Flexible Shape Measurement System for Chemical Plant Using Magnetic Sensors

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Abstract: We propose a flexible computer vision system using magnetic sensors. The system enables a flexible free scanning of a CCD camera and a laser slit using 3D magnetic sensors. Many numbers of views of each model from different angles can be taken on measuring the configuration between a CCD camera and a laser slit projector simultaneously. The information of different views is combined to reconstruct the 3D object on a computer display. In this paper, the application for pipe measurement is introduced. Experimental results show the feasibility of our system.

1 INTRODUCTION

Replacement or construction of new pipes is often carried out for the renewal of the superannuated facilities in a chemical plant and general factory. Generally, as the facilities in the plant are running continuously, the period of the replacement work should be minimum time to keep the productivity. In order to cope with this requirement, detailed and exact data (drawing) of the pipe arrangements are indispensable. However, almost all drawings do not correctly match with the state of current pipe arrangements in the factory. Therefore, the re-measurement of the pipes is required frequently at the plant. Generally, the re-measurement is conducted by manually using a metal tape measure etc. and it causes the redo of the replacement or construction works since the accuracy of the manual measurement is uncertain.

Recently, the three-dimensional measurement systems with a laser scanner are widely used in various fields (Faugeras, 1996; Ochiai, 1988; Torras, 1992). These systems have begun to be utilized also for the equipment measurement in chemical plants. The measurement system can obtain thousands of point cloud data with three-dimensional position in a few second. Point cloud data are sets of vertices in a three-dimensional coordinate system. The point cloud data are useful for the fundamental data to grasp the situation of the facilities in the plant. In the typical measurement system with a laser scanner, an infrared laser is sent out and reflected back to the system. The distance is measured by the time of flight of the laser pulse between the device and target, or the shift in the wavelength of the return beam(Pueschel, 2013). However, since these laser scanners are generally fixed on the stable ground with a tripod, the setting position is restricted and the unmeasurable area are existed such as the narrow or pipes crowded area etc. These areas have to be measured by conventional way using metal measure etc. Therefore hand held measurement system for the measurement in such a crowded area has been required.

In this paper, hand held measuring system using magnetic sensors is introduced. This system is based on the slit-ray projection method. Slit-ray is projected on the surface of an object and the reflected light is recorded by a CCD camera. Three-dimensional position on the slit is calculated on considering the configuration of the CCD and the laser projector. Proposed system with magnetic sensors enables us a separated free scanning of each of a CCD camera and a laser slit projector. The magnetic receiver (Polhemus Inc.) is attached in each of a CCD camera and a laser projector. The magnetic transmitter is placed on the fixed table and the magnetic fields are generated from the transmitter. The magnetic receiver detects the each three-dimensional position and the orientation of the

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CCD camera and the laser projector at 60Hz on considering the received magnetic strength and direction. Many numbers of views of a model from different orientations are taken on measuring the configuration between a CCD camera and laser-slit simultaneously. User directs the laser on the measuring target and the CCD detects the image from the position where the reflected light is visible. It enables the flexible measurement for a complex area. The information of different views can be combined to reconstruct the 3D object on a computer display with minimum loss of data.

For one of the applications of our system, the shape measurement of pipes is introduced in this paper. The proposed system was applied to measure the shape and arrangements of pipes. Furthermore, 3D temperature measurement is introduced for one of the application of our system. Experimental results show the feasibility of our system.

2 SYSTEM SETTING

Figure 1 shows the setup of the measurement system. The system consists of a CCD camera, slit laser projector. Electric magnetic receiver is attached on each of the CCD camera and the slit laser projector. The magnetic transmitter is placed on the fixed table near the magnetic receivers. A slit ray is projected on the surface of the measuring object and the CCD camera records the reflected light that appears on the surface of the object. The transmitter of the electro-magnetic sensor generates the magnetic field and the magnetic field is detected by the each of the magnetic receiver. The signal from the magnetic receiver is sent to the main controller to calculate the three-dimensional position and the orientation (Azimuth, Elevation, Roll) of the receiver. (McCallum, 1996, 1998; Nixon, 1998).

