Compact Three-dimensional Vision for Ubiquitous Sensing

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***Abstract*—We herein propose two computer vision systems that make use of the Microsoft KINECT sensor for ubiquitous sensing in raising stock and in industrial fields. The first system is a three-dimensional (3D) thermo-sensing system that detects 3D shape data and 3D temperature data simultaneously. These data are automatically combined, and the 3D shape and temperature distribution are reconstructed on the computer. The second system is a handheld 3D measurement system that uses a slit-ray projector in conjunction with the KINECT sensor. The 3D shape of the target is reconstructed on a computer using the detected data. These two systems are sufficiently compact and the measurement can be performed via online processing. As such, these systems will be useful in ubiquitous data acquisition systems in various fields. Typical applications of the proposed systems include environment sampling, health monitoring of animals, monitoring of facilities in raising stock, and industrial fields. The experimental results of the present study demonstrate the feasibility of the proposed system.**

Keywords-computer vision; KINECT; thermo-sensing; three-dimensional sensing.

I. INTRODUCTION

In realizing a ubiquitous society, the development of a compact system that can detect various data at a site is effective. Once they have been detected digitally, the data can be distributed through a network and can be used effectively. Recently, Charge coupled device (CCD) cameras have been made more compact and have been incorporated into a number of mobile phones. Indeed, mobile phones containing CCD cameras are considered to be the most familiar data acquisition system. Although CCD cameras capture primarily two-dimensional image data, three-dimensional (3D) data (point cloud) are required for various applications.

A point cloud is a set of vertices in a 3D coordinate system. Point clouds are used in Computer-Aided Design (CAD) data and robot vision systems. In recent years, inexpensive devices, such as the Microsoft KINECT sensor [1]-[4], which detects 3D point cloud data, have become available. The KINECT sensor is composed of a random dot projector and an Infrared (IR) camera. Random dots are projected from the laser projector, and the reflected light from the surface of objects is recorded by the IR camera. The dots recorded by the IR camera are triangulated in order to calculate the 3D position of an object based on the configuration of the laser projector and the IR camera. Such devices are useful for motion capture or modeling systems, which do not require high accuracy. Recently, The KINECT sensor has also been used in ubiquitous computing [5]-[8].

In using the KINECT sensor, there is no limitation on the measurement area size because individual 3D point cloud data sets recorded from different positions can be combined. The Iterative Closest Point (ICP) algorithm [9]-[13] is often used to combine data sets. This algorithm automatically determines the overlapping area between 3D point cloud data sets and constructs a single 3D image. The KINECT sensor can obtain thousands of point cloud data sets in real time and so is a very attractive sensor. We herein introduce two applications using the KINECT sensor.

In recent years, thermal imaging measurement technology has developed rapidly. Infrared thermography has been used in animal sciences. Non-destructive evaluation in raising stock or in animal research is one example of such an approach. However, since images used in such evaluations are two-dimensional thermal images, quantitative information such as the area, the 3D shape, and the roughness of the heat source, cannot be obtained. In order to obtain the quantitative information, we herein propose a measurement system that uses the KINECT sensor in conjunction with thermography to produce 3D shapes and 3D thermo-grams. Periodically evaluating the condition of Japanese black cattle during the growth process is important [14]. In addition to the weight and size of cattle, the body temperature should be measured as primary evaluation criteria. Quantitative measurement of 3D temperature and shape can be established using the proposed system. The proposed system can be a useful tool for monitoring the condition of cattle in breeding farms.

