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Precision Measurement Method of Pipe Diameter Based on Linear Array Camera

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Abstract- **This research will provide simple, easy, fast and low-cost and real time laser alignment model to measure the pipe line diameter with the handheld laser, camera, projector and the personal computer as hardware. Based on the experimental results, this approach will play a great role in academic research and in different research area that deals with the straight pipes in their everyday life. Moreover, the measurement techniques can achieve total online measurement and it provides high precision and stability. In addition, we present a novel method to measure the diameter of straight and seamless plastic pipes. A pair of line-structured lasers, which locate on different sides of the pipe but in a common plane, cast on the pipe to create two elliptical arcs. The CCD camera captures these two arcs. Major and minor axis radii and spatial 3D coordinates of every corresponding elliptical cross-section center can be calculated through ellipse fitting. A pair of line-structured laser sensors, each of which includes a line-structured laser and a CCD camera, are placed at every sampling cross section of the pipe, and thus the pipe's cross-section diameter and furthermore the straightness of the pipe can be solved. We provide an on-line machine vision method for measuring a seamless steel pipe's diameter and straightness, including the design of the system, the deduction of the mathematical model, and the research of the experimental results**

Index terms- **Line-scan calibration, 3D coordinates measurements, radius, non-contact scan, Handhold-Laser, calibration board and projector, image and light plane**

1.INTRODUCTION

The use of linear Array Cameras for measurement of pipe diameter in areas such as the automotive industry, construction and restoration of buildings, bio-engineering, and in systems of monitoring and railroad detection is increasing [7]. Line scan technology is replacing 2D matrix cameras because it increases the efficiency and accuracy in measuring. (The 1D data that line scan provides are easier and faster than 2D images and the size of line scan cameras takes advantages of matrix cameras) However it seems that only scant information appears to be available about measurement of pipe diameter based on line array camera. Multi line precision measurement method has been proposed to calculate the pipe diameter (radius).

With the 3D scanner we can get the 3D information of object or scene, the extraction of the laser stripe center from image is the most important steps throughout the whole process of measuring [13]. There are numerous researches done on the accuracy in obtaining 3D information of objects and measurement, but speed, effectiveness, accuracy and speed remained as an issue to handle with the 3D scanner we can get the 3D information of object or scene. The extraction of the laser stripe center from image is the most important steps throughout the whole process of measuring. There are numerous researches done on the accuracy on obtaining 3D information of objects and measurement, but speed, effectiveness, accuracy and the cost remained as an issue to handle

So far no satisfactory method has been in practical to solve the online automatic measurement of the pipe diameter. Therefore, the straightness evaluation has to be accomplished manually by the operators. This not only in low measurement speed but also makes the production quality and quantity into human errors. Over the years, different measurement methods for the related applications have been explored. These includes the use of alignment of telescopes, jig transits, optical levels, the engineering theodolite and so on [18] however, none of these are directly suitable for the 100 percent online measurement of the pipe diameter accurately. Junichi used laser beam to obtain the straightness by moving target on mirror along the measured line or the measured central axis [11]. However, there are two determinant factors for the laser beam stability. the first one is the air flow in the beam path and the second is the air flow effect which can be reduced by setting a camera around the beam path for small measurement ranges. The other problem is the drift of the beam resulting from the Beam shaking or dancing due to the thermal deformation of the parts of the laser. all those challenges are our main issue to deal with and find a suitable solution in my research.

The low drift of 3 nm over the working distance of about 200 mm can be expected by the stabilization using water cooling for the laser tube [20] However, this is not sufficient to the pipe diameter measurement method for longer parts such as working distance up to 1 m. The above method is not subjected to the effects, but like Junichi's method, it cannot implement the non-contact measurement, since during the measurement, the moved target or reflection mirror must be used.

The alignment system of He-Ne laser light source, a photoelectric detector, and the lenses, with the advancement of machine vision technology, visual gauging or inspection technique based on off-the-shelf charge coupled device CCD, semiconductor laser, image grabber and image processing device, is becoming an alternative for 100 percent online measurement in industrial application we are going to use all the mentioned appliances in our research as seen in section 2. This method offers the desired properties of being non-contact with proper precision, high speed and easy to operate.

In this research we developed a laser visual alignment measuring technique to implement 100 percent online and non- contact measurement of diameter in medium size of plastic Pipe. [18] In the last decade, new generic calibration approaches have been developed. The generic approaches were based on the fact that all imaging systems perform a mapping from incoming scene rays to photosensitive elements on the image detector. this mapping is described by a set of virtual sensing elements called raxels and special structured light patterns are used to extract the parameters of raxel. a more generic method was presented and the images of a planar calibration object are used to determine the mapping between rays and pixels. The linear array camera calibration methods have been applied on a wide variety of central and non-central 2D cameras [21]. In contrast, for the generic calibration method has not been studied yet and an accurate calibration method was still not fruitful. In this this research, we propose a precise calibration method for the liner array camera based on the different calibration approach.