The positions and the direction of the CCD camera and the laser projector are detected at a rate of 60 Hz during the measurement; therefore, it enables the flexible measurement by a free scanning of the CCD camera and the laser.

3 MEASUREMENT PROCEDURE

The relation between the camera coordinates and the receiver coordinates is shown in Figure 2. The measurement procedure is to estimate the intersection between the laser plane and the vector from the focal point F of the CCD camera. The laser

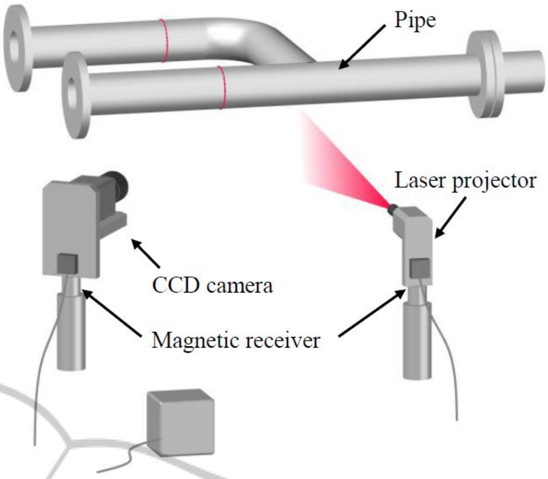

Figure 1: Setup of the measuring system.

plane and vector from the focal point of the CCD camera is detected on real time during the measurement by the magnetic sensors.

The electro-magnetic sensor receiver attached on the laser slit projector enables the real-time detection of laser plane information. The information detected by the magnetic receiver is the three-dimensional position (x_{ow}, y_{ow}, z_{ow}) and the orientation (Ψ: Azimuth, Θ: Elevation, Φ: Roll) of the magnetic receiver itself. This information is used to determine the equation of the laser plane. The arbitrary three points on a laser plane on receiver coordinates originated at the receiver position are converted into the world coordinates (x_{rw}, y_{rw}, z_{rw}) originated at the transmitter position by the following formula.

$$\begin{bmatrix} x_{rw} \\ y_{rw} \\ z_{rw} \end{bmatrix} = RPY(\Psi, \Theta, \Phi) \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} + \begin{bmatrix} x_{ow} \\ y_{ow} \\ z_{ow} \end{bmatrix} \tag{1}$$

where

$$RPY(\Psi, \Theta, \Phi) =$$

$$= \begin{bmatrix} C_\Psi & -S_\Psi & 0 \\ S_\Psi & C_\Psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_\Theta & 0 & S_\Theta \\ 0 & 1 & 0 \\ -S_\Theta & 0 & C_\Theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_\Phi & S_\Phi \\ 0 & S_\Phi & C_\Phi \end{bmatrix}$$

$$= \begin{bmatrix} C_\Psi C_\Theta & C_\Psi S_\Theta S_\Phi - S_\Psi C_\Phi & C_\Psi S_\Theta C_\Phi + S_\Psi S_\Phi \\ S_\Psi C_\Theta & S_\Psi S_\Theta S_\Phi + C_\Psi C_\Phi & S_\Psi S_\Theta S_\Phi - C_\Psi S_\Phi \\ -S_\Theta & C_\Theta S_\Phi & C_\Theta C_\Phi \end{bmatrix}$$

C: Cos., *S*: Sin.
Ψ: Azimuth, Θ: Elevation, Φ: Roll

Three arbitrary three points on a laser plane are converted to world coordinates originated at the transmitter position by (1) and the laser plane equation is determined on the world coordinates as following equation.

$$[x, y, z]\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \tag{2}$$

where

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} x_{rw1} & y_{rw1} & z_{rw1} \\ x_{rw2} & y_{rw2} & z_{rw2} \\ x_{rw3} & y_{rw3} & z_{rw3} \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

The detection process of the laser plane information is executed at 60Hz. The point appeared on the image plane is explained by using the camera coordinates with an origin at focal point as following.

$$u = f \cdot \frac{X}{Z}, v = f \cdot \frac{Y}{Z} \tag{3}$$

This relation can be expressed by matrix as following.

