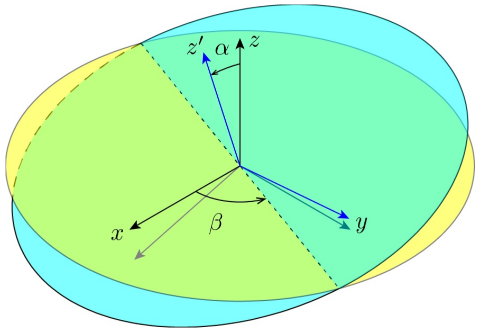

Fig. 2. Parameterization of leveling.

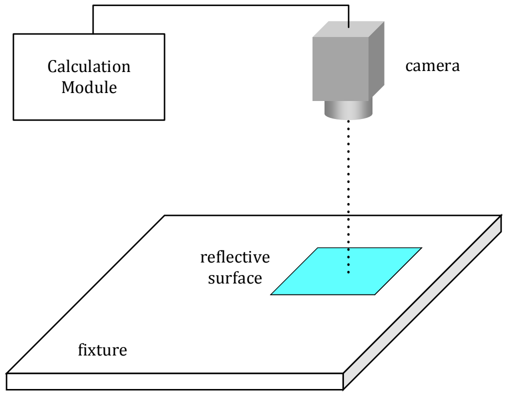

Fig. 3. Basic leveling measurement system.

In this system, tilt of the reflective surface from reference to current configuration is converted as the displacement of marker's image through reflection, as the camera view shown in Fig. 4. Distance D of this displacement relates to the amount of tilt; direction shows the tilting axis. Section view of the system is shown in Fig. 5. Please notice that the reflected virtual image by tilted surface may not be in the camera's image plane. But it would be observed as if it were in the image plane along the extension line from the camera, which is also the marker in our system.

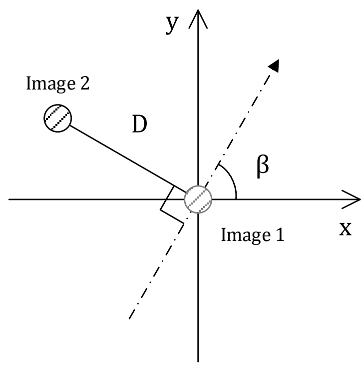

Fig. 4. Displacement of marker's image in the camera view.

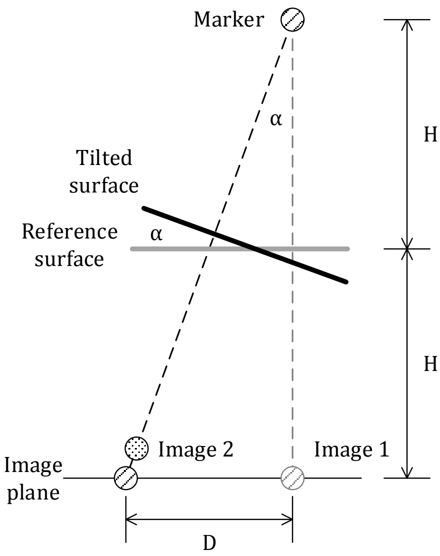

Fig. 5. Section view of the ideal system.

We can calculate the amount of leveling as

$$\alpha = \tan^{-1}\left(\frac{D}{2H}\right), \tag{2}$$

where H is the distance between marker and the mirror. Movement of marker's image would always be perpendicular to the rotation axis, so we have (as in Fig. 4)

$$\beta = \operatorname{atan2}\left(-D_x, D_y\right), \tag{3}$$

where $D = (D_x, D_y)$ is the image's displacement vector in the camera frame.

C. Sensitivity Analysis

In an ideal system as in Fig. 5, we should have

- precise values of H and D;
- reflective surface parallel with camera's image plane.

But practical system is never ideal. We conduct the sensitivity analysis on parameters as follows.

1) Imprecise H and D: Imprecise H and D will lead to imprecise α. By taking derivative we can get

$$\delta\alpha = \frac{2H}{D^2 + 4H^2}\left(\delta D - \frac{D}{H}\delta H\right). \tag{4}$$

As we can see, if in the measurement system the height H is large, small errors in H and D would only have very limited influence on α. This also tells us that we don't need a camera with very high resolution, since the error because of resolution would be reflected in D.