The algorithm has two Independent two steps; the first step was to recover the projection of the imaging system using the mapping technique. By which the imaging system is considered as a whole and the calibration task is converted into setting up the correspondence between incident rays and the corresponding image points. The technique is still effective even if the lens distortion is high and asymmetric due to the system calibration. For the light spot within the FOV, the plane passing through the light spot in camera coordinate frame can be computed accurately due to the excellent approximation properties of the multiquadric. From a practical point of view, this plane should be transformed to world coordinate frame to realize the 3D coordinate measurement by multi-plane constraint. Consequently, the second step, the extrinsic camera parameters process, is followed to realize this coordinate transformation. Theoretically, the proposed method could be a generic and accurate camera calibration approach. Both simulative and real experiments will validate the effectiveness of the proposed method [21].

In section 2 we introduce the fundamentals of the visual alignment system and it's modeling. Then we describe in section 2.1 how to obtain the coordinates of the centers of elliptical arc via the visual sensing. In section 2.2 the calibration of the measurement system is given. Lastly in section 3 this novel method is verified by experiments in the diameter (radius) 140mm length Pipe.

2. MEASURING METHODOLOGY

The purpose of 3D scanner is usually to create a point cloud of geometric samples on surface of the pipe [1]. Those points can be processed for further measurements systems other There is a big number of methodologies used in 3D scanning and each and one method has pros and cons. For example, one of the major benefits of using the pseudo-random codification approach is that it is easy to implement for 3D shape measurement major disadvantage to this technique is that it is difficult for such technique to achieve high spatial resolution as it is limited by the projector's resolution in different directions.

Apart from contact scanning which needs the physical contact with the object explained above, in this research I proposed the non-contact scanning system that includes the following materials: one camera, one projector, hand-held line laser, personal computer (PC), and one background calibration board. In this research I propose different technologies to make the camera getting the center line from images, but I will not discuss all of them in this research.

The cameras are set on one straight line and remain static when scanning and the laser irradiates the pipe vertically. Different images will be obtained respectively. There is a laser line in each image at the same time. With the position of laser line in two images. the projector puts a set of structured laser stripe of the object while the camera is capturing the images of the laser stripe patterns. The image will be processed to reconstruct the 3D shape of the object We can calculate the real position and the coordinates of the points lying on the laser line. By moving the laser, the 3D data of the pipe are obtained as the scanning process goes on. The system development will use the C/ C++ language and windows API, the library to be used is Open CV

2.1. Measuring principle system modeling

The measurement of Pipe Diameter refers to that the 3D coordinates of the points in the central axes of the object below therefore, as there are enough numbers of measured points along the pipe of the work piece, its diameter may be estimated. The key point in the measurement is how to identify the 3D coordinates of the points along the measured line. The used method of the pipe for the external diameter is illustrated in fig. 1. The laser source, camera, and the image plane are placed along the pipe. The laser beam form the laser source is magnified by the cylinder lens and transformed into light plane resulting in an elliptical arc, as intersecting the axes 'external surface. The images of the elliptical arcs sensed by the CCD cameras are transmitted to the image grabber through the multiplexes controlled by the personal computer to be digitized and stored in the frame memory. And again the 3D world coordinates of the arc center system Xw, Yw, Zw can be computed through image processing. Then the Pipe Diameter is estimated by an algorithm giving all the arc center coordinates.

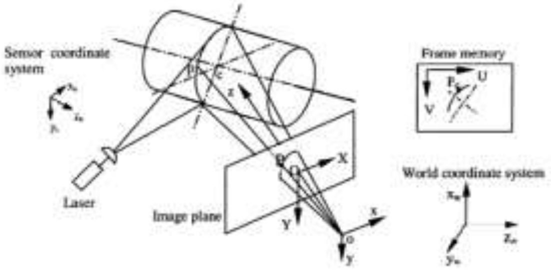

Figure 1The measurement principle of the center elliptical arc by the sensors

As illustrated in Fig. 1, the central axis 'Xs and Ys are on the light plane, the equation of which in the sensor coordinate system is z_s = O. Suppose that the rotation and translation vector of x_s and y_s axis in the sensor coordinate system to the camera coordinate system is known as, $(r2, r5, r8)^T$ and (t_x, t_y , t_z) The number of CCD sensor pixels in the X- direction is N_{cx}, and the center to center distance between adjacent pixels in CCD image plane is dx in X− (scan line) direction; the number of CCD sensor pixels in the Y − direction is N_{cy} , and the center to center distance between adjacent sensor pixels in Y − direction is d_y . During scanning, the discrete signals picked up by each row of the sensor pixel array are firstly converted to an analog signal, which is then sampled by the computer image grabber into a number of discrete samples and put in a row of a frame buff Usually, there exists imperfect match between the computer image grabber and the camera hardware. so uncertainty scale factor sx should be introduced, which is the ratio between the number of CCD sensor pixels in a row array and the number of picture pixels in a row of the computer image frame memory. The vertical scale factor needs no calibration since there is an exact one-to-one correspondence between lines in the computer frame memory to lines in the CCD sensor array. Therefore, the equation relating the image coordinate system to the sensor coordinate system is as follows

$$\begin{cases} d = \frac{d_x N_{cx}}{N_{fx}} \\ y_d = d_y (V - V_0) \\ r = \sqrt{X_d^2 + Y_d^2} \\ f\frac{r_1 x_s + r_2 y_s + T_x}{r_7 x_s + r_8 y_s + T_z} = X_d (1 + k_1 r^2 + k_2 r^4) \\ f\frac{r_4 x_s + r_5 y_w + T_x}{r_1 x_s + r_8 y_s + T_z} = Y_d (1 + k_1 r^2 + k_2 r^4) \end{cases} \quad (1)$$