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{4}$$

In order to convert this camera coordinates into the receiver coordinates with an origin at the receiver, parameters (k_{11}-k_{33}) are introduced on considering the rotation and displacement as following.

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} \\ k_{21} & k_{22} & k_{23} & k_{24} \\ k_{31} & k_{32} & k_{33} & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \tag{5}$$

Equation (5) indicates the relation between the camera coordinates and the receiver coordinates. This equation can be converted also as following.

$$\begin{cases} (k_{31}u - k_{11})x + (k_{32}u - k_{12})y + (k_{33}u - k_{13})z = k_{14} - u \\ (k_{31}v - k_{21})x + (k_{32}v - k_{22})y + (k_{33}v - k_{23})z = k_{24} - v \end{cases} \tag{6}$$

The eleven parameters k_{11}-k_{33} can be determined by setting some corresponding coordinates that the values are already known. The calibration setup is shown in Figure 3. The image of the scale board is recorded by the CCD camera and is displayed on the computer display. A mouse device and a keyboard set the camera coordinates and the receiver coordinates, respectively.

The equation (6) indicates the two planes. The intersectional line between these planes indicates the line from the focal point F to the measuring point on the receiver coordinates. The line can be expressed with an extra parameter t as following.

$$\begin{cases} x = f \cdot t + m \\ y = g \cdot t + n \\ z = h \cdot t + l \end{cases} \tag{7}$$

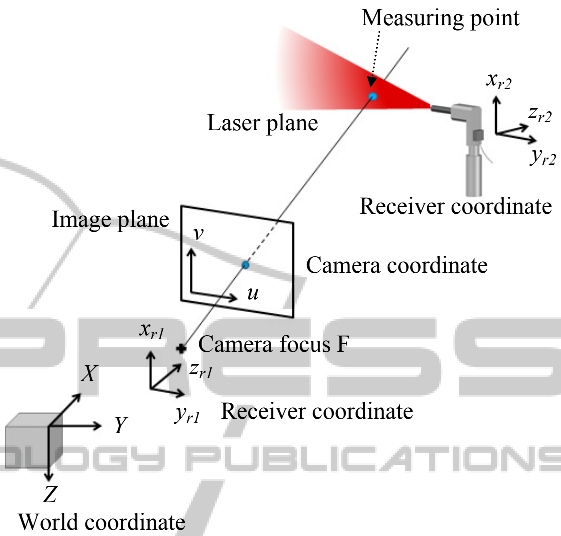

Figure 2: Relation between camera coordinates and receiver coordinates.

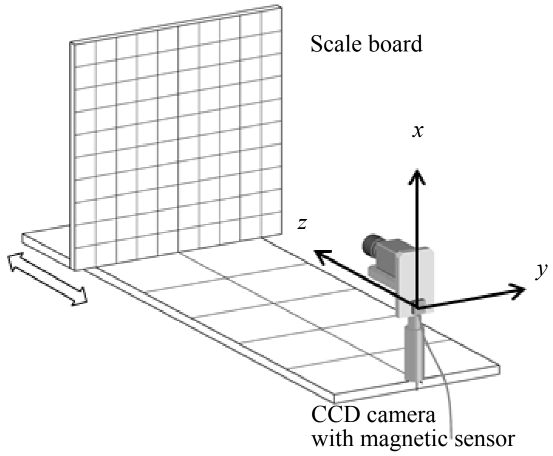

Figure 3: Calibration setup.

where (f,g,t) is a vector that the direction is from focal point of the camera to the measuring point and (m,n,l) is a point located on the line on the receiver coordinates. This receiver coordinates can be converted to the world coordinates with an origin at the transmitter as following formula.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = RPY(\Psi,\Theta,\Phi)\begin{bmatrix} f\cdot t+m \\ g\cdot t+n \\ h\cdot t+l \end{bmatrix} + \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} \tag{8}$$

Where *RPY* is an orientation of the receiver and (w_x, w_y, w_z) indicates the position of the receiver.

