A Model of Automatic Detection System for Weld Defects Based on Machine Vision

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Abstract. To realize weld defects detection and measure automation based on machine vision, such as dimension, shape, displacement and numbers in a given length (area), it's necessary to build a mathematic model for the imaging system. Precision of model directly affects precision of measurement for defects. In this paper, a model was built including some nonlinear factors, i.e. the input screen shape (spherical surface) of the x-ray image intensifier and the distortion of the image in CCD at small distance. A kind of reason why the electromagnetic distortion generates is given in this paper, too.

1 Introduction

It's one of the most reliable and most extensively used methods in nondestructive testing to detect the defects in weld by radioscopy. It is still one of research focuses of the technology of detection automation for weld defect based on X-ray real-time image. Generally, the system of detection automation for weld defect based on X-ray real-time image consists of the ray source, work piece under testing, x-ray image intensifier, industry CCD camera, the image card and computer, etc(**Fig.1**). The x-ray image intensifier converts the invisible X-ray image containing information of defects in work piece into visible image and intensifies it. Industry CCD camera and the image card converts the analog signals into the digital image. The computer and corresponding software process the real time image to decide whether defects exist and gain all data of defect. Because computer judges them depending on the image, the relation on displacement, dimension, and shape has to be built between the real scene and the corresponding image, that is, the mathematic model has to be built to depict the imaging process of the system. Here, the model means the geometry model, that is, it's a relation between 3-D coordinates of the work piece under testing and 2-D coordinates of the corresponding image. Precision of model directly influences precision of measurement for defects, however, the common models ignore those nonlinear factors so that the error is obvious. In this paper, the model was built including some nonlinear factors, i.e. the input screen shape (spherical surface) of the x-ray image intensifier and the distortion of the image in CCD at small distance. Limited by length of the paper, calibration and experiment on the system model will be given in other papers.

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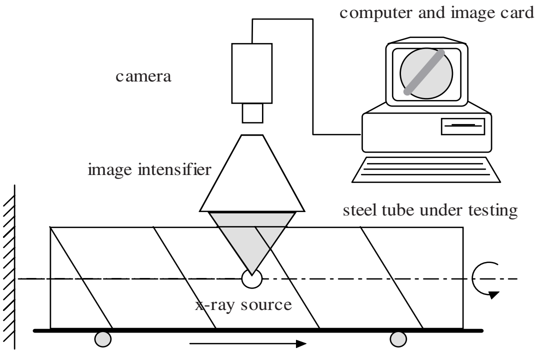

Fig. 1. The system configuration

2 Some Theoretical Foundations

2.2 The Model of Camera

Pinhole model is one of the most common and simple camera models. The principle is indicated in **Fig. 2.** However, in many occasions the model can not depict the imaging process of camera, for example, imaging at close distance and imaging by wide-angle lens, which results in distortion in image. A general camera can be reasonably seen as pinhole after some linear or nonlinear revisions are added in the model.

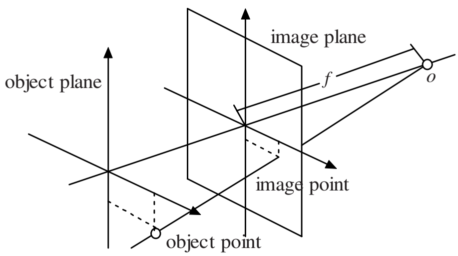

Fig. 2. The pinhole model of camera

Two-plane model does not require all light beams pass the optical center. Given any one pixel at image plane, the displacements of corresponding points of intersection can be calculated at two calibrating planes so that the beam that generates the pixel can be determined [5].

2.3 The Model of X-Ray Image Intensifier

For the model of x-ray image intensifier, the main problems considered are geometry distortion and electromagnetic distortion. The former is caused by the curved surface of the input screen of x-ray image intensifier, and the latter is caused by electromagnetic effects. The shape of input screen is usually sphere surface or hyperboloid. In this paper, it's modeled as sphere surface. In literature [1], it's modeled as hyperboloid and as plane in literature [2]. It's difficult to model electromagnetic distortion because the electromagnetic intensity is time-variable and difficult to forecast. In literature [3], it's modeled as sine function and in literature [2], the followed formula is used to model electromagnetic distortion,

$$\begin{cases} x_p' = x_p + D_{ex}(x_p, y_p) \\ y_p' = y_p + D_{ey}(x_p, y_p) \end{cases},$$

Where $D_{ex}(x_p, y_p)$ and $D_{ey}(x_p, y_p)$ are imaging distortion that the system generates at x and y directions respectively.