Where N_{fx} is the number of pixels in a line sampled by the computer k_1 and k_2 the radial distortion coefficients of CCD camera lens

Fig: 1 Illustrates the model of CCD camera adopted as a pin-hole projection model the image coordinate system is $O - XY$ where O is the origin which is the intersection of the image plane with the optical axis of the CCD Camera. Here X is chosen parallel to the rows of the CCD camera pixel array. The camera coordinate system is $O - XY\ Z$ with the point O coinciding with the optical center of the camera at the distance f to the image plane. Here f represents the focal distance of the camera. The z axis coincides with its optical axis then, the x axis and y axis are parallel to the X and Y axis respectively. The sensor coordinate system is defined on the light plane. The world coordinate system is built on similar way. P is an arbitrary point on the arc formed by the intersection of the light plane with the cylindrical point P (Xs, Ys, O) is the coordinate of the point P in the point P in the sensor coordinates system and P (Xw , Yw , Zw) is the point P in the world coordinate system. the non-distorted coordinate of the point P in the image coordinate system is P (XY) and the distorted coordinate on the image plane is $P_d(Xd, Yd)$. the Pd (UV) is the corresponding row and column numbers of image pixel in computer frame memory. (UV) denotes the pixel position of the principle point O in computer frame memory can be calculated in two steps as given in the following:

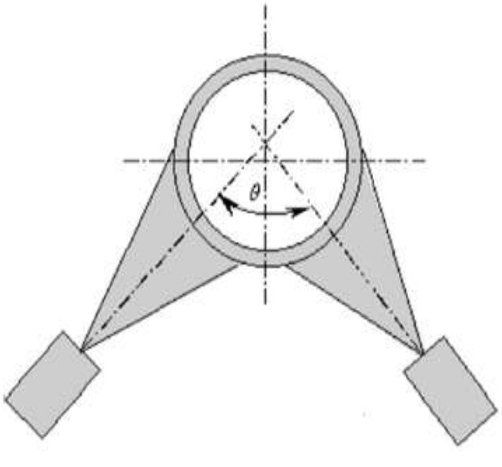

Figure 1 Arrangement of visual sensors

Fig. 1&2 Illustrates the model of CCD camera adopted as a pin-hole projection model the image coordinate system is O-XY where O is the origin which is the intersection of the image plane with the optical axis of the CCD Camera. Here X is chosen parallel to the rows of the CCD camera pixel array. The camera coordinate system is O-XYZ with the point O coinciding with the optical center of the camera at the distance f to the image plane. Here f represents the focal distance of the camera. The z-axis coincides with its optical axis then, the x- axis and y-axis are parallel to the X- and Y-axis respectively.

The sensor coordinate system is defined on the light plane. The world coordinate system is built on similar way. P is an arbitrary point on the arc formed by the intersection of the light plane with the cylindrical point P (X_s, Ys, O) is the coordinate of the point P in the point P in the sensor coordinates system and P (X_w, Y_w, Z_w) is the point P in the world coordinate system. the undistorted coordinate of the point P in the image coordinate system is P(XY) and the distorted coordinate on the image plane is P_d (X_d, Y_d). the P_d (UV) is the corresponding row and column numbers of image pixel in computer frame memory. (UV) denotes the pixel position of the principle point O in computer frame memory can be calculated in two steps as given in the following

Relation between sensor coordinate system and world coordinate system

As demonstrated in fig.2. the relation vector $(R_{1,} R_4, R_7)^T$, $(R_2, R_5, R_8)^T$ and translation vector $(t_x,t_y,t_z)^T$, between sensor coordinate system and the world coordinate system is known, $P(x_w, y_w, z_w)$ in the world coordinate system can be computed from $p(x_s, y_s, O)$ in the sensor coordinate system.

The computation matrix is

$$\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} = \begin{pmatrix} R_1 & R_2 & T_x \\ R_4 & R_5 & T_Y \\ R_7 & R_8 & T_z \end{pmatrix} \begin{pmatrix} X_s \\ Y_s \\ 1 \end{pmatrix} \qquad (2)$$

In practical measurement, the digital image of elliptic arc as shown below can be acquired after the image of ellipse arc formed by from intersection between the light plane and the cylinder is sampled by image grabber and the personal computer. Then again each and every coordinate point of the elliptic arc in the frame memory can be calculated through image processing

