A POINT CLOUD INTERPOLATION TECHNIQUE FOR ENHANCING MEASUREMENT OF A 3-D COORDINATE MEASURING MACHINE

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ABSTRACT
This paper presents a Point Cloud Interpolation Technique (PCIT) to enhance the resolution of point cloud measured by using an automatic laser scanning Coordinate Measuring Machine (CMM). This CMM machine is developed in-house. This technique is to increase a number of points contained in any sets of point cloud which represent the cross section profiles of an object surface. The resolution of raw data obtained from scanner is limited by a resolution of the camera used for digitizing points. To enhance resolution of point cloud means increase detail or information of shape especially when high slope area occurred in the measured object. High slope area is not easy to measure with typical low resolution CMM. To overcome this problem, PCIT can divide the raw data point cloud (low resolution point cloud) into a number of point sets. These point sets are used to generate piecewise smooth curves by applying least square fitting. Then the curves are resampling to obtain higher resolution point cloud or modified point cloud. The new point cloud obtained by combining these point sets can be used to represent high slope areas or to generate cloud points for discontinuing surface. The new point cloud can be imported to commercial CAD systems and can be used in reverse engineering application.

KEY WORDS
Point Cloud Interpolation Technique (PCIT), Curve Reconstruction, Coordinate Measuring Machines (CMM).

1. Introduction

A coordinate measuring machine (CMM) is a device that analyzes a real-world object to collect data on its shape. The purpose of a CMM is usually to create a point cloud which represented geometric shape of an object surface. These points can be used to interpolate the shape of the object (a process call reconstruction). A point cloud is a set of vertices defined in a three-dimensional coordinate system. Due to the typical configuration of a CMM, these vertices are usually defined in X-Y-Z coordinates system, and are typically intended to be used to reconstruct surfaces of the object which the point cloud obtained. A Coordinate Measuring Machine, e.g. laser scanning CMM, is used for measuring points along defined cross sections of an object. This research project, we develop an automatic laser scanning CMM, coordinate information of point cloud is obtained by using a 2-camera system with a laser line. A laser line is projected on to the surface of an object. The camera system is used to digitize a specified number of points on the laser line as shown in Figure 1. A computer motion control system is developed to accurately project a laser line to cover entire surface of the object surface. A laser scanner is a line-scan device, which means that it is only able to measure points that are in the plane of the laser sheet or section as show in figure 1. Figure 2 show 3D-scanner developed in-house. This 3D scanner uses 2-camera system with a line laser that mounted on Cartesian robot. The line laser is aligned in the Y-axis. The Cartesian robot is controlled to move along X-axis so that the whole surface of the object will be digitized. Sharp features consist of high frequencies, or the area which consist of high slope, cannot be properly measured by the finite resolution of the CMM in the first place. Curve reconstruction techniques purposed in this paper can suppress the inherent noise embedded in the point cloud. When the object surface contains sharp features, the requirement of being resilient to noise is especially challenging since noise and sharp features are ambiguous, and most techniques tend to smooth important features or even amplify noisy samples. We use PCIT for reconstructing piecewise smooth curves from a potentially noisy point cloud. This point cloud is conveniently be imported to commercial CAD rather than curves. PCIT can be used to reduce noise and delete outlier from measured point cloud, which is common result from measuring by CMM. In summarize. The PCIT can deal with any point cloud of each section, which contains noise, outliers and sharp features.

Figure 1. Schematic diagram of laser scanning.
Figure 2. A 3D CMM using stereo vision with line laser, developed by Chulalongkorn University.

2. Point Cloud Interpolation Technique (PCIT)

A cross section of the surface of an object, as depicted in Figure 3a, is measured by the CMM to acquire the raw data point cloud. The resolution of raw data point cloud is limited by resolution of the camera used in the CMM. Thus, rather low resolution, of typical camera available in the market, is improperly illustrated detail of sharp features (see figure 3b). To improve this problem, PCIT can be used to improve the existing resolution of the raw data point cloud and show more detail of sharp features. After applying PCIT, the resolution of point cloud is improved and can be used to better represent the apparent sharp feature (see figure 3c) than the ones used in typical CMM.

