Design and Implementation of Photogrammetry Based Product Re-Realization

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Abstract: - This study presents an experimental procedure of reverse engineering system for rapid modeling and manufacturing of products with complex freeform surfaces. Its ultimate purpose is to explore a fast, efficient, economical and practical route to reproduction of existing physical objects with digital camera and CNC machine tools for small and medium-sized manufacturers on a P2P-based multimedia collaborative environment. This paper focuses on developing a prototype of photogrammetry based 3D digitization, B-spline surface model reconstruction, and tool path generation based on Open CASCADE kernel. Experiments show that the method is applicable for reverse modeling of freeform objects with moderate accuracy requirements. Therefore, the presented schema is a valid alternative to laser scanning techniques and coded light-based triangulation approaches with an important reduction of the hardware costs and time.

Key-Words: - Reverse engineering, Photogrammetry, Point cloud, B-Spline, Tool path generation

1 Introduction

Nowadays, globalization has begun to drive industries to operate in a highly competitive environment. Besides delivering more competitive products with higher quality, lower prices, customized, and innovative products, the time-to-market of products has become a crucial issue. In order to deal with this challenge, rapid production methods have been developed and incorporated into many phases of the product life cycle. Many companies are becoming increasingly multi-sited, operating with partners around the world, and are more reliant on reverse engineering (RE) technology, which significantly enables fast design based on an existing physical object, typically, for parts comprising of freeform surfaces [1, 2, 3]. Some researchers have begun to focus their attentions to internet based collaborative solutions which integrated RE with remote manufacturing.

Reverse engineering is a product development methodology and a kind of process of engineering backward for constructing CAD models of an existing physical object whose CAD models are unavailable, unusable, or insufficient, by digitizing the existing product to acquire the explicit 3D points position, processing the digitized 3D data, and then reconstructing it as a 3D CAD model, which are used for analysis, manufacturing or other downstream applications [4, 5].

As the first step of RE, digitization is the process of acquiring point coordinates. Generally, 3D object measurement techniques in manufacturing industry can be classified into contact methods, like coordinate measuring machines (CMMs), low magnitude electromagnetic transducers, ultrasonic imaging; and non-contact methods, like laser scanners, structured light digitizers, computed tomography, photogrammetry systems. Contact techniques are usually slow, but at the same time they are more accurate. Non-contact techniques are fast but less accurate.

Computer controled coordinate measuring machines (CMMs) are the most commonly used contact measuring devices for extracting the 3D coordinates from part surfaces. While the point data is highly accurate and its widely available operator's skill, CMM scanning process is very slow and sometimes it is difficult to scan large objects. Moreover, the CMM probe diameter introduces surface offsets, which may be difficult to remove. In addition,the surface may be delicate or flexible.

Among non-contact optical digitizers, the laser scanner is the most common solution because it is fast, robust and wide range relative to other methods. Compared to CMM touch probes, laser scanner has the advantages of speed, non-contact sensing. The primary drawbacks are high cost, less accuracy, and slow data acquisition because of extensive processing.

Many non-contact 3D scanners, known as range-based methods, are available based on triangulation (with laser light or stripe projection), time-of-flight, continuous wave, interferometry or reflectivity measurement principles. They have been widely adopted in many application areas, are becoming a very common tool for the scientific community but also for non-expert users such as cultural heritage professionals.

However, image-based measurement technique still remains the most complete, economical, portable, flexible and widely used approach for geometric surfaces of architectural objects or for precise terrain and city modeling. The research and application of image-based reverse engineering systems for mechanical products are relatively young. In most cases, the most impressive and accurate results still remain those achieved with interactive approaches.

Otherwise, in many applications, a single measurement method that satisfies all the project requirements is still not available. Photogrammetry and laser scanning have been combined in particular for complex or large architectural objects, where no technique by itself can efficiently and quickly provide a complete and detailed model. At the moment it can safely be said that, for all types of objects and sites, there is no single modeling technique able to satisfy all requirements of high geometric accuracy, portability, full automation, photo-realism and low cost as well as flexibility and efficiency.

In addition, although RE seems easy to create a simple 3D CAD model, the generation of high accuracy point cloud and precise CAD model of a complex object still requires considerable effort. Serious challenges must be overcome, if sufficient accuracy is to be obtained and if models produced from sensed data are truly useful for manufacturing operations.

With the new computer vision techniques emerging in recent years, image-based stereo measuring technology has been receiving significant attention and wide application in both research and industrial communities because of its great potential to significantly aid the process and further enhance the quality of 3D mechanical product digitization. Comparing with expensive and special hardware of CMMs and laser scanners, image-based measurement method mainly depends on software technologies, and has the advantages of cheap device, portable and fast. These features will promote reverse engineering (RE) to play a more prominent role in manufacturing industry, particularly in small and medium enterprises (SMEs).