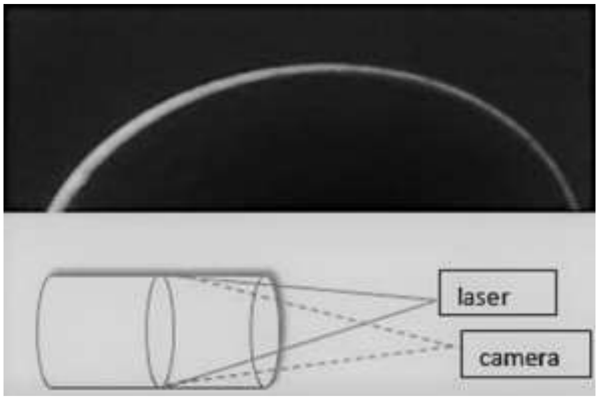

Figure 3 Experimental design

Suppose the coordinate of elliptic arc center, that is the intersection between light plane and axis, is c (X_w, Y_w, Z_w) in the world coordinate system, and C (X_{cs}, Y_{cs}, O) in the sensor coordinate system. The corresponding coordinate in the frame memory is C (u, v). Theatrically, the coordinate of the point C in world the coordinate system can be given as follow;

Firstly, compute the coordinate C (u, v) in frame memory with the points coordinates of the elliptical arc in the frame memory by image processing, then using the Eq. (1), one can compute its corresponding world coordinate Z_w). But in practice, as the pin-hole perspective model of CCD camera is a non-linear projection, this method gives significant systematic error [14]. Therefore, the more accurate algorithm is to first obtain each point's coordinate P (X_s, Y_s, O) of the elliptic arc in the sensor coordinate system using Eq. (l), then compute the coordinate C (X_{cs}, Y_{cs}, O) Of the center of elliptic arc in the sensor coordinate system. Although there are many methods to compute the center coordinates and its diameter [4], the computation time and accuracy have been major problems, especially for 100% online measurement of white plastic pipe in such case where the length of 750 mm the maximum allowable measurement time is 10 minutes. So during online measurement it is vital to use fitting method to calculate those parameters, in practice it is not easy to accurately compute Coordinates C($X_{cs}Y_{cs}$,0) in the sensor coordinate system with the small arc as shown m Fig. 3, due to the noise in the curve image. The influence to the curve image by the noise tends to be huge in horizontal direction than that in the vertical one, since the re-sampling of the video signal of the CCD camera is carried out row by row. As a result, the arc becomes a parabola rather than an elliptic arc. Therefore, we place the visual sensors at the two sides of the seamless pipe along its axis. Two visual sensors form a group, and the planes of the laser lights are adjusted to make them coplanar. The two sensor coordinate systems in the light plane thus coincide.

On the light plane, we can obtain two back projection arcs obtained by the group of two visual sensors. As the two arcs in an ellipse circle act as a geometric constraint in space, we can now compute the center coordinates C (X_{cs}, Y_{cs}, O) accurately and speedily by means of least square fitting method. As an ellipse is described by the general conic equation:

$$Ax^2 + Fxy^2 + By^2 + Cx + Dy + 1 = 0 \tag{3}$$

The equation to compute the coordinates is:

$$X_{cs} = \frac{DF - 2BC}{4AB - F^2} \tag{4}$$

$$Y_{cs} = \frac{CF - 2AD}{4AB - F^2} \tag{5}$$

$$R = \sqrt{\frac{AD^2 + BC^2 - CDF + 4AB - F^2}{2(AB - F^2/4)(A + B + \sqrt{(A-B)^2 + F^2}}} \tag{6}$$

Where R is the short axis length of the elliptical arc, that is the diameter of the ellipse formed by the light plane intersecting the measured pipe. A, B, C, D and F may be obtained by the following equation:

$$\begin{bmatrix} A \\ B \\ C \\ C \\ D \end{bmatrix} = \begin{bmatrix} \sum_{i=0}^{n-1} x_{si}^4 & \sum_{i=0}^{n-1} x_{si}^2 y_{si}^2 & \sum_{i=0}^{n-1} x_{si}^3 y_{si} & \sum_{i=0}^{n-1} x_{si}^3 & \sum_{i=0}^{n-1} x_{si}^2 y_{si} \\ \sum_{i=0}^{n-1} x_i^2 y_{si}^2 & \sum_{i=0}^{n-1} y_{si}^4 & \sum_{i=0}^{n-1} x_{si} y_{si}^3 & \sum_{i=0}^{n-1} x_{si} x_{si}^2 & \sum_{i=0}^{n-1} y_{si}^3 \\ \sum_{i=0}^{n-1} x_{si}^3 y_{si} & \sum_{i=0}^{n-1} x_{si} y_{si}^3 & \sum_{i=0}^{n-1} x_i^2 y_{si}^2 & \sum_{i=0}^{n-1} x_{si}^2 y_{si} & \sum_{i=0}^{n-1} x_{si} y_{si}^2 \\ \sum_{i=0}^{n-1} x_{si}^3 & \sum_{i=0}^{n-1} x_{si} y_{si}^2 & \sum_{i=0}^{n-1} x_{si}^2 y_{si} & \sum_{i=0}^{n-1} x_{si}^2 & \sum_{i=0}^{n-1} \sum_{i=0}^{n-1} x_{si} y_{si} \\ \sum_{i=0}^{n-1} x_{si}^2 y_{si} & \sum_{i=0}^{n-1} y_{si}^3 & \sum_{i=0}^{n-1} x_{si} x_{si}^2 & \sum_{i=0}^{n-1} x_{si} y_{si} & \sum_{i=0}^{n-1} y_{si}^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=0}^{n-1} x_{si}^2 \\ \sum_{i=0}^{n-1} y_{si}^2 \\ \sum_{i=0}^{n-1} x_{si} y_{si} \\ \sum_{i=0}^{n-1} x_{si} \\ \sum_{i=0}^{n-1} y_{si} \end{bmatrix}$$