Figure 3. PCIT can improve resolution of point cloud
(a) A Cross section of a surface with sharp feature.
(b) The raw data point cloud obtaining from the typical CMM. (c) The dense point cloud which the resolution is improved by applying PCIT.

PCIT approach can be divided into three procedures as following (see figure 4)

1.) Firstly, point cloud classification is obtained from the raw data point cloud and the point cloud is separated into point-set.
2.) After that, the curve reconstruction method is used for constructing the curves from each point-set to form piecewise smooth curves.
3.) Lastly, resampling procedure is used to transform the piece-wise smooth curves to a dense point cloud or a better resolution point cloud, which can be properly used to show more detail of the sharp feature. The result data can be simply formatted to commercial CAD software.

Figure 4. Processing Procedure of PCIT

3. Point Cloud Classification

3.1 Robust Estimation Technique

The main disadvantage of curve reconstruction by least-squares fitting is its sensitivity to outliers. The outliers contain miss measured data by using CMM probe (in this case is camera) and it has a large influence on the fitting because square the residuals will magnify the effects of these outlier data points (see figure 5). To solve this problem, we apply a robust estimation technique to detect the outliers. This technique will exclude outliers from curve fitting. The Robust estimator technique, based on
forward-search and iterative algorithm, is used to overcome the fitting problem due to the outlier [1].

![Figure 5](image1)

Figure 5. (a) A single outlier can cause fitting to fail. (b) Exclude outlier from fitting can get better result.

### 3.2 Forward Search and Iteration Refitting Algorithm

The basic idea of forward search algorithm begins with a model fitting to a small outlier-free subset of points and then iteratively refining the subset by adding one sample at a time, while monitoring values of residual [2]. If the value of residual exceeds the specified threshold of maximal tolerated residual, the associated point will be classified as outlier point and will be excluded from the fitting. The residual plot is a standard method in regression analysis for identifying outliers [1]. The amount of initial sample points depends on degree of fitting model. If model has m degree, initial sample points set will have at least m+1 points [3].

### 3.3 Ordered Point Cloud

In each section of point cloud, point is organized in sequence. The first point is start from the leftmost of the Y-axis; next sequence is the closest point on the right, and so on until last point on the rightmost. Thus these points in each section are arranged in order to start from left to right (see figure 6). The ordered point cloud is handy for forward search; with the initial sample points set are chosen at the beginning of the order. An each forward search is only adding next point to the order until the last point of the set.

![Figure 6](image2)

Figure 6. Scanned point in each scan section.

### 3.4 Classification

Point cloud classification also use forward search and iteration refitting (Robust estimation technique) to divide point cloud into point-set. While using robust estimation technique, residual value will always be monitored to detect outliers and any discontinuity points. The discontinuity point has residual more than a discontinuity threshold but will not exceed the outlier threshold. Distinction of outlier and discontinuity point is indicated by value of residual, the outlier is exclude from fitting but the discontinuities points is use to fit as a first point in a next point-set. So, each point-set will not have outlier due to robust estimation technique. Now we are able to construct sharp features by reconstructing curves form each point-set. The sharp feature is displayed by intersection of any two adjacent smooth curves. If point cloud classification is neglect, during the curve reconstruction, this procedure will construct only a single smooth curve. This curve misses a sharp feature data. (See figure 7)

![Figure 7](image3)

Figure 7. Point cloud classification use to form the sharp feature (a) Smoothen sharp feature cause reconstruction curve from single point-set. (b) Sharp feature can reveal by reconstruction curve from multiple point-set.