2) Non-parallel Reference Surface and Image Plane: As in Fig. 6, when the camera's image plane is γ degree of angle away from being parallel with the reference surface, the triangle is not right-angled. According to the law of sines,

$$\frac{D}{\sin\alpha} = \frac{2H}{\sin\left(\pi/2 - \alpha - \gamma\right)} \tag{5}$$

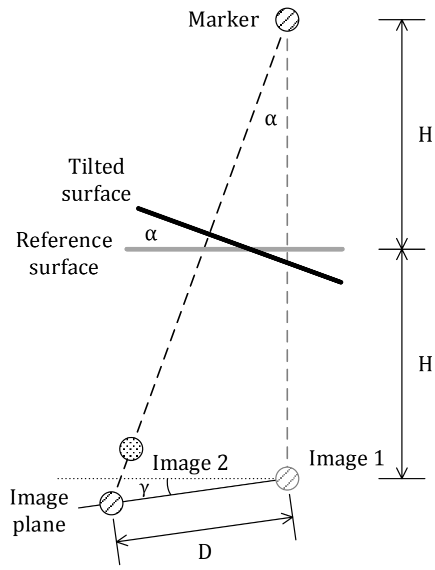

Fig. 6. Section view of the system when the reference surface is not parallel with camera's image plane.

$$\alpha = \tan^{-1}\left(\frac{\cos\gamma}{2H/D + \sin\gamma}\right). \tag{6}$$

Around the working point of $\gamma = 0$, we have

$$\delta\alpha|_{\gamma=0} = -\frac{D^2}{4H^2 + D^2}\delta\gamma. \tag{7}$$

We should try to have the camera's image plane as parallel as possible with the reference surface (usually by adjusting the camera calibration board). And a large H could decrease the measurement error due to non-parallelism.

The sensitivity analysis implies that height H between camera and reference surface should be large enough in order to suppress noises and deviations in practical cases.

III. Leveling Compensation in Robotic System

With the help of proposed measurement method, we can get the leveling deviation of current pallet from the reference pallet. The robot, usually a 6-axis robot, can then compensate such difference by its movements. A typical application of leveling measurement in a robotic system is shown in Fig. 7. Comparing with the basic system in Fig. 3, here we conduct the leveling calculation in the robot controller.

Direct result of leveling measurement is with respect of the vision frame. For robot to compensate such deviation, we need to transform the measurement result, specifically speaking the angle β as in (3), to the robot coordinates system. Such transformation can be obtained by robot-camera calibration.

Traditional robot-camera calibration needs the robot to touch the origin of camera calibration board by a probe. We may further notice that only the relative orientation of vision and robot frames matters, and the translational relation is not needed. Therefore, we can use any coordinate frame parallel with the vision frame. Instead of using a physical probe, we further propose to use a virtual probe, for instance a laser

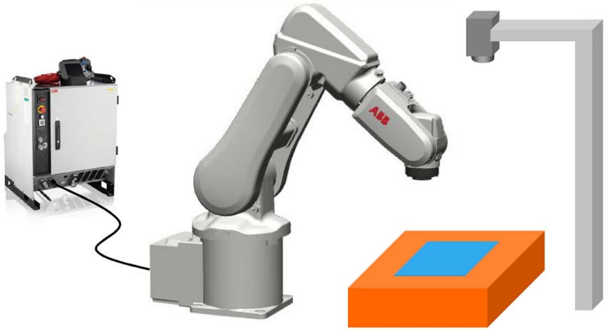

Fig. 7. Leveling measurement in a robotic system.

pointer. As shown in Fig. 8, we let the robot translate in the $\mathbf{xy}$ plane, and the camera would detect and locate the laser point. By robot movements and corresponding laser point coordinates, relative orientation can be calculated. This can be easily automated because no physical contact happens during the identification process.

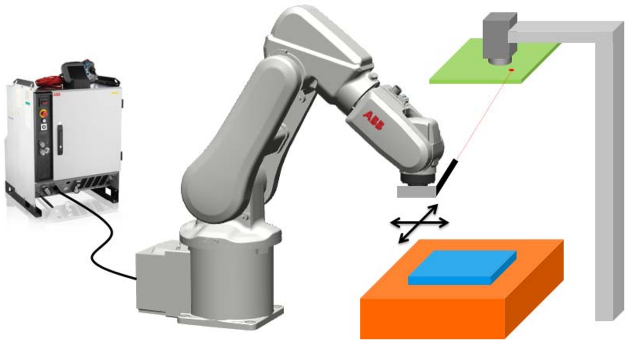

Fig. 8. Orientation identification with the help of laser pointer.