After the coordinate point C in the sensor coordinate system and the diameter R of axes are obtained using the below equations, the coordinate of C ($X_{w,}$ $Y_{w,}$ Z_w) in the sensor coordinate system can be given by the Eq. 1. According to the elliptical evaluation principle, the diameter of the pipe can be computed by using the evaluation method given below

2.3 Calibration of line-scan cameras for precision Measurement

Camera calibration is necessary for precision measurement especially in industrial optical metrology. The quality of calibration has a significant impact on measurement results. Calibration of matrix cameras is one of the most active research areas in both computer vision and photogrammetry. Much effort has been made to facilitate the calibration procedure. Unfortunately, the methods cannot be directly used for line-scan cameras. On the other hand, the research of line scan camera calibration is not as popular as matrix camera calibration.

Calibration of linear array cameras for precision measurement must have a large calibration volume and be flexible in the actual measurement area. A high-precision calibration method has been introduced in this research. Instead of using a large 3D pattern, a small planar pattern and a pre-calibrated matrix camera to obtain plenty of points with a suitable distribution have been used to ensure the precision of the calibration results.

The matrix camera removes the necessity precise adjustment movement and links the linear array camera to the world to enhance flexibility in the measurement field. By the results from the experiment, it’s been concluded that the proposed method came up with a practical solution to calibrate the cameras for precision measurement.

Mono-dimensional imaging devices have characteristics of high resolution and high frame rate; these characteristics result in new possibilities for measurement of high-speed continuous moving objects with higher accuracy the reason to use, the line-scan cameras have been widely used in vision measurement instead of matrix cameras, particularly in real-time applications.

Patterns used for matrix camera calibration in static calibration are not reliable because line-scan cameras cannot illustrate where a given point in 3D space will be projected into the camera. Thus, static calibration methods usually utilize patterns consisting of several feature lines. The intersection points of the camera’s viewing plane with the feature lines are used for calibration. Coordinates of these intersection points are calculated according to pattern geometry, based on the principle of cross-ratio invariance.

The approach was easy to implement due to its simplicity the results of the calibration depend on the precision of the displacements. To overcome this limitation, more practical approaches are proposed, 3D patterns with multiple planes were employed. A single capture is enough to estimate the parameters. to change the position of the pattern during calibration is not necessary. Compared with Horaud’s method, these methods are easier and more flexible to use but, they are restricted to scant space points and small calibration volume for the pattern size was limited, and results in a negative influence on the parameters. Although a large pattern is helpful, it is expensive to manufacture; difficult to handle and transport especially in the actual measurement field. Therefore, static calibration still cannot fulfill the demands of precision measurement, particularly when the lens has a large distortion. Scanning calibration is another type of calibration method.

Drareni outlined a novel method that estimated the parameters offline-scan cameras using a planar grid pattern. The pattern moves with a constant velocity relative to the camera, resulting in a 2D image.

The correspondences between the points on the pattern and the image points are determined directly. The advantage of this method is that the algorithm was linear and simple, since the parameters are solved by a series of matrix operations. After obtaining the image coordinates by a simple center-extraction algorithm, the major drawback is that the target’s motion must be orthogonal to the camera’s orientation, which is difficult to achieve.

Compared to static calibration methods, scanning calibration methods employ more points, which would contribute to the precision of the parameters.

However, scanning calibration is not usually permitted in the measurement field, because it is difficult to provide a pure linear motion for the pattern under the actual measurement conditions, where there are many restrictions on experimental arrangements.

The general aim was to provide a calibration method of linear array cameras for precision measurement and design planar pattern that is easy to use portable. With the help of the matrix camera, we can move the pattern freely and obtain many intersection points with a suitable distribution, which results in accuracy increasing. The method works without precise movement adjustment and the obtained parameters are with respect to the world coordinates frame directly. These characteristics would facilitate the experiment in the actual measurement field.

A line-scan camera is regarded as a special camera that consists of only one array of pixels at the center position. Central projection is satisfied along the pixel array direction. The projection center and the pixel array define the viewing plane. Furthermore, lens distortion should be included in the camera model for precision measurement. The lens distortion of line-scan cameras exists only in the central projection direction, and it is negligible in the other direction since the distance from the principal point to the pixel array is too small.

The key in proposed method was how the correspondences between space points and image points are established, to eliminate the effect of perspective eccentricity, ring markers are used instead of solid circular markers. So far, more accurate measurement can be obtained when the target plane is not parallel with the camera.