The position of measuring point on the world coordinates can be determined as the intersection between the laser plane and the line from focal point of the CCD camera to measuring point. The position *(X, Y, Z)* can be calculated from (2) and (8). It is rearranged as following.

$$\begin{bmatrix} A & B & C & 0 \\ 1 & 0 & 0 & -f\cdot RPY(\Psi,\Theta,\Phi) \\ 0 & 1 & 0 & -g\cdot RPY(\Psi,\Theta,\Phi) \\ 0 & 0 & 1 & -h\cdot RPY(\Psi,\Theta,\Phi) \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \\ t \end{bmatrix} = \begin{bmatrix} 1 \\ m\cdot RPY(\Psi,\Theta,\Phi)+w_x \\ n\cdot RPY(\Psi,\Theta,\Phi)+w_y \\ l\cdot RPY(\Psi,\Theta,\Phi)+w_z \end{bmatrix} \tag{9}$$

4 EXPERIMENTS

Since the system is based on the principle of triangulation, the angle between the CCD camera and the laser slit influences the measurement accuracy. Therefore, in this experiment, the angle between the CCD and the laser slit was changed by 5 degree, and the accuracy of the measurement was evaluated. Figure 4 shows the example of the measurement accuracy in this experiment when a plane board was set at distance 426 mm from the CCD. The results of the measured positions were evaluated at the known position on the plane board on each angle between the CCD camera and the laser. When the angle between the CCD camera and the laser slit was over 20 degree, the error was less than 1 mm.

In the measurement using our proposed system, an operator projects the laser slit on the target and the slit ray reflected on the surface of the target is recorded by the CCD camera from the angle where the slit ray is visible. CCD camera and laser projected can be moved separately and it enables us the flexible measurement. The pipe can be reconstructed from more than two sets of the cross-sectional point cloud data. The photograph of measured pipes is shown Figure 5. They are made of plastic and the diameters are 114 mm. Figure 6 shows the point cloud data obtained by our system and Figure 7 shows the reconstructed pipe from the point cloud data.

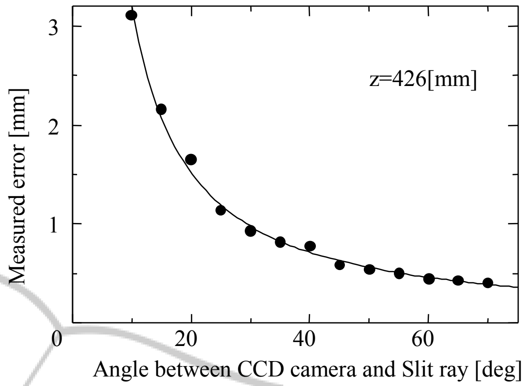

Figure 4: Measurement accuracy.

Figure 5: Photograph of measured pipes.

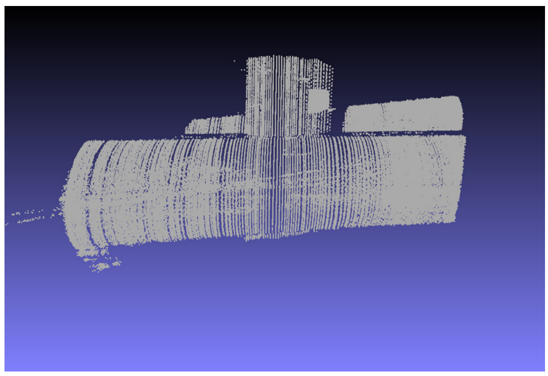

Figure 6: Point cloud data of measured pipes.