Another application of the proposed system is the measurement of facilities in industrial fields, such as the chemical industry. However, the original data obtained by the KINECT sensor is not sufficiently accurate for industrial applications. On the other hand, the slit-ray projection method [15]-[17] (i.e., shape from structured light), which has high measurement accuracy, is widely used in industrial applications and robot vision systems. In this method, a laser slit is projected onto the surface of the target object and the laser streak generated on the surface is detected by a CCD camera. The 3D position data of the laser slit is estimated by triangulating the orientation of the laser projector and the CCD camera [18][19]. In the present study, we introduce a point cloud data acquisition system that uses slit ray projection and a KINECT sensor. The proposed system is sufficiently compact to allow its use as a hand-held device. During measurement, the user directs the laser slit ray at the target. The KINECT sensor then detects point cloud data while the CCD camera simultaneously detects the laser streak generated on the surface of the target. The user manually scans the system by directing the laser slit ray along the measurement pipe. The point cloud data obtained using the KINECT sensor is used to determine the movement of the system by adjusting overlapping data in consecutive frames using the ICP algorithm. The data obtained by the laser slit-ray projection method are more accurate than the original point cloud data obtained by the KINECT sensor because the data are obtained using a high-resolution camera. The pipe cross section is estimated based on data obtained by the slit-ray projection method. The 3D shape of the pipe is constructed on a computer from cross sections obtained from different positions. The proposed system enables onsite measurement in chemical plants and can be used in obtaining information on the current condition inside the plant, which can be used in plant evaluation and maintenance.

Two systems that use the KINECT sensor are introduced in the present paper to use as effective tools for realizing a ubiquitous society. The remainder of the present paper is organized as follows. Section 2 describes the proposed 3D thermo-sensing system using the KINECT sensor, and Section 3 describes the application of the proposed system. Section 4 describes a pipe measurement system that uses the slit-ray projection method in conjunction with the KINECT sensor. Section 5 describes the pipe reconstruction results obtained using the proposed system. Finally, the paper is concluded in Section 6.

II. THERMO-SENSING SYSTEM USING THE KINECT SENSOR

The measurement system is shown in Figure 1. The 3D thermal-sensing system is established using a 3D measurement sensor (KINECT sensor) and a thermograph (NEC, 320×240, 60 Hz). A flowchart of the measurement procedure is shown in Figure 2. The 3D shape measurement is performed using the KINECT sensor, while the thermograph simultaneously captures a thermal image. The corresponding temperature data obtained by thermography is then allocated to the reconstructed surface shape of the object on a computer. This allocation is established using a pre-determined conversion matrix, which is determined during the calibration process.

Calibration is important in determining the coordinate conversion between global coordinates and thermography coordinates. Generally, the calibration process in a 3D measurement system is complicated and not universal. In the proposed system, the thermography coordinates have to be determined precisely in the calibration process because they influence the temperature mapping accuracy onto the surface of the object. A suitable calibration method for thermography is proposed.

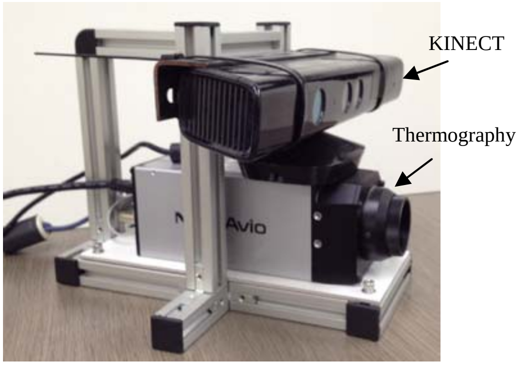

Figure 1. Measurement system.

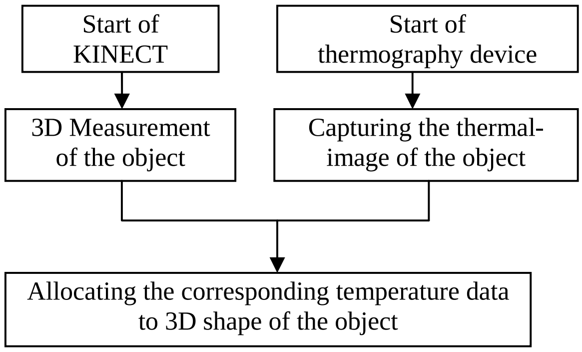

Figure 2. Measurement procedure.