In the initial estimation of the parameters, the distortion is neglected while obtaining the intersection points, which cause errors in the image points. Furthermore, the intersection points were calculated according to the image points. So, the intersection points would be further affected, and the obtained intersection points are not the true space points corresponding to the image points. Therefore, it is necessary to refine the parameters via a nonlinear optimization. In the optimization process, the distortion was included. On the other hand, we recomputed the intersection points for each iteration by the current viewing plane and the pattern geometry instead of using the cross-ratio invariance of the image points. Once an initial estimation of the parameters has been carried out, an optimization procedure was applied to minimize the re-projection error and be represented.

In experiment the proposed algorithm using a Dalsa Spyder3 linear array camera of 4096 pixels was tested, with a pixel size of 10 μm and a focal length of 50 mm. To ensure the accuracy, we used a glass calibration target with a photolithographic pattern. The size of the pattern was 152 mm × 152 mm. The accuracy of the pattern was less than 1 μ m, and the flatness of glass was less than 5 μ m. The pattern has been illuminated by an LED array to ensure the detection of the intersection points with subpixel accuracy. The matrix camera used is an Imperx Bobcat B3320 with a 25 mm lens. The external trigger output of the matrix camera served as the frame trigger of the line-scan camera to synchronize image acquisition. The images were acquired at a line rate of 1000 Hz via a GigE interface. The average values were used for the calibration algorithm. For simplicity, we set the matrix camera coordinate system as the world coordinate system.

It was noticed that after the optimization, the maximum value of the re-projection errors was 0.42 pixel and the root mean square value to be 0.10 pixel. And the distortion coefficients are quite stable. The deviation of the focal length was larger when fewer groups are used. This is primarily since the depth distribution of the points varies considerably among the combinations of the groups.

With the results obtained above, it was concluded that the method requires the pattern to move to different positions and orientation of the pattern are measured and transformed to the world coordinate frame by a matrix camera. The proposed method has been verified by real data, so the Proposed method was effective compared to the others. There is no critical requirement for the relative position between the line-structured laser and the CCD camera, but the relative position must not be changed after system parameters are calibrated. Also, measurement precision is highly dependent on system parameter calibration. These system parameters can be divided into two parts.

Camera Intrinsic Parameters

Camera intrinsic parameters include U_0, V_0, s_x, k, and f. These parameters can be determined from Tsai's radial alignment constraint (RAC) model [18].

Transformation Parameters

Transformation parameters9 include r_1, r_4, r_7, r_2, r_5, r_8, t_x, t_y, t_z , R_1 , R_4 , R_7 , R_2 , R_5 , R_8 , T_x , T_y and T_z . These parameters are available from sensor calibration and global calibration. As shown in Fig. 2, a target made of three tensed wires is placed where the work piece to be measured will be. Three points, p_1, p_2, and p_3, on the wires are illuminated by the laser. We can use these three points to gain the relation between light plane coordinate system and image plane coordinate system, and the relation between light plane coordinate system and world coordinate system. In this way, we complete the sensor calibration and global calibration.

Sensor calibration

The relative position between the CCD camera and light plane can be obtained from sensor calibration. From the Eq. 1 the coordinate of three points p_1, p_2, and p_3 in the light plane coordinate system is (x_{Li}, y_{Li},0) and that in the image plane coordinate system is (X_i, Y_i). And the transformation between them is:

$$\begin{bmatrix} \mathrm{x_i} \\ \mathrm{y_i} \\ 1 \end{bmatrix} = \begin{bmatrix} \mathrm{fr_1} & \mathrm{fr_2} & \mathrm{ft_x} \\ \mathrm{fr_4} & \mathrm{fr_5} & \mathrm{ft_y} \\ \mathrm{r_7} & \mathrm{r_8} & \mathrm{t_z} \end{bmatrix} \begin{bmatrix} \mathrm{x_{Li}} \\ \mathrm{y_{Li}} \\ 1 \end{bmatrix} \tag{7}$$

The orthogonal transition is:

$$\begin{cases} r_1 r_2 + r_3 r_5 + r_7 r_8 = 0 \\ \quad r_1^2 + r_4^2 + r_7^2 = 1 \\ \quad r_2^r + r_5^r + r_8^r = 1 \end{cases} \tag{8}$$

From the above equations. And we can come up with the values of r_1, r_4, r_7, r_2, r_5, r_8, t_x, t_y, and t_z.