### 4. Curve Reconstruction

#### 4.1 Least Square Fitting

A Method of least-squares fitting requires a parametric model that relates the response data to the predicted data with one or more coefficients. The result of the fitting process is an estimation of the model coefficients. To obtain the estimated coefficients, the least-squares method is used to minimize the summed square of residuals. The residual for the ith data point, $r_i$, is defined as the difference between the observed response value $y_i$ and the fitted response value $\hat{y}_i$, and is identified as the error associated with the data

$$r_i = y_i - \hat{y}_i \quad \text{residual} = \text{data - fit} \quad (1)$$

The summed square of residuals is given by

$$S = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \quad (2)$$
4.2 Error Distribution

When fitting data that contains random variations or measured point cloud with noise, there are two important assumptions that are usually made about the error:

- The error exists only in the response data, and not in the predictor data.
- The errors are random and follow a normal (Gaussian) distribution with zero mean and constant variance, $\sigma^2$.

The second assumption is often expressed as

$$\text{error} \sim N(0, \sigma^2)$$  \hspace{1cm} (3)

The errors are assumed to be normally distributed because the normal distribution often provides an adequate approximation to the distribution of many measured quantities. Although the least-squares fitting method does not assume normally distributed errors when calculating the parameters of the estimation, the method works best for data that does not contain a large number of random errors with extreme values. The normal distribution is one of the probability distributions in which extreme random errors (outlier) are uncommon.

4.3 Linear Least Square

Linear least-square is the method to fit a linear model to a set of data. A linear model is defined as an equation that is linear in the coefficients e.g. polynomial equation.

The form of the equation of m-degree polynomial can be written as:

$$y = \beta_1 + \beta_2 + \ldots + \beta_m x^{m-1}$$  \hspace{1cm} (4)

So, the model of linear least square in matrix form is:

$$X\beta = y$$  \hspace{1cm} (5)

The solution of linear least square fitting is defined by the coefficients which fit the equations best in the sense of solving the quadratic minimization problem. Estimation of a coefficient or a prediction of a model can be obtain from:

$$\hat{\beta} = \arg\min_{\beta} S(\beta)$$  \hspace{1cm} (6)

A projection matrix is defined as:

$$H = X(X^TX)^{-1}X^T$$  \hspace{1cm} (7)

Residuals are given by:

$$r = (1 - H)y$$  \hspace{1cm} (8)

So, the predicted response values, $\hat{y}$, will be:

$$\hat{y} = Hy$$  \hspace{1cm} (9)

A hat (circumflex) over a letter denotes an estimate of a parameter or a prediction from a model. The projection matrix $H$ is called the hat matrix. Residual is different between observed response values ($y$) and predicted response value ($\hat{y}$), also call fitting error. In our work, any residual is an observation used to identify outlier and discontinuities point.
5. Experiment Result

In experiment, we implement the PCIT technique by simulating a section point cloud that has a random noise and outlier. A fourth degree of polynomial model is used to reconstruct the curve. Trapezoidal shape is used for testing the technique. The shape of the trapezoid model or object has sharp features. Because of the effect of noise and low resolution of the raw data point cloud, we will have to obscure corners at the sharp edge (figure 9). After implementing the PCIT, we will obtain the estimated curves for each point cloud set. And these curves can be used to form piecewise smooth curves as shown in figure 10. In this case, a sharp feature can be formed by two adjacent intersection curves. Figure 11 shows the error of the fit curves as compared to the actual profile section. The discontinuities shown in the figure are to confirm the location of the sharp features.

Figure 9. Trapezoid point cloud section.

Figure 10. Curve from PCIT.

Figure 11. Error of curve from PCIT compares to object model.

6. Conclusion

This paper focuses on Point Cloud Interpolation Technique (PCIT) which is a method using as a robust estimator. It can eliminate outlier and reduce noise, so that, better point sets can be obtained from sharp features inherent in the object surfaces or discontinuing surfaces. The PCIT will divide the raw data point cloud (low resolution point cloud) into a number of point sets. These point sets are used to generate piecewise smooth curves by using least square fitting. Then the curves are resampling to obtain higher resolution point cloud or modified point sets. The new point cloud obtained by combining these point sets can be used to represent high slope areas or to generate cloud points for discontinuing surface. The new point cloud or the modified point cloud can be imported to commercial CAD systems.

Acknowledgement

Part of this our work is sponsored by Chulalongkorn University under Chulalongkorn University Centenary Academic Development Project.

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