A standard cube is used to match the coordinates among the global coordinate system and the thermography coordinate system, because a thermal image can be recorded by thermography. The calibration setup is shown in Figure 3. The 3D shape of the standard cube is measured using the KINECT sensor, and the thermal image of the standard cube must be recorded simultaneously by thermography because the recorded thermal image is used to determine the calibration parameters.

The relationship between the thermography coordinates (u, v) and the global coordinates (x, y, z) of a point is as follows:

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

where k_{11} through k_{33} are parameters that consider the rotation, scale, and displacement between the thermography coordinates and the global coordinates. These parameters are the elements of conversion matrices and are determined by inputting some corresponding positions between the thermography coordinates and the global coordinates. Here, k_{11} through k_{33} can be determined by inputting no less than

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six corresponding points into Eq. (1).

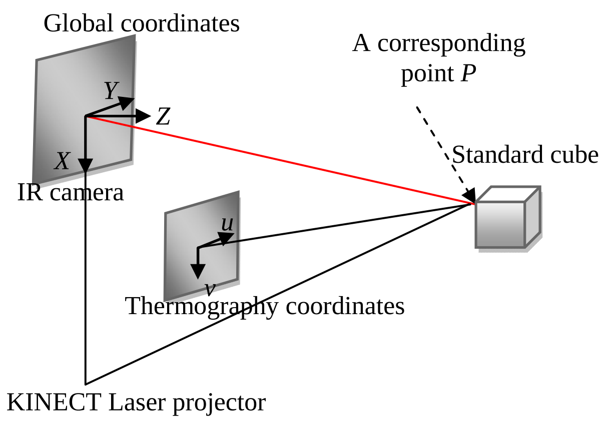

Figure 3. Calibration setup.

Equation (1) can be rewritten as follows:

$$\begin{cases} u = (k_{11}x + k_{12}y + k_{13}z + k_{14}) / (k_{31}x + k_{32}y + k_{33}z + 1) \\ v = (k_{21}x + k_{22}y + k_{23}z + k_{24}) / (k_{31}x + k_{32}y + k_{33}z + 1) \end{cases} \quad (2)$$

Once k_{11} to k_{33} are determined, the thermography coordinates can be calculated using Eq. (2), and the corresponding temperatures can also be mapped on the reconstructed surfaces of the object.

Based on the presented mathematical model, it is possible to determine the parameters that contain the position and posture of the IR camera. Once the 3D shape of the object is measured, the corresponding temperature is mapped from the thermal-image using Eq. (2).

III. APPLICATION TO MEASURE THE TEMPERATURE IN CATTLE

Periodically evaluating the condition of Japanese black cattle during the growth process is important. The weight, size, posture, body shape, and body temperature are measured as the primary evaluation criteria.

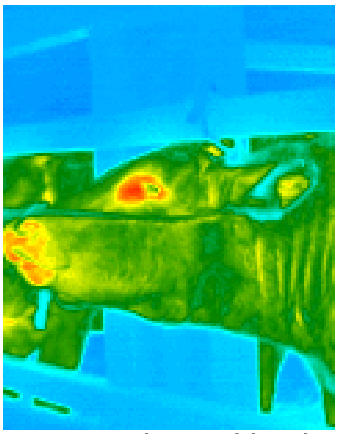

Figure 4. Two-dimensional thermal image.

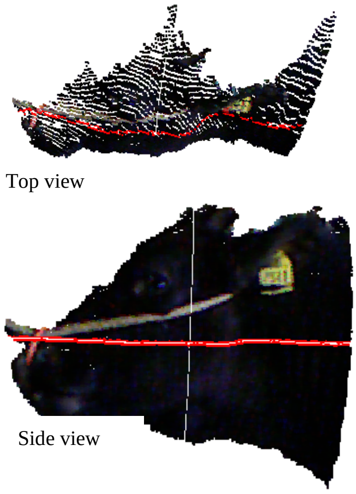

Figure 5. Point cloud data of the face of a cow.

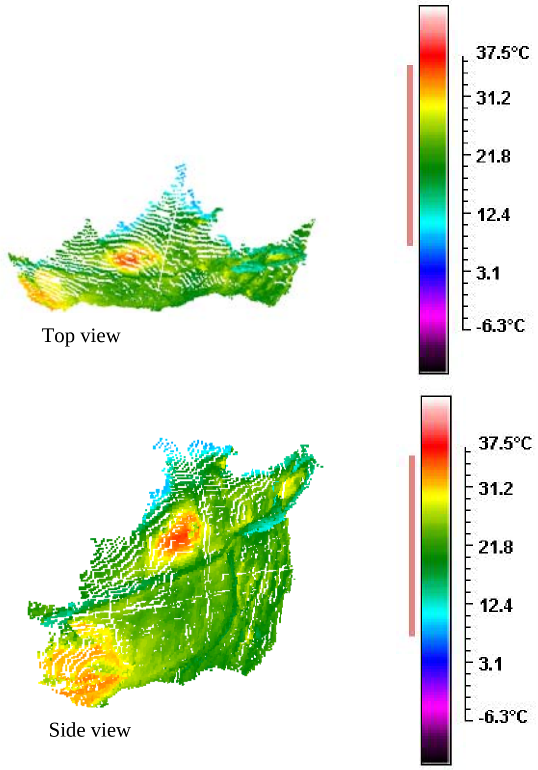

Figure 6. Constructed 3D thermal image.

A computer vision device can be a useful tool for evaluating the condition of cattle. Therefore, we used 3D thermo-sensing to measure the body shape and temperature of cattle.

Figure 4 shows a two-dimensional thermal image recorded by thermography. The image in this figure contains the temperature distribution of a cow's head but not quantitative information such as the dimensions of the cow's head. Figure 5 shows the point cloud data detected by the KINECT sensor. The temperature data contained in the

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thermal image is mapped to point cloud data. Figure 6 shows the constructed 3D thermal image that was calculated using the proposed method. Since this result contains the 3D quantitative shape of the cattle along with temperature information, the information is useful for animal science, for example, in budget calculation.

IV. APPLICATION FOR PIPE MEASUREMENT

In the chemical plant, the shapes and the arrangement of existing pipes should be investigated before the replacement or the construction of new pipes. Generally, measurement is conducted manually using a metal tape measure and is a cumbersome task. Recently, A number of laser scanners have been introduced for use in the measurement of pipes. The laser scanner is a very attractive option because thousands of sets of point cloud data can be obtained in a short time. However, the volume of data obtained is very large, because the data includes unnecessary information such as ground data, wall data, and data related to other equipment. Extra work is required in order to extract the appropriate information from the huge volume of point cloud data for the design of new pipes. Therefore, the development of an effective method is required in order to extract the desired information from the point cloud data. In addition, certain pipes that are located at high positions that the laser cannot reach are not measured, because the laser scanner is fixed on stable ground.

Figure 7 shows the measurement system. A high-resolution CCD camera (resolution: 3,488×2,616) is attached to a Microsoft KINECT sensor. A laser slit projector (20 mW), which must be held within 300 to 500 mm from the CCD camera, is also attached to the measurement system. During the piping measurement, the user directs the laser slit ray at the target. The KINECT sensor then detects point cloud data, while the CCD camera simultaneously detects the laser streak generated on the pipe surface. The cross-sectional shape is estimated from the image of the laser streak obtained by applying the slit-ray projection method (i.e., shape obtained from structured light). The user manually scans this system by directing the laser slit ray along the pipe. The movement data (i.e., the amount and direction of movement) are estimated from the point cloud data detected by the KINECT sensor. The 3D pipe shape can be constructed on the computer from two or more sets of cross-sectional shape data obtained from the laser streak. Figure 8 shows a flowchart of the measurement procedure. The measurement system is first directed at area 1 on the target. The KINECT sensor and the laser slit measurement system are synchronized so that they are not affected by the movement of the system. The user can change the position of the measurement system by directing the system at the second measurement area (area 2). The KINECT sensor and the laser slit measurement system then detect data from this area. The point cloud data must include data from the overlap between areas 1 and 2 in order to estimate the movement of the system. Movement data (i.e., the amount of movement and the orientation of the measurement system) are estimated using the ICP algorithm [5]-[9]. The point cloud data is combined and a single pipe is constructed on the computer. The orientation of the cross section measured using the laser slit can also be determined by allocating the cross-sectional data of the constructed pipe. Thus, the shape of the entire pipe can be estimated from two or more cross-sectional data sets.

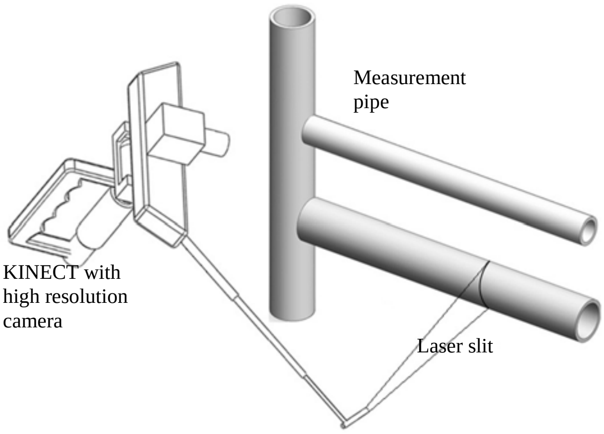

Figure 7. System for piping measurement.

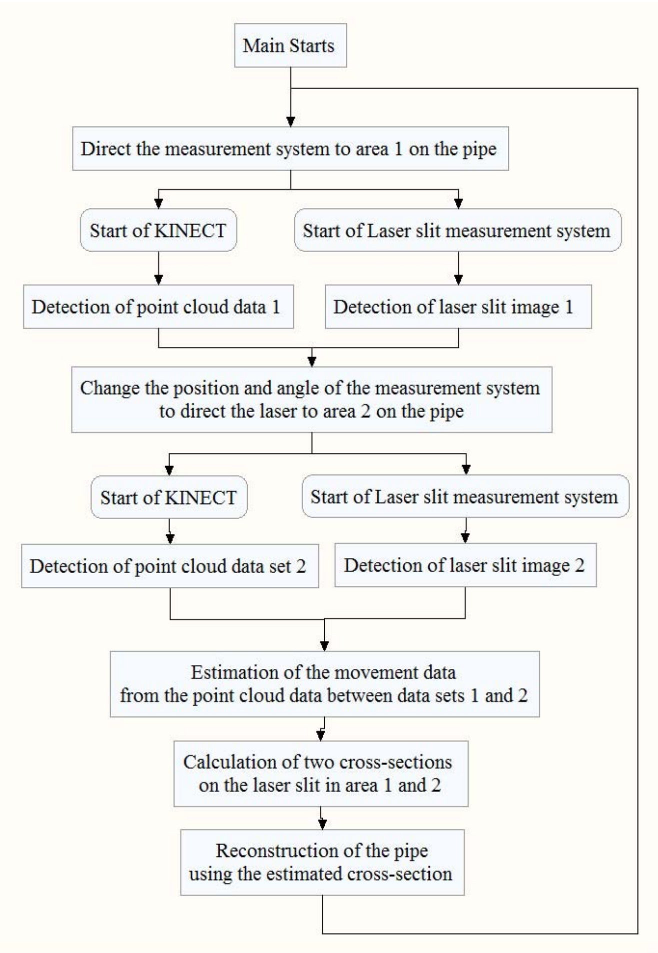

Figure 8. Flowchart of the measurement procedure.