During robot teaching with the golden pallet, a good programming practice is to setup a *work object* frame [17] at the pallet, and define all the robot targets relative to this work object frame. After we get the leveling results in production, we can modify the coordinates of work object frame. In particular in the ABB system, we can simply apply the measured orientation to the *oframe* field [17] of the work object frame. All the taught targets will be automatically updated, thus the leveling error can be compensated.

IV. Leveling Measurement Verification

A. Experiment Setup

In this section, we come up with an experiment to verify the proposed leveling measurement method. As the experiment setup shown in Fig. 9, a piece of mirror is attached to the robot end-effector. We use the Cognex smart camera with 1200×1600 pixel resolution, and with two different lens of focal length 16 mm and 35 mm. With a large focal length, we

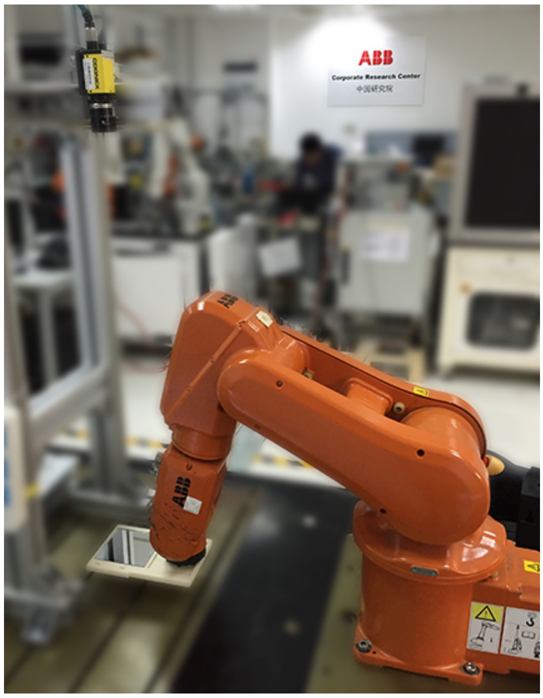

Fig. 9. Verification experiment setup of leveling measurement.

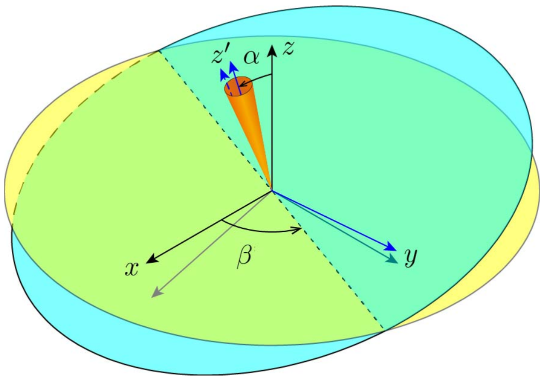

Fig. 10. Error angle and error cone.

have a larger ROI[1]/FOV[2]ratio. Therefore, we would expect to have finer measurements of displacements of marker's image, and thus smaller errors.

According to our sensitivity analysis, precision of value H and parallelism between mirror and camera image plane are not very important as long as H is large enough. As a result, distance between camera and initial mirror plane is measured by a ruler with $H = 660\ mm$, and we use no special tool to adjust the camera and calibration board (not shown in the figure) with respect to mirror.

Since the mirror is mounted on the robot, we rotate it a little bit ($1°$ in our case) about the $\mathbf{x}$ axis and $\mathbf{y}$ axis in robot frame respectively. The corresponding coordinates of marker's