This serves as a motivation to find a new strategy to acquire sampled 3D data of existing physical product from a set of photographs made with digital camera, extract feature using computer vision, specify the interesting points with markers, reconstruct B-spline surface model and achieve feature-based modeling, then analyse and modify the design to obtain its new CAD model, finally generate CNC tool path for manufacturing. Figure 1 shows the overall flowchart of a photogrammetry based reverse engineering system.

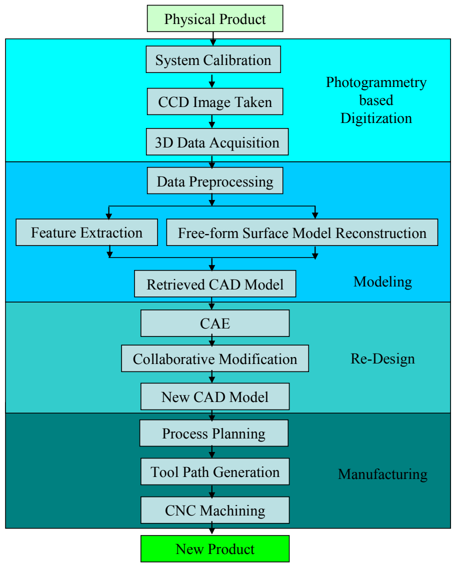

Figure 1 The overall flowchart of photogrammetry based reverse engineering system

This paper will expatiate these processes with focus on photogrammetry based 3D digitization, B-Spline surface model reconstruction, and tool path generation in the following sections to describe a prototype of reverse engineering system for SMEs.

The paper is organized as follows: Section 2 is devoted to introduce some related works. Section 3 introduces photogrammetry based digitization. Section 4 describes an algorithm for B-spline surface model reconstruction. The proposed algorithm for tool path generation is presented in Section 5. As its implementation, a practical example is presented in the following section 6. Finally, conclusions and future works are briefly expressed in section 7.

2 Related Work

Up to now, there have been many academic reverse engineering prototypes and a lot of commercial systems.

2.1 Image-based Measurement

Image-based methods (including photogrammetry) use 2D image measurements (correspondences) to recover 3D object information through a mathematical model or they acquire 3D data using methods such as shape from shading, texture, specularity, contour (medical applications) and 2D edge gradients. Using projective geometry or a perspective camera model, image-based methods are very portable and the sensors are often low cost.

Vision systems are used to acquire intensity images. A 3D image, which is normally called a range image (RI), is a map of depth information at different points on a scene. For example, with stereo scanning approach, the z coordinate can be found using two cameras to view the part from two different views. Triangulation is used to find the range information.

Zheng Jian-dong, et al [6] presented a flexible, portable and economical approach to reconstruct 3D curve structures of free-form objects from a sparse set of unordered images taken by a hand-held CCD camera. Their proposed method had the following advantages: (1) no extra registration was needed for the digitized data obtained from different views; and (2) there was no redundancy in the digitized data for model reconstruction. Their experiments showed that the system was applicable for reverse modeling of freeform objects with moderate accuracy requirements.

Nicola D'Apuzzo [7] presented a method to measure and track moving surfaces of human body parts from multi-image video sequences acquired simultaneously by several cameras. The surface measurement process was based on multi-image photogrammetry and the tracking process was based on least squares matching techniques. The main advantages are the capability to dynamically measure surface parts with high accuracy and the possibility to extract motion information from the acquired data without using markers. As functionality demonstration, human face measurement and modeling, and full body motion capture were presented.

Fabio Remondino [8] presented a method for the 3D shape model reconstruction of static human body from monocular uncalibrated image sequence. Mostly based on photogrammetric techniques, the bundle adjustment with self-calibration was used for accurate orientation and location of the cameras and for accurate reconstruction of the human shape. Extraction of correspondences on the body using a least squares matching algorithm and reconstruction of the 3D body model in point cloud form were also included.

David G. Lowe [9] presented a method for extracting distinctive invariant features from images that can be used to perform reliable matching between different views of an object or scene. These features were used for object recognition by the process of matching individual features to a database of features from known objects using a fast nearest-neighbor algorithm, followed by a Hough transform to identify clusters belonging to a single object, and finally performing verification through least-squares solution for consistent pose parameters.

Seyed Yousef Sadjadi [10] investigated the feasibility of developing an Archaeology/ Architectural Information System (A/AIS) based on a fusion of digital photogrammetry, CAD and geographical information system (GIS), to provide the spatial information for architects working with historic buildings and archaeologist. Nineteen digital photographs supported the presented Hunter Memorial (located at the University of Glasgow) project by a Kodak DC4800 digital camera. Each key point or feature that was to be modeled should be visible on two or more photos. Processing these photographs was achieved with PhotoModeler and the creation of 3D models starts with the connection of 3D points, edges, curves and cylinders in AutoCAD.