With research to the construction and imaging principle of x-ray image intensifier, it's noticed that photoelectrons from photoelectricity cathode are very sensitive to electromagnetic field. To prevent disturbance from outside electromagnetic field, shell of x-ray image intensifier is made of glass or other nonmagnetic material [6]. Thus disturbance from outside electromagnetic field can be ignored; however, inside the x-ray image intensifier the moving electrons generate electromagnetic field that makes electrons change their traces. The electromagnetic field is an annular field that encircles the optical axis and the intensity is inverse proportion with the distance between a point and the central axis of image intensifier and direct proportion with the number of electrons that traverse a plane during a time unit. The annular field distorts linear weld to shape of "S", which is consistent with phenomenon that is watched in manufacture occasion. Thus it's the real reason why electromagnetic distortion is generated.

2.4 Projective Geometry

In projective space $\mathbf{P^n}$, points are expressed in homogeneous coordinates, which are often shown with the number 1 in the rightmost position, e.g., $[x_1', \cdots, x_n', 1]^T$. This point is equivalent to any point that differs only by non-zero scaling. The one-to-one mapping from the n-dimensional Euclidean space $\mathbf{R^n}$ into $\mathbf{P^n}$ is given by the followed formula [4]:

$$[x_1', \cdots, x_n']^T \rightarrow [x_1', \cdots, x_n', 1]^T$$

The introduction of projective space and homogeneous coordinate made the expressions of formula simpler.

3 The Proposed Model

3.1 Definition of Some Coordinate Systems

At first, some coordinate systems are defined to be used in model (**Fig. 3**).

3D object coordinate system, whose origin is the centre of a circle from section of steel tube and Z axis is coaxial with the axis of steel tube, is fixed on work piece under testing. The movement of steel tube is spiral synthesized by rotating movement encircling Z axis and translation along Z axis. Any point M on steel tube can be expressed as $M = [X_M \; Y_M \; Z_M]^T$, and as $M = [X_M \; Y_M \; Z_M \; 1]^T$ in homogeneous coordinates;

The origin of 3D world coordinate system is defined in the ray source, that is, optical center of the central projection. Z axis of world coordinate system parallels with the optical axis of x-ray image intensifier (the hypothesis is reasonable because there is always a radial that parallels with the optical axis of x-ray image intensifier). $\bar{Y}$ - $\bar{Z}$ plane of world coordinate system is the plane determined by $\bar{Y}$ axis and the optical axis of x-ray image intensifier. The coordinates of the point M are denoted by $\bar{M} = [\bar{X}_M \; \bar{Y}_M \; \bar{Z}_M]^T$ and $M = [X_M \; Y_M \; Z_M \; 1]^T$ in homogeneous coordinates. It's considered that object coordinate system translates into world coordinate system by a 3x3 rotation matrix R_M and a 3x1 translation vector T_M. In projective space, the transform can be expressed by a 4x4 matrix S_M, that is,

$$S_M = \begin{bmatrix} R_M & T_M \\ 0 & 1 \end{bmatrix}_{4\times 4}$$

Thus the transform of point M between world coordinate system and object coordinate system can be expressed as,

$$\bar{M} = S_M M \tag{1}$$

The matrix S_M contains six unknown parameters, which are three Euler angles α, β, γ and three translation parameters t_x, t_y, t_z.