2.4 Global calibration

The goal of global calibration is to establish a relation between the world coordinate system and each sensor's light plane coordinate system. We can use two theodolites to build the world coordinate system $O_wX_wY_wZ_w$, which is just the measurement system's world coordinate system. And with theodolites, we can get the world coordinates of p_1, p_2, and p_3. From Eq. 5, we can get transformation of these three points between world coordinate system and light plane coordinate system. From Eqs. (l) and (2), we know that there are 24 unknowns in the measured model. They are the effective focal length of the camera f, uncertainty scale factor. s_x, the coordinates of the optical center O in the image coordinate system (U_0, V_0)), the coefficients of radial distortion k_l and k2, the rotation vector (r_2, r_5, r_8) and translation vector $(t_x, t_y, t_z)^T$ between sensor coordinate system and camera coordinate system, and the rotation vector (R_1 R_4,R_7) , (R_2, R_5,R_8) and translation vector (T_X, Ty, Tz) between sensor coordinate system and world coordinate system. These unknown parameters can be extracted by the internal and external calibration of the visual sensor. The parameters f_x .s_x, U_o, V_0, k_l, *and* k_2, which are internal unknowns of camera, are calibrated by the internal calibration. Up to now there are many methods for the calibration. The basic principle lies in using the coordinates of the 3D or 2D target in a world coordinate system and their correspondences in the image coordinate system, to extract these parameters by some linear or nonlinear optimal method according to Eqs. (l) and (2). Among these methods, the most popular one is Tsai's RAC calibration method [12]. The Other 18 parameters of the rotation and translation vectors, which are external parameters of visual sensor, can be extracted by external or global calibration. Firstly, use the calibration target which consist of three thin wires to generate three non-collinear points on the light plane. second, compute these points' coordinates, both in the world or global coordinate system (GCS), or in theodolite coordinate system (TCS) by two theodolites, and in the sensor coordinate system (SCS) by sensors and image processing. Then calculate the rotation vector (R_1 R_4, R_7), (R_2, R_5, R_8) and translation vector (T_X, T_y,T_z) by solving the non-linear equations or least Fig. 5. Global calibration of measuring system. square fitting according to Eq. (2). Lastly, with the internal parameters of the camera and those points' coordinates in the image coordinate system, extract the rotation (r_x, r_5, r_8) and translation vector $(t_x, t_y, t_z)^T$ by the optimization method

3. EXPERIMENTAL RESULTS

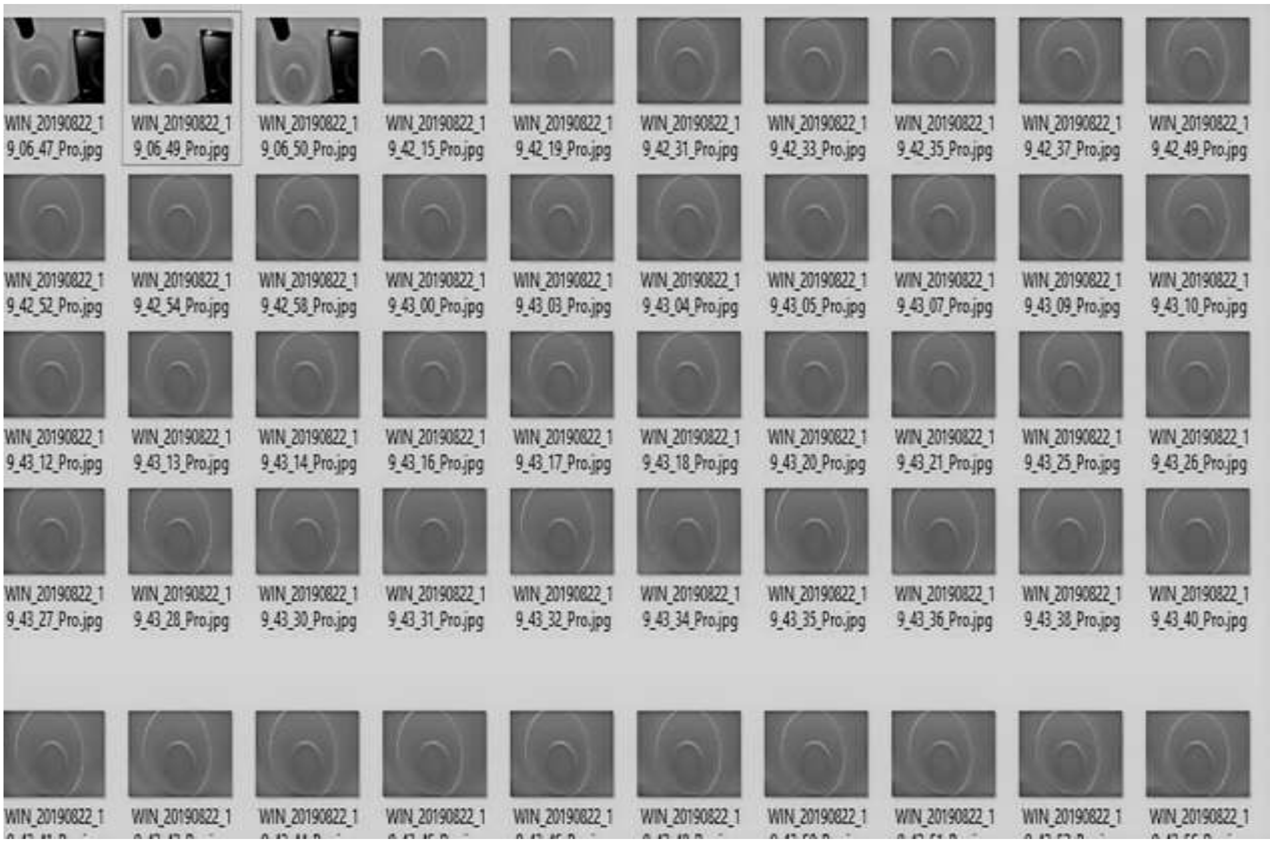

Figure 4 Experimental layout

In order to test the proposed method and obtain the measurement precision of the visual alignment measurement technique presented previously, we constructed a model of visual alignment experiment system as shown in below. Using CCD camera and one cylindrical laser, visual sensor groups, each of the group consisting of camera and cylindrical laser sources sensors arranged at the two sides. The camera used here. The center to center distance between two adjacent sensor elements in X-direction dx 0.980 m, and in Y-direction d_y 0.6357 The nominal focal length of the camera lens f is 25 mm. The sampling range of the image grabber is 512 pixels' x 512 pixels. The arrangement of sensors on one side is given in below.