[1]ROI: Region of Interest
[2]FOV: Field of View

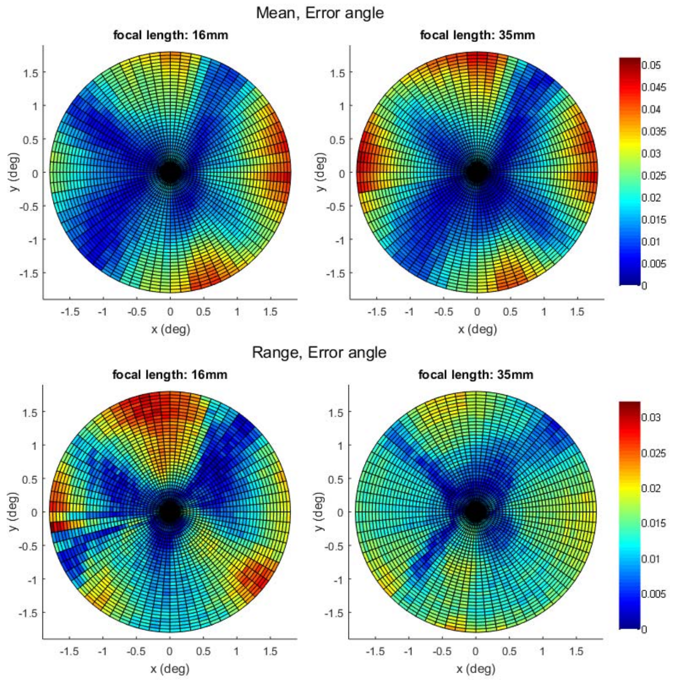

Fig. 11. Mean and range of experiment errors for both lens.

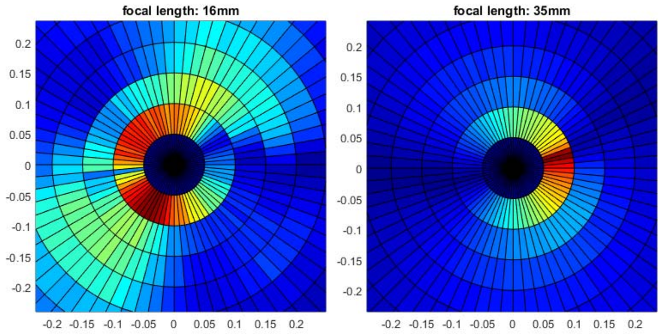

Fig. 12. Error of β in the region of small α angle.

image in the vision frame are recorded, based on which we can identify the relative orientation of robot and vision frames.

In the experiment, robot is programmed such that α varies from $0.05°$ to $2°$ with step $0.05°$, and β varies from $-175°$ to $180°$ with step $5°$. Since the rotation range is small, we can treat the robot motion command as actual rotation values, and compare the measured leveling at each mirror configuration. We repeat the experiment procedure for 5 times for both lens of focal length 16 mm and 35 mm.

B. Experiment Results

It is not good to directly compute the errors of α and β angle, since we would meet the parameterization singularity around $\alpha = 0$:

$$\left.\frac{\partial \mathbf{z}'}{\partial \beta}\right|_{\alpha=0} = \left.\begin{pmatrix} \sin\alpha\cos\beta \\ \sin\alpha\sin\beta \\ 0 \end{pmatrix}\right|_{\alpha=0} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}. \tag{8}$$

In other words, when $\alpha \approx 0$, a small difference in leveling situation may lead to a large error in β. Instead, we calculate the angle between actual and measured normal vectors, as the angle between solid and dashed $\mathbf{z}'$ in Fig. 10. This presents an error cone (see also in Fig. 10) within which the measured normal vector locates around the actual one.

Mean value and the ranges of error angle at each tilt configuration are shown in Fig. 11. Color of red represents large error and blue stands for small value. From the results we can conclude that the proposed leveling method has quite good accuracy performance. Maximum error angles for both 16 mm and 35 mm lens are about $0.06°$. The small the α angle is, the better accuracy we can get. Error distributes unevenly with different β, and with similar pattern, for both 16 mm and 35 mm lens. The unevenness and difference between two lens could be caused by residual camera distortion after calibration, slight non-parallelism of mirror and calibration board at reference configuration, and the non-flatness of mirror surface.

Surprisingly, the mean performance of 16 mm lens is at the same level as the 35 mm lens. It may be resulted from the large value of H. However, the max error of 16 mm lens is slightly larger. In addition, from the figure of error range we can see that 35 mm lens has more stable performance.

If we check the error of β in the region of small α angle, as shown in Fig. 12, we do observe much larger errors with 16 mm lens than the 35 mm one. But the error angles are small as in Fig. 11 in the neighborhood of reference mirror configuration, which coincides with our discussion of parameterization singularity.