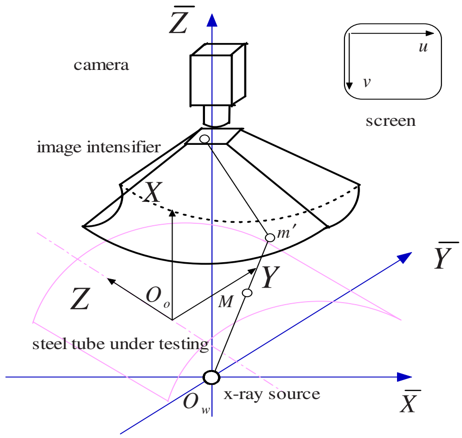

Fig. 3. Sketch of some coordinate systems

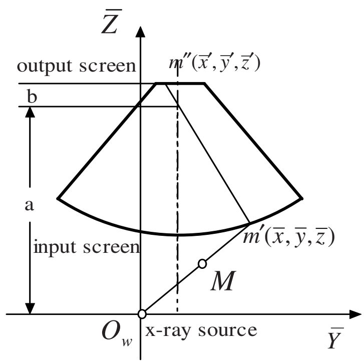

Fig. 4. Geometry transform in the image intensifier

2D image coordinates system, is used to represent pixel coordinates of the image formed at the camera. The image point m corresponding to object point M can be expressed as $m = [u_M \; v_M]^T$. The origin of image coordinates system is at top-left corner of computer screen and x axis is rightward horizontally and y axis is downward vertically.

3.2 Models of Every Imaging Part

The imaging system can be partitioned into three parts:

1. Object-input screen of image intensifier (**Fig. 4**). The image point m' in the input screen of image intensifier corresponds to the point M in the work piece under testing and the coordinates of m' are calculated as the intersection of the line containing the origin of world coordinates system and the point M with the sphere surface, input screen of image intensifier.

According to rule that the world coordinates system is set, the coordinates of the sphere center is expressed as $(0, y_0, z_0)$, then the sphere surface is defined in world coordinates system by

$$\overline{X}^2 + (\overline{Y} - y_0)^2 + (\overline{Z} - z_0)^2 = R^2 \tag{2}$$

With R is the radius of the sphere.

The coordinates of m' in the world coordinates system are expressed as $m'(\overline{x}, \overline{y}, \overline{z})$, the line containing the origin of world coordinates system and the point M with the sphere surface is defined in world coordinates system by

$$\frac{\overline{X}}{\overline{X}_M} = \frac{\overline{Y}}{\overline{Y}_M} = \frac{\overline{Z}}{\overline{Z}_M} \tag{3}$$

That is,

$$\overline{X} = \frac{\overline{X}_M}{\overline{Z}_M} \cdot \overline{Z} \tag{4}$$

$$\overline{Y} = \frac{\overline{Y}_M}{\overline{Z}_M} \cdot \overline{Z} \tag{5}$$

Uniting the formulas(2),(4),(5), the coordinates of m can be gained as,

$$\begin{cases} \overline{x} = \overline{X}_M \cdot \dfrac{(z_0 \overline{Z}_M + y_0 \overline{Y}_M) \pm \sqrt{\Delta}}{\overline{X}_M{}^2 + \overline{Y}_M{}^2 + \overline{Z}_M{}^2} \\ \overline{y} = \overline{Y}_M \cdot \dfrac{(z_0 \overline{Z}_M + y_0 \overline{Y}_M) \pm \sqrt{\Delta}}{\overline{X}_M{}^2 + \overline{Y}_M{}^2 + \overline{Z}_M{}^2} \\ \overline{z} = \overline{Z}_M \cdot \dfrac{(z_0 \overline{Z}_M + y_0 \overline{Y}_M) \pm \sqrt{\Delta}}{\overline{X}_M{}^2 + \overline{Y}_M{}^2 + \overline{Z}_M{}^2} \end{cases} \tag{6}$$

With $\Delta = 2y_0 z_0 \overline{Y}_M \overline{Z}_M + R^2 \cdot (\overline{X}_M{}^2 + \overline{Y}_M{}^2 + \overline{Z}_M{}^2) - y_0{}^2 \cdot (\overline{X}_M{}^2 + \overline{Z}_M{}^2) - z_0{}^2 \cdot (\overline{X}_M{}^2 + \overline{Y}_M{}^2)$, "$\pm$" means two intersections and "$-$" should be selected based on real condition.

The part contains three unknown parameters R, y_0 and z_0.

2. The part of image intensifier. The image point $m'(\overline{x}, \overline{y}, \overline{z})$ in the input screen of image intensifier is projected through the optical center of the image intensifier onto the output screen as point $m''(\overline{x}', \overline{y}', \overline{z}')$, which is calculated as the intersection of the line containing the point $m'(\overline{x}, \overline{y}, \overline{z})$ and the optical center of the image intensifier with the output screen.