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Figure 9 shows the calibration setup of the high-resolution CCD camera. A calibration board is installed on the laser slit plane. An image of the scale on the calibration board is obtained by the CCD camera and is used to determine the calibration parameters. The relationship between the coordinates (u,v) of the CCD camera and the global coordinates (x,y) of the scale board is as follows:

$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}k_{11}&k_{12}&k_{13}\\k_{21}&k_{22}&k_{23}\\k_{31}&k_{32}&1\end{bmatrix}\begin{bmatrix}x\\y\\1\end{bmatrix} \qquad (3)$$

where k_{11} through k_{32} are parameters that express the rotation, scale, and displacement between the camera coordinates and global coordinates. The global coordinate system is based on the measurement system and moves with the system. These parameters are determined by inputting corresponding positions between the camera coordinates and the global coordinates. These parameters are input using a mouse for the camera coordinates and a keyboard for the corresponding global coordinates.

Parameters k_{11} through k_{32} are determined by inputting four or more corresponding points into Eq. (3). The function for converting camera coordinates to global coordinates is given as follows:

$$\begin{bmatrix}x\\y\end{bmatrix}=\begin{bmatrix}k_{31}u-k_{11}&k_{32}u-k_{12}\\k_{31}v-k_{21}&k_{32}v-k_{22}\end{bmatrix}^{-1}\begin{bmatrix}k_{13}-u\\k_{23}-v\end{bmatrix} \qquad (4)$$

All points on the laser streak are converted to global coordinates, and the cross-sectional shape of the pipe is estimated.

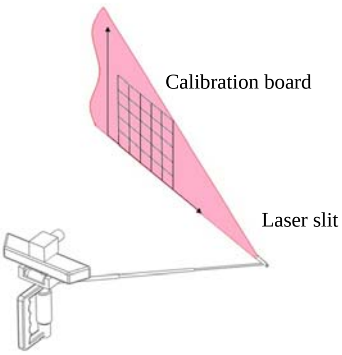

Figure 9. Calibration setup.

Figures 10(a) and 10(b) show images of the laser streak on the pipe captured by the CCD camera and the KINECT sensor, respectively. The laser streak detected by the CCD camera is clearer and more stable than the point cloud data obtained using the KINECT sensor. The resolution of the KINECT camera is 640×480, whereas the resolution of the CCD used in the present is 1,280×1,024.

The difference in the resolutions influences the measurement accuracy. The laser slit data in the point cloud data is replaced by the data of the slit-ray projection method.

(a) CCD camera image (b) KINECT image

Figure 10. Point cloud data obtained by the CCD camera and the KINECT sensor.

Figure 11. Estimated pipe cross section.

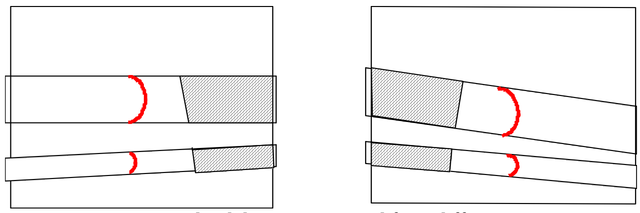

Figure 12. Point cloud data sets captured from different positions.

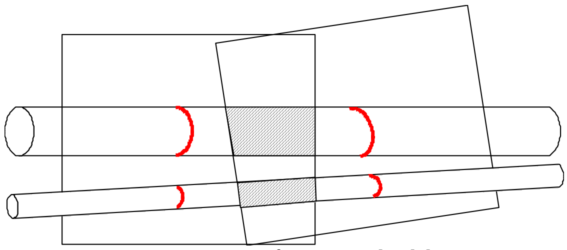

Figure 13. Connection of two point cloud data sets.

The two-dimensional coordinates (x,y) of Eq. (4) are mapped to 3D coordinates (x,y,z) by this replacement because the point cloud data have 3D coordinates.

The cross-sectional shape (ellipse) can be determined by applying the least-squares method to the data in Figure 10(a), as shown in Figure 11.