2.2 Modeling and Manufacturing in RE

In the last decades, a number of investigations have been made into CAD modeling and manufacturing in reverse engineering [11].

Yinling Ke, et al [12] developed a reverse engineering software RE-SOFT, with sectional feature based strategy and surface feature based strategy, for modeling industrial components from point cloud to surfaces without using triangulation. For the sectional feature based strategy, slicing, curve feature recognition and constrained fitting were introduced. The surface feature based strategy relied on differential geometric attributes estimation and diverse feature extraction techniques.

Charlie C. L. Wang, et al [13] developed a fuzzy logic concept based prototype system for constructing a feature human model to be stored in a 3D digital human model database by unorganized cloud points obtained from 3D laser scanners. The whole procedure consisted of three steps: (1) removing noisy points and adjusting the orientation of the human model; (2) constructing feature-based mesh surface from cloud points, and (3) extracting semantic features of the human model.

R. S. Lee, et al [14] presented a systematic approach towards the development of a remote collaborative reverse engineering system for a concurrent product and process development environment by using STEP standard, CSCW methods and a hybrid network of Internet and ISDN. Key information, recorded in STEP, could be used as a formal and neutral data exchange for heterogeneous systems, or as a decision-making support for manufacturability evaluation.

William B. Thompson, et al [15] presented a prototype of a reverse engineering system which used manufacturing features as geometric primitives. The approach had two advantages over current practice. The resulting models could be directly imported into feature-based CAD systems without loss of the semantics and topological information inherent in feature-based representations. In addition, the feature-based approach facilitated methods capable of producing highly accurate models, even when the original 3D sensor data had substantial errors.

Y. H. Peng, et al [16] presented an approach for the direct generation of NC tool paths from physical parts with trimmed patches. Three types of control points were determined to construct an underlying trimmed NURBS surfaces. NC tool paths were then generated based on these trimmed surfaces. For three-axis machining, this algorithm could efficiently handle possible interferences in the vicinity of contact edges of compound surfaces.

Shin-Ichiro Takahashi, et al [17] introduced a real time 3D imaging system by handling the 3D shape and the color information as point cloud. It could be mounting with more small scale equipment since employing the range images without voxel method. They used only 4 cameras at the modeling stage. Their system could enhance the transmission efficiency by eliminating the connectivity information. Moreover, by applying the cylindrical method to the real time 3D imaging system, the overlaps and the annoying artifacts were removed efficiently in real time.

A. Epureanu, et al [18] presented a new programming approach based on a proposed hardware and control architecture for the reconfigurable manufacturing tool machine. A new CAM was described based on virtual machining algorithm that optimized feedrate scheduling based on geometric simulation and aimed to improve the efficiency of cutting process developed using a reconfigurable machine, configured as lathe with a specific architecture. A searching procedure was proposed to find the parameter values corresponding to cutter locations along tool path during generation of the final surface.

Damir Vucina, et al [19] presented a systematic general procedure for the optimized redesign of existing objects. It included 3D scanning of the existing object to import an initial solution for the geometry and "freeze" the shape of sections which must not be changed. The rest of the object was re-engineered such that its shape was optimized for given excellence criteria and constraints. GA optimizers and FEA simulation tools were applied within the framework of a specifically developed custom workflow which used inter-application calls, control scripts and data mining.

2.3 PhotoModeler

PhotoModeler [20], developed by Eos Systems Inc (Vancouver, BC, Canada), is a famous commercial close-range photogrammetry and image-based modeling software, with the advantages of 3D measurements and 3D point sets accurately and efficiently from photographs, and with 3D modeling features such as lines, curves, surfaces and NURBS, in engineering, architecture, film, forensics, and more. With the latest release version 6.3, PhotoModeler's new RAD (Ringed Automatically Detected) Targets, provide automatic detection and matching of points across multiple photographs in addition to helping to set up the orientation of a scene or object to be measured. PhotoModeler works with any digital camera and with film or video camera images. Its camera orientation feature automatically determines the position of the camera when the image was taken, and its camera calibrator is used to measure camera's focal length, principal point, digitizing aspect ratio, and lens distortion.

A typically automated PhotoModeler 6.3 measurement project is a four-step process:

(1) simply place a few special RAD targets on the object or in the scene;

(2) take some digital photographs of the object from different angles;

(3) load these photographs into PhotoModeler Automation system;

(4) press the Run RAD project button.