The three-dimensional temperature distribution can be measured using thermography attached on our system (Li, 2013). Figure 8 shows the three-dimensional temperature measurement system. In order to allocate the temperature data into the 3D

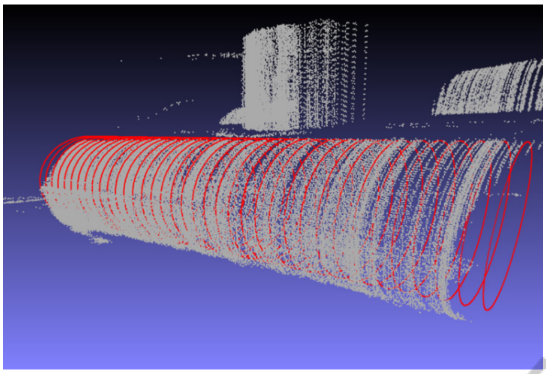

Figure 7: Reconstructed pipe from the point cloud data.

shape data, it is necessary to calibrate the thermography since the corresponding position relationship between thermography coordinates and world coordinates need to determine in advance. The relationship between thermography coordinates (u_t, v_t) and world coordinates (x,y,z) is formulated as follows.

$$s\begin{bmatrix}u_t\\v_t\\1\end{bmatrix}=\begin{bmatrix}h_{11}&h_{12}&h_{13}&h_{14}\\h_{21}&h_{22}&h_{23}&h_{24}\\h_{31}&h_{32}&h_{33}&1\end{bmatrix}\cdot\begin{bmatrix}x\\y\\z\\1\end{bmatrix} \tag{10}$$

Where, it is called as thermography calibration that estimates the parameters (h_{11} to h_{33}). These parameters can be determined by inputting some corresponding coordinates between the thermography coordinates and the world coordinates. Equation (11) can be written as follows.

$$\begin{cases}u_t=\dfrac{(h_{11}x+h_{12}y+h_{13}z+h_{14})}{(h_{31}x+h_{32}y+h_{33}z+1)}\\ v_t=\dfrac{(h_{21}x+h_{22}y+h_{23}z+h_{24})}{(h_{31}x+h_{32}y+h_{33}z+1)}\end{cases} \tag{11}$$

Once parameters h_{11} to h_{33} and world coordinates of measurement points on the surface of a target object are determined, the corresponding thermography coordinates can be calculated by equation (11). Therefore, the corresponding temperature data can be allocated to the reconstructed shape of a target object. Figure 9 shows the reconstructed three-dimensional shape with temperature of a plastic pipe.

5 CONCLUSION

Three-dimensional measurement system which enables a separated free scanning of a CCD camera and a laser slit has been introduced. An operator can change the configuration flexibly between a CCD camera and a laser slit according to the complexity of the target. It should take a larger angle between a laser and camera for a smooth area, and smaller angle for a complicated area. Since the angle between the CCD camera and the laser influences the measurement accuracy during the measurement, the result depends on the operator's experience. It is desirable to record the reliability on a measurement result with digital data.

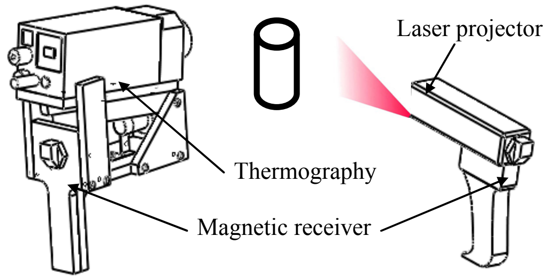

Figure 8: Three-dimensional temperature measurement system.

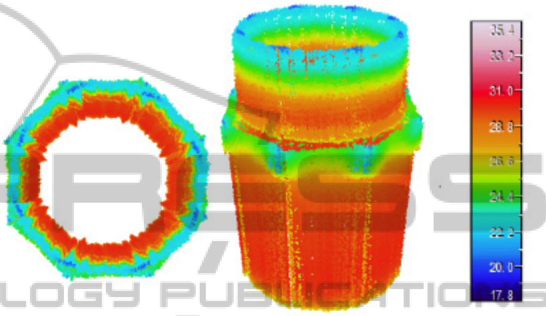

Figure 9: Reconstructed three-dimensional shape with temperature.

For one of the applications of our system, the shape measurement of pipes is introduced in this paper. The proposed system was applied to measure the shape and arrangements of pipes. Furthermore, 3D temperature measurement is introduced for one of the application of our system. Experimental results show the feasibility of our system.

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