More than two point cloud data sets were obtained at different positions, as is shown in Figure 12. Each data set contains data that overlaps with data from another data set, as indicated by the shaded regions in Figure 12. These point cloud data sets are connected using the ICP algorithm as shown in Figure 13. The ICP algorithm of the Point Cloud Library (PCL) open-source framework is used in the proposed system.

V. RESULTS OF PIPE RECONSTRUCTION

The position and orientation of the estimated cross-section between images are then determined, and the pipe is constructed by the computer, as shown in Figure 14. In other words, the coordinates for each measurement position are converted to a common coordinate system (global coordinate system) by this connection. The proposed method can thus construct the shape of the entire pipe in a common coordinate system from point cloud data from different portions on the pipe.

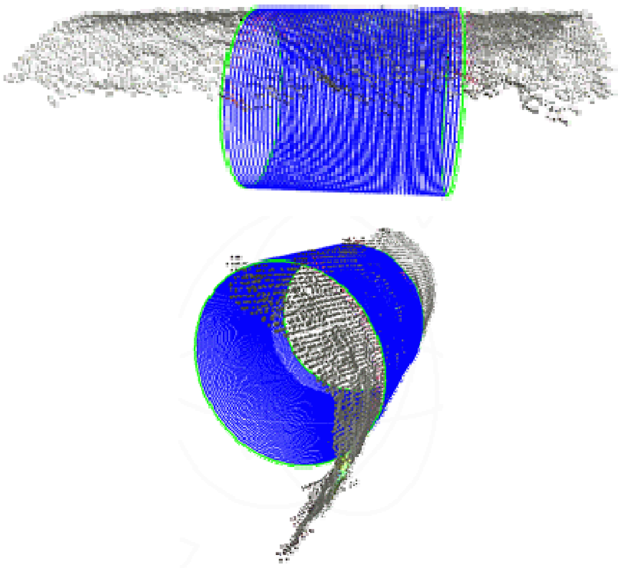

Figure 14. Pipe reconstructed on a computer.

Figure 15 shows a photograph of the pipe measured in the present experiment. The original point cloud data contains a great deal of redundant data. Six images were captured from different positions and were used to construct point cloud data on the computer. Each image includes a single slit-ray streak.

Figure 15. Photograph of the measured pipe.

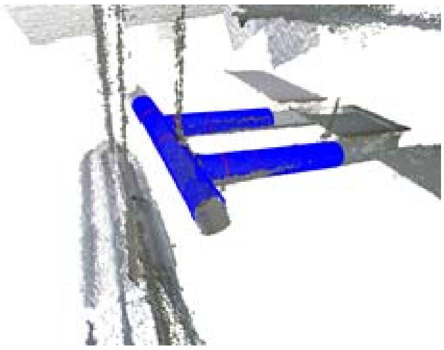

Figure 16. Pipe reconstructed on the computer.

Three pipes are reconstructed in Figure 16. Several sections are used to reconstruct each pipe. The measurement error in measuring the pipe size is less than 2 mm for distances under 2,000 mm and 0.3% over distances over 2,000 mm.

VI. CONCLUSION

Two computer vision systems that used the KINECT sensor for ubiquitous sensing in raising stock and in industrial fields were introduced. One of these systems is a 3D thermo-sensing system that detects 3D shape data and 3D temperature data simultaneously. Measurement of the 3D temperature distribution was realized by mapping thermal data obtained by thermography to the 3D position obtained by the KINECT sensor. The 3D temperature distribution of the cow head is measured for one application of the proposed system.

The other system is a handheld 3D measurement apparatus that uses a slit ray projector in conjunction with the KINECT sensor. The 3D shape of the target is reconstructed using the detected data on the computer. The measurement of pipe equipment is introduced in the present paper.

These two systems are sufficiently compact, and measurement can be performed via online processing. As such, these systems can be useful as tools for ubiquitous data acquisition systems in various fields. The experimental results obtained in the present study demonstrate the feasibility of the proposed system in raising stock and in industrial applications.

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