V. Leveling Compensation Validation

In order to validate our leveling measurement and compensation method, we apply it to our demonstration line which assembles USB disks. In one robot station as shown in Fig. 13, a pallet holding the PCB board, USB housing and cover inside would be lifted and well positioned by a lifting mechanism. The robot will sequentially pick up the PCB board and place it into the housing, and pick up the cover and assemble it with the housing by snap-fit connection. We place a piece of mirror on the pallet and use the Cognex camera to measure its leveling.

For better visual observation, we intentionally block up one side of the lifting mechanism to create the tilt about $1°$, as shown in Fig. 14. This leveling will be measured and compensated by robot movements. We compare the assembly performance with or without the leveling compensation. Fig. 15 shows the moment before snap-fit. Obviously as in Fig. 15(a), if we do not sense and compensate the pallet leveling, the gap between cover and housing on the left hand side is much larger than that on the right hand side. This will lead to a failure of snap-fit and a product in bad quality. As a comparison, with leveling compensation the gaps on both sides are nearly the same as in Fig. 15(b), which demonstrates the effectiveness of the proposed method.

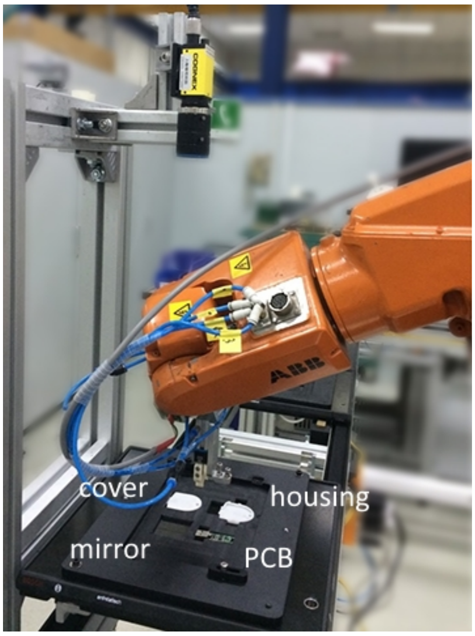

Fig. 13. Validation experiment setup of leveling compensation.

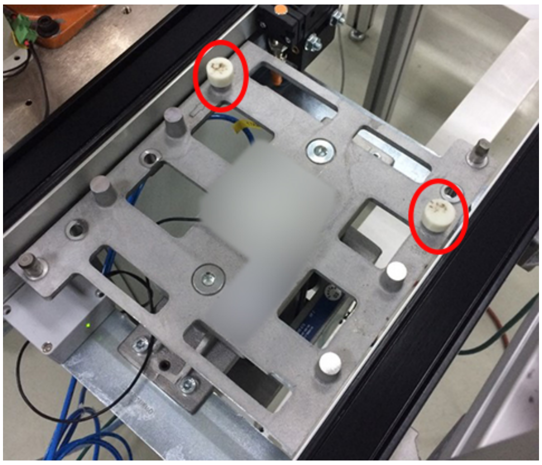

Fig. 14. Blocking up one side of the lifting mechanism to create leveling.

VI. Conclusion

We propose a leveling measurement method in this paper, which takes advantage of a reflective surface and vision system to convert the plane leveling into displacement of the marker's image. We describe the basic system with its working principle, and analyze the parameter sensitivity. Implementation issue and leveling compensation approach with robotic systems are stated.

To examine the measurement performance, we conduct a verification experiment and compare the measured leveling with robot motion. Results show quite good accuracy of the proposed methods. A further validation experiment of deploying it in a USB disk assembly station demonstrates that our measurement system can effectively sense and compensate the leveling error.

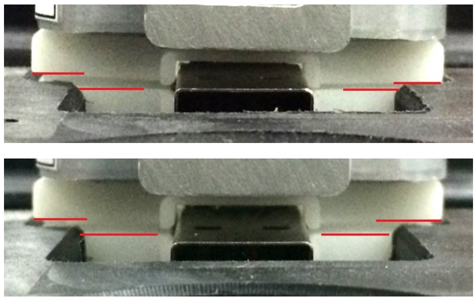
(a)
(b)

Fig. 15. Validation result. (a) assembly without leveling compensation; (b) assembly with leveling compensation.

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