System is given below, we can see that the effective focal length of the camera is not equal to the nominal one, and there is an Offset of the image center from the camera 's optical center. As shown in below, the offset in the vertical direction can be as much as 40 pixels. The radial distortion coefficient kl is enough to satisfy the precision requirement, the magnitude order of which is 10^{-4}. After the alignment measurement system was calibrated, we measured the straightness of a plastic pipe, whose nominal radius is 70 mm and length 1500 mm. The visual sensor is 400 mm away from the pipe. For the same circumference measurement, the measurements were taken at the same time. The measurement results were obtained for every 75^0 when circumrotated and next calculate the offset of every point coordinate along the pipe centerline from the base line. Then we calculate the maxim offset. Thus, the pipe's straightness can be evaluated as twice of the maxim offset. From the results, we observe that the measurement mean value is 0.557 mm with a standard deviation of 0.015 mm. In order to estimate the measurement precision of the alignment measuring system, we used a CMM to measure the pipe straightness and obtained the result of 0.50 mm. Therefore, our measurement precision for the alignment is tested to better than 0.06mm

4. DISCUSSION AND CONCLUSION

The alignment system presented above proved to be successful in the experiments. In practice, in order to obtain high measurement precision, no less than three visual sensor groups along the axes to be measured should to be used. With more measurement points used, a higher measurement precision is achievable when the pipe straightness is evaluated. For the 1500 mm long seamless steel pipe, more than five sensor groups are advisable. From the result as shown, we can observe that the experimental device is quite high in precision. Even so, better precision is still achievable. In this experimental system, due to the limitation of worktable size, the distance between sensor and the pipe was set only to 400 mm. The focal length of the camera, which is 25 mm, is a bit bigger. The measurement field of view at 400 mm from the camera is only about$50 mm$, which can cover only 1/8 of the pipe's circumference with the corresponding central angle form the pipe central line being about400. If the focal length of the camera is smaller, such as 8-16 mm, the central angle of the covered scope will be bigger than 900, and the measurement precision would be improved. The trace to the source of the measurement precision base is a steel ruler of 1000 mm long in the global calibration. If a high precision Invar ruler is used, and a precise calibration target can be obtained. Furthermore, the single measurement time of this experimental system is shorter than 2 seconds while that of CMM (including fixing time of the pipe) is about 15 minutes. Therefore, the developed model and system offers its unique advantage over the traditional methods for the diameter measurement of the pipe who’s the product time is only a few tens of seconds. Thus, it can be concluded that the laser visual alignment measurement technique is an important method for on-line and non- contact measurement. It cannot only fulfill 100% on-line measurement, but also gives high measurement precision.

A precise two-step calibration method for the linear array camera has been defined. In the first step, the mapping technique is employed to recover the projection mapping of the linear array camera by interpolating the correspondence between incident rays and image points. For the light spot within the measuring system, the plane passing through the light spot in camera coordinate frame can be calculated accurately. The second step is the calibration of extrinsic parameters, which realizes the coordinate transformation from the camera coordinate frame to world coordinate frame. In principle, the proposed method can be applied to calibrate any single viewpoint camera even if its distortion is high and asymmetric. The realized method eases the pinhole model and only extrinsic parameters are concerned in the simplified model. Therefore, the coupling between extrinsic parameters and other parameters is avoided.

In addition, the nonlinear optimization, which is used to compute the parameters of the simplified pinhole model, is better conditioned since fewer parameters are needed and more accurate initial iteration value is obtained due to the good performance of the mapping technique. Both computer simulation and real data have been used to validate the RBF-based mapping technique by evaluation of angle mapping accuracy. The mean value of the angle mapping error is 0.091 arc sec and 1.8 arcsec, respectively. Coordinate measurement experiment based on multi-plane constraint is also carried out to verify the whole calibration process by evaluation of the 3D coordinate measurement accuracy.

The proposed method promotes the maximum value of 3D coordinate error along X, Y and Z directions from 7.82 mm, 3.77 mm and 2.65 mm to 0.43 mm, 0.21 mm and 0.16 mm, respectively, compared with conventional method. Experimental results demonstrate that the proposed method is effective and the whole system calibrated by the proposed method satisfied most large-scale metrology and dynamic position-tracking applications that require sub-millimeter accuracy. In future work, firstly beam splitter prism will be introduced to the optical system. The new camera will consist of two orthogonal linear CCDs, which are used to detect the two incident angles of the 3D ray. The two angles can be calculated by the proposed RBF-based mapping technique and they correspond to four planes passing through the light spot. Therefore, one more constraint will be added for each camera, which is beneficial to improve the measurement accuracy. Secondly, the application of the proposed method for the calibration of 2D cameras will be studied for vision measurement

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