The optical center of the image intensifier is expressed as $O_I(0, y_0, a)$, then

$$\frac{\overline{X}}{\overline{x}} = \frac{\overline{Y} - y_0}{\overline{y} - y_0} = \frac{\overline{Z} - a}{\overline{z} - a} \tag{7}$$

The formula of the output screen is

$$\overline{Z} = a + b \tag{8}$$

Then,

$$\begin{cases} \overline{x}' = \dfrac{b}{\overline{z} - a} \cdot \overline{x} \\ \overline{y}' = y_0 + \dfrac{\overline{y} - y_0}{\overline{z} - a} \cdot b \\ \overline{z}' = a + b \end{cases} \tag{9}$$

The part contains two unknown parameters a and b.

3. The part of camera-output screen of image intensifier. The camera takes visible light images from the output screen of the image intensifier. With short distance between object imaged and camera, the distortion has to be considered if pinhole model of camera is used. Particularly, the revision of the distortion is required when the images are used to measure.

Corresponding to object point M, the coordinates of the image point on the output screen are expressed as $m''(\overline{x}', \overline{y}', \overline{z}')$. All image points on the output screen are coplanar, so model of the part may ignore the $\overline{Z}$ ordinate. The image point $m''(\overline{x}', \overline{y}')$ is projected on the CCD as the image point $m(\tilde{u}, \tilde{v})$ by the matrix $B_{3\times3}$, that is,

$$\begin{pmatrix} \tilde{u} \\ \tilde{v} \\ 1 \end{pmatrix} = B_{3\times3} \cdot \begin{pmatrix} \overline{x}' \\ \overline{y}' \\ 1 \end{pmatrix} \tag{10}$$

The matrix $B_{3\times3}$ contains nine unknown parameters, which depict displacement transform of the camera, the focus, the coordinates of optical center of the camera and the scales factors of two coordinates, etc.

Furthermore, the image distortion of the camera is considered. The main distortion is in radial direction. The distortion is centrosymmetric and is expressed by a polynomial. The coordinates of the revised image point m can be defined by

$$\begin{cases} u = \tilde{u} \cdot \left[1 \pm k \cdot (\tilde{u}^2 + \tilde{v}^2)\right] \\ v = \tilde{v} \cdot \left[1 \pm k \cdot (\tilde{u}^2 + \tilde{v}^2)\right] \end{cases} \tag{11}$$

Where k is the factor that represents distortion and "+" means pincushion-like distortion and "$-$" means barrel-like distortion.

The part contains ten unknown parameters.

In conclusion, the formula (1),(6),(9),(10),(11) forms the model of the system containing the ray source, work piece under testing, x-ray image intensifier, industry CCD camera, the image card and computer with 21 unknown parameters which need to be determined by calibration.

4 Calibrations

Calibration is a process that all unknown parameters of the model are determined. Some of the parameters are supplied by the machine but the precision is inadequate and they are changed as it is installed. Some of the parameters can be measured though they are not supplied. Some of parameters are difficult to measure. Calibration contains two steps. At first, the projection matrix need be confirmed from the real object to the corresponding image. Secondly, every unknown parameter is calculated from the projection matrix by some method. It's noticed that the second step is always not required.

Calibration is an important research area and the method can be partitioned into two kinds. One kind is conventional and based on an object that contains some feature points whose relative coordinates are known accurately. The other kind is self-calibration. Based on complex degree and reliability of calibration, this paper used the first kind of method. What need do is to confirm coordinates of those image points corresponding to known object points in real world, and then by using the model and some methods such as the least square method, nonlinear optimization method, the unknown parameters can be calculated. Another method is to calculate the approximate values of the parameters of the linear model, then to calculate precise values based on the approximate values by iterative method.

5 Conclusions

To the automatic weld defects detection system based on machine vision, a precise model is a precondition to measure automatically dimension, shape, and position of defects. It is also helpful to understand the imaging principal of the system. This paper analyzed every part of the system in detail in order to build a model that contains some nonlinear factors such as the sphere characteristic of the input screen of image intensifier and the imaging distortion of camera. The model can be helpful to realize high precision measurement.

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