The result, which is a highly accurate 3D point set that reflects the real-world object or scene, can be modeled with point, line, curve, edge, cylinder, and shape marking, more can create NURBS surfaces from lines, edges, and curves, and ultimately exported in a variety of CAD formats such as Autodesk DXF (2D and 3D), 3D Studio 3DS, JPEG, Wavefront OBJ, VRML (1 and 2), IGES, OpenNURBS/Rhino, STL, TIF, and Google Earth's KML and KMZ.

3 Photogrammetry based Digitization

3.1 What is Photogrammetry?

By definition given by the American society for photogrammetry and remote sensing (ASPRS), in the mapping sciences, photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment through the processes of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena.
Here, as its name implies, photogrammetry is a 3D coordinate measuring technique that uses photographs as the fundamental medium for metrology (or measurement). We say commonly photographs, but it may be also imagery stored electronically on tape or disk taken by video or CCD cameras or radiation sensors such as scanners. Its most important feature is the fact, that the objects are measured without being touched.
The fundamental principle used by photogrammetry is triangulation. By taking photographs from at least two different locations, so-called "lines of sight" can be developed from each camera to points on the object. These lines of sight (sometimes called rays owing to their optical nature) are mathematically intersected to produce the 3D coordinates of the points of interest. Even closer to home, triangulation is also the way human two eyes work together to gauge distance (called depth perception).
Principally, depending on the lense-setting, photogrammetry can be divided into: far range photogrammetry (with camera distance setting to indefinite), and close range photogrammetry (with camera distance settings to finite values).
With digital techniques widely available during the last decade, close range digital photogrammetric techniques provide the means to do exactly that, particularly with respect to the spatial information, by allowing 3D coordinates of photographed features to be accurately gathered, and archived in an information system. This greatly enhances the flexibility of data usage, allowing it to be translated and interpreted in many different forms, including output as drawings or as 3D CAD models.
Mostly, 3D objects are photographed from several positions, where any object-point should be visible on at least two, better three photographs. Using control points and triangulation points the geometry of the whole block of photographs is reconstructed with high precision. Then the image coordinates of any desired object-point measured in at least two photographs can be intersected. The results are the coordinates of the required points. In that way, the whole 3D object is digitally reconstructed.

3.2 Camera Model

Ideal pinhole camera model is employed in this paper. In Figure 2, $P_w(X_w, Y_w, Z_w)$ is the 3D coordinates of an arbitrary point P of the object surface in 3D world coordinate system $O_wX_wY_wZ_w$. O_cxyz is camera coordinate system, and coordinate system centre O_c is the optical centre of the camera, and z-axis coincides with the optical axis of the camera. $P_c(x, y, z)$ is corresponding point of P_w in camera coordinate system. O_iXY is retinal coordinate system of the camera; image centre O_i is the intersection of optical axial z and image plane of the camera; X-axis and Y-axis parallel with the x-axis and y − axis of the camera coordinate system respectively. $P_u(X_u, Y_u)$ is the retinal coordinates of P point in this ideal pinhole model. ouv is pixel coordinate system of the camera, and the coordinate unit of acquired image in the frame buffer is pixel, denoted as P(u, v). The effective focal length f is the distance between the optical centre and the image plane [21].

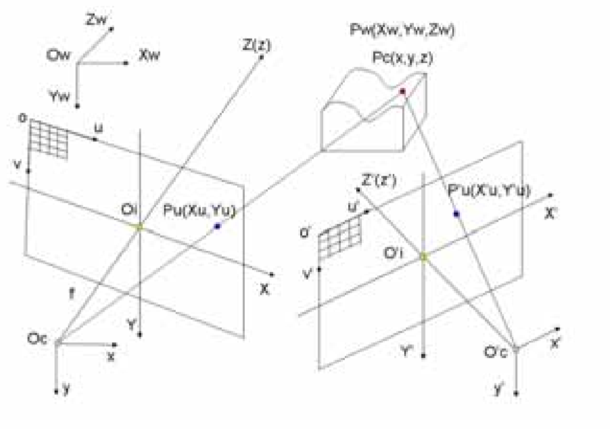

Figure 2 Pinhole camera model and geometric relationship.

The steps of transforming 3D world coordinates to pixel coordinates are as following:
(1) Transform from 3D world coordinates $P_w(X_w, Y_w, Z_w)$ to 3D camera coordinates $P_c(x, y, z)$:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \bullet \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} + T \quad (1)$$

R is a 3×3 orthogonal rotation matrix; T is a 3×1 translation vector. R determines the orientation of camera which relatives to the world coordinate system. Its matrix elements can be expressed by three angles, γ, β and α, and γ, β α are the rotation angle degrees that coordinate system rotates around the X_w − axis and Y_w − axis respectively.

$$R=\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

Its matrix elements are expressed as:

$r_{11} