Paper title:

Calibration, Parameter Estimation, and Accuracy Enhancement of a 4DI Camera Turntable System

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Abstract

The 4DI system, a real time three-dimensional (3-D) imager, is a laser range data sensing system for making continuous geometric measurements of 3-D surfaces. This paper concentrates on the objective of improving the resolution and accuracy of this system using a camera-turntable arrangement. A fast and inexpensive way to capture dense range data for 360° viewing of an object is provided. After the system calibration procedure and parameter estimation operations, the method to improve the data resolution by object rotation is derived. By oversampling the object surface and then using a 3-D smoothing and resampling operation, the accuracy of the data can be improved maintaining a given spatial resolution. The method of removing the low credibility data points is also discussed.

Keywords--- 3-D imaging, range data sensing and enhancement, system calibration, parameter estimation
I. INTRODUCTION

The Four Dimensional Imager (4DI) system [1] uses a pattern of projected light planes to illuminate a scene and two video cameras to acquire the data. Given the approximated location of the object as compared with the calibrated locations of those laser planes, range measurements are calculated using triangulation between the binary stereo images from the two cameras. The major advantage of this system is that it can make much faster measurements than most of the other single-camera ranging sensors. The entire scene of interest can be illuminated simultaneously thus 3D measurements of tens of thousands of points can be accomplished from a single pair of stereo images. The data acquisition time is less than 0.1ms, which makes real-time measurement possible.

The integration of a turntable into the 4DI system will increase the flexibility and data density of the data collection process. Therefore it is possible to collect ranging surface data that is not easily achievable using a single stationary laser plane since 4DI has multiple laser planes at each angular view. In this paper, we show the improvements of the resolution and accuracy by this integration. The software methods for calibration, parameter estimation, and accuracy enhancement are discussed. In Section II, the 4DI system and turntable set-up are described. In Section III, the set-up is calibrated and various ranging accuracies are evaluated. In Section IV, the system parameters and evaluations are put to good use in the final design of the data collection process involving rotation of the turntable. The post-processing of the data to obtain higher accuracy is presented in Section V. A brief conclusion is drawn in Section VI.

II. THE 4DI CAMERA TURNTABLE SET-UP

The physical set-up is shown in Fig.1.
In Fig. 1, the XYZ coordinate system was predefined by the software program of the 4DI system. The origin $O$ is 38 inches away from the cameras and it is the center of the Field of View (FOV). (There are other 4DI system configurations with smaller FOV and higher accuracy.) The turntable is placed near the origin within the FOV. Notice that generally the center of the turntable is not at $O$ and the turntable rotational axis is not necessarily parallel to $OY$. In our system setup, there are 33 laser planes.

III. SYSTEM CALIBRATION AND PARAMETER ESTIMATION

A planar sample of one mil surface accuracy has been used extensively in all the calibration and range data accuracy evaluations.

3.1 4DI System

The following calibrations and data accuracy evaluations for the original 4DI system are considered:
3.1.1. 4DI System Parameter Setting and Robustness Testing

First of all we chose a wide range of parameter settings and test the performance of the system. The adjustable parameters of the 4DI system include the "Max. Z-Range", "Min. Z-Range", "Vertical Sampling Density", and "Video Levels". The impact of the environmental illumination is also considered in the testing. This experiment is to find the optimal parameter settings that lead to the minimum variance on the planar sample (one mil error). The results of this experiment determine the parameter settings for all of the following experiments.

On our system, we found out that the Z range should be as compact as possible, or as close as possible to the range of the object. The "Vertical Sampling Density" can be 400 through 1000, bearing no impact on the variance of the data collected. The "Lo Video Levels" can take a value of 2 through 50, yielding similar variance on the data, as long as the noise captured by the cameras is on a relatively low level.

3.1.2. Range Errors versus Distance from the 4DI Camera

The purpose of this experiment is to evaluate the range errors at different positions on the turntable. These results are used to define the most favorable working region where errors are minimums.

Range errors are calculated at about 20 longitudinal positions along the Z-direction (Z = -5” to 4”, note that Z = 0 point is 38 inches away from the camera). Results show that the favorable working region lies between the planes Z = -3 and Z = 1, where error is confined to less than 7 mil. Also a set of 3 different horizontal positions on the turntable of approximately identical range values (Z = 0) from the 4DI camera is tested. The process is repeated for another set at a different distance value (Z = −3). The maximum error is within eight mils.

The procedure to calculate the range errors is as follow:
. Collection of the planar range data at a given position.
. Fitting of a planar surface to obtain the surface equation.
. Calculation of range errors using the equation values as the reference.
. Calculation of standard deviation error to represent the distance or range accuracy at a given position.

3.1.3. Range Error due to Surface Curvature

The purpose of this experiment is to evaluate the range accuracy for different curvatures facing the 4DI cameras. The experiment and the calculation procedure are similar to those of 3.1.2, except that instead of changing the distance of the planar sample from the cameras we change the angle by which the planar sample faces the cameras. All experiments are conducted in the working region established in the earlier section. The angles of all surfaces are calculated from the planar equations after the plane-fitting operations. Range errors are computed at various angles, which indicates an additional 1 to 2 mils error for those curvatures making an angle larger than 40°, and more than 3 mils error for an angle of 60° or up.

From above evaluations, we know the depth of the FOV is 4 inches. Therefore if consider the rotation of the object, the size of the object should be less than 4”×4”×4” to achieve the lowest range error (7 mils or less, before any processing).

3.2 Turntable

3.2.1. Parameter Set Extraction

The turntable parameter set includes the intersecting point \((x_0, z_0)\) of the turntable axis at \(y_0=0\) plane defined by the 4DI system, and directional angles \(\alpha, \beta, \gamma\) of the turntable axis. These parameters can be easily derived if we have the equation for the axis.
The planar sample is used to obtain the equation for the axis. By putting the planar sample on the turntable and rotating the turntable, we take three sets of surface data at three different angles and then fit three planar equations.

\[ P_i: a_i x + b_i y + c_i z + d_i = 0, \quad i=1,2,3 \]

The two dihedral planes between \( P_1 \) and \( P_2 \), are:

\[ D_{12}: q x + r y + s z + t = 0 \]

where

\[
q = \frac{a_1}{\sqrt{a_1^2 + b_1^2 + c_1^2}} \pm \frac{a_2}{\sqrt{a_2^2 + b_2^2 + c_2^2}}
\]

\[
r = \frac{b_1}{\sqrt{a_1^2 + b_1^2 + c_1^2}} \pm \frac{b_2}{\sqrt{a_2^2 + b_2^2 + c_2^2}}
\]

\[
s = \frac{c_1}{\sqrt{a_1^2 + b_1^2 + c_1^2}} \pm \frac{c_2}{\sqrt{a_2^2 + b_2^2 + c_2^2}}
\]

\[
t = \frac{d_1}{\sqrt{a_1^2 + b_1^2 + c_1^2}} \pm \frac{d_2}{\sqrt{a_2^2 + b_2^2 + c_2^2}}
\]

Similarly we can get \( D_{23} \). By carefully examining the angles between these planes, we can select one plane from \( D_{12} \) and one from \( D_{23} \) such that their intersection line is the turntable rotational axis. Assume the selected two planes are

\[ D_j: q_j x + r_j y + s_j z + t_j = 0, \quad j=1,2 \]

Then the rotation axis is
where

\[
\begin{align*}
  f_1 &= \frac{s_1 t_2 - s_2 t_1}{r_1 s_2 - r_2 s_1} \\
  f_2 &= \frac{q_2 s_1 - q_1 s_2}{r_1 s_2 - r_2 s_1} \\
  g_1 &= \frac{r_1 t_2 - r_2 t_1}{r_2 s_1 - r_1 s_2} \\
  g_2 &= \frac{q_2 r_1 - q_1 r_2}{r_2 s_1 - r_1 s_2}
\end{align*}
\]

The direction numbers of the axis are \((l, f_2, g_2)\). The directional cosines \([\cos \alpha, \cos \beta, \cos \gamma]\) are

\[
\begin{bmatrix}
  1 \\
  f_2 \\
  g_2 \\
\end{bmatrix}
\frac{1}{\sqrt{1 + f_2^2 + g_2^2}}\begin{bmatrix}
  f_2 \\
  g_2 \\
\end{bmatrix}
\frac{1}{\sqrt{1 + f_2^2 + g_2^2}}
\]

This axis intersects \(y=0\) plane at point

\((-f_1 f_2, 0, g_1, g_2(f_1 f_2))\)

For our set-up, a set of ten experiments were conducted to arrive at the average values of \(X_0 = 0.74200\)”, \(Z_0 = -0.63403\)”, and \(\alpha = 89.8146\), \(\beta = 0.2861\), \(\gamma = 89.8514\). The standard deviations of these parameters are:

\[
\begin{align*}
\text{Dev}(x_0) &= 0.000515” \\
\text{Dev}(z_0) &= 0.002767” \\
\text{Dev}(\alpha) &= 0.069843 \text{ degrees} \\
\text{Dev}(\beta) &= 0.111854 \text{ degrees} \\
\text{Dev}(\gamma) &= 0.191415 \text{ degrees}
\end{align*}
\]
3.2.2. Angular Error Estimation

The turntable angular errors are calculated using the 4DI system as the reference. In this experiment the planar sample is put on the turntable, and the table is rotated for certain angle $\theta$ according to the reading of the turntable. On the other hand, we collect two sets of data of this planar sample before and after the rotation, respectively, and fit two planes $P_1$ and $P_2$. If we know the rotation axis of the turntable (which can be obtained without knowing the rotation angles), we can calculate the angle of the rotation as follows: First, find a plane $P_0$ that is perpendicular to the axis. Then find the intersection line $L_1$ between by intersecting $P_0$ and $P_1$, and the line $L_2$ between $P_0$ and $P_2$. The angle between $L_1$ and $L_2$ is the rotation angle, $\theta'$. Therefore, the angular error = $\theta' - \theta$.

In this error estimation, we are not certain which is more accurate, 4DI angle $\theta'$ or the turntable reading $\theta$. At any rate, the discrepancies between the two can be estimated. Fortunately our angular errors are within 0.6% and considered negligible (See the following Table). If these errors were larger and displayed a consistent pattern, then a correction formula could be used to reduce the discrepancies between the two so as to provide more accurate transformation results.

The following Table shows our results.

| Turntable Reading (TTR) | Calculated Value (CV) | $|TTR-CV|$ | $\frac{|TTR-CV|}{CV}$ |
|-------------------------|-----------------------|----------|---------------------|
| 5                       | 4.96605               | 0.0340   | 0.60%               |
| 10                      | 10.0061               | 0.0061   | 0.06%               |
| 12                      | 11.9844               | 0.0156   | 0.13%               |
| 15                      | 14.9485               | 0.0515   | 0.34%               |
| 20                      | 20.0111               | 0.0111   | 0.20%               |
| 22                      | 21.9906               | 0.0094   | 0.04%               |
| 26                      | 25.8738               | 0.1262   | 0.48%               |
| 32                      | 31.8564               | 0.1436   | 0.45%               |
| 40                      | 39.8501               | 0.1499   | 0.37%               |
| 50                      | 49.8562               | 0.1438   | 0.29%               |
| 60                      | 59.8305               | 0.1695   | 0.28%               |
| 70                      | 69.8808               | 0.1192   | 0.17%               |
IV. RESOLUTION ENHANCEMENT BY ROTATION

In this Section we discuss the principle of resolution enhancement by using a turntable to rotate the object and then transforming data from different views into one view. First we derive the transformation of an arbitrary point \((x, y, z)\) to point \((x’, y’, z’)\), which is a rotation of \(\theta\) degrees around an arbitrary axis in space. The rotational axis intersects \(y=0\) plane at \((x_0, y_0, z_0)\), and has direction numbers \([l, f_2, g_2]\). (See fig. 2)

\[
\begin{align*}
\beta &= \text{ArcCos} \left( \frac{f_2}{\sqrt{l^2 + f_2^2 + g_2^2}} \right) \\
\varphi &= \text{ArcCos} \left( \frac{1}{\sqrt{1 + g_2^2}} \right)
\end{align*}
\]

![Fig. 2 The rotation of a point around an arbitrary axis in space](image-url)
The rotation of the point can be accomplished by combining a series of simple transformations such as translation and rotations around the three coordinate axes [2]. In fact, the transformation matrix $T$ can be written as

$$T = T_0^{-1}R_y^{-1}R_z^{-1}\Psi R_z R_y T_0$$

where

$$T_0 = \begin{bmatrix}
1 & 0 & 0 & -x_0 \\
0 & 1 & 0 & -y_0 \\
0 & 0 & 1 & -z_0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

is for translation from $O'$ to $O$;

$$R_y = \begin{bmatrix}
cos\phi & 0 & sin\phi & 0 \\
0 & 1 & 0 & 0 \\
-sin\phi & 0 & cos\phi & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

is for rotation of angle $\phi$ around $Y$-axis;

$$R_z = \begin{bmatrix}
cos\beta & -sin\beta & 0 & 0 \\
sin\beta & cos\beta & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

is for rotation of angle $\beta$ around $Z$-axis;

$$\Psi = \begin{bmatrix}
cos\theta & 0 & -sin\theta & 0 \\
0 & 1 & 0 & 0 \\
sin\theta & 0 & cos\theta & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

is for rotation of angle $\theta$ around $Y$-axis.

In other words,

$$\begin{pmatrix}
x' \\
y' \\
z'
\end{pmatrix} = T \begin{pmatrix}
x \\
y \\
z
\end{pmatrix}.$$

Now we rotate the turntable with the object of interest on top. If we can read or calculate the turntable rotational angle $\theta$, then all the data points collected after the rotation can be transformed back to the previous data set using $T$. By doing so, we can get the $360^\circ$ viewing of the object, and obtain higher resolution as well.
In Fig. 3, (a) and (b) are the data obtained from a single viewing angle of a vase. (c) and (d) show the combined data from 68 views. This is a data set for 360° viewing of the vase. One can see the color-coded (periodically) range contours on the surface of the vase, the periodicity and continuity indicate that the error introduced by the data transformation is relatively small and negligible.

V. ACCURACY ENHANCEMENT BY DATA SELECTION AND 3-D SMOOTHING

Using the finding of Section III, high curvature data (60 degrees and up) facing the 4DI camera, are subject to higher error therefore are removed prior to spatial transformation. This operation can be accomplished by looking at the local gradient in Z-direction in the original data sets.

To increase the range data accuracy, we oversample the surface and then use a Gaussian interpolation and resampling algorithm to smooth the combined data and resample the result onto a square grid with the desired spacing (resolution). (This is often called uniform resampling operation).

In Fig. 4, the range data of an engine blade are collected and processed. (a) shows a set of data collected for the planar sample with surface error one mil. The error in the data is apparent. The largest deviation from the mean is about 20 mils. (b) through (f) are, respectively, the data from one view; combined data for the whole blade; “selected” high credibility data for one side of the blade; smoothed and resampled data from previous data; and another view for the previous data. (g) is a zoom-in view of (f). (h) is a zoom-in view of one original data set. Comparing (g) and (h), one can see that after these operations the resolution and accuracy have been apparently improved.

VI. CONCLUSION
In this paper, we present a method to improve the resolution and accuracy of a 4DI system by using a camera-turntable configuration. This is also a very fast and inexpensive way to achieve dense range data for 360° viewing of an object. Our results showed that this method could yield higher resolution and more accurate range data as well as 360° viewing of point cloud for the object of interest. The data collection process is rather rapid because of the design of the 4DI system. If a computer controlled stepping motor system is used to rotate the turntable, it is estimated to take two to three minutes to obtain combined 360° viewing range data at a pixel spacing of five to ten mils (60 to 80 viewing angles with a maximum of 33 laser planes per viewing and with a total of up to 2.5 million points) for a object. Some surface reconstruction methods [3, 4] could then be applied to our processed data set to reconstruct accurate 3-D image of the object.

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REFERENCES

Fig. 3 Data rotation and combination to obtain higher resolution and 360° viewing of a vase. (a) Illustration of multiple lines ranging data from a single view of the vase. (b) A side-view of (a). (c) Result of combining 68 views ranging data 360° around the vase. (d) A 3-D rotated view of (c).
Fig. 4  (a) A set of data for the planar sample. (b) The data from one view of the blade. (c) Combined data from 114 views. (d) Selected high credibility data for one side of the blade. (e) Smoothed and resampled data from (d). (f) Rotated view of (e). (g) A rotated zoom-in on (f). (h) A rotated zoom-in on (b), with the same zoom factor as (g).
Figure and table captions:

**Fig. 1** The 4DI camera-turntable set-up

**Fig. 2** The rotation of a point around an arbitrary axis in space

**Fig. 3** Data rotation and combination to obtain higher resolution and 360° viewing of a vase. (a) Illustration of multiple lines ranging data from a single view of the vase. (b) A side-view of (a). (c) Result of combining 68 views ranging data 360° around the vase. (d) A 3-D rotated view of (c).

**Fig. 4** (a) A set of data for the planar sample. (b) The data from one view of the blade. (c) Combined data from 114 views. (d) Selected high credibility data for one side of the blade. (e) Smoothed and resampled data from (d). (f) Rotated view of (e). (g) A rotated zoom-in on (f). (h) A rotated zoom-in on (b), with the same zoom factor as (g).

**Table 1** Turntable Angular Error Estimation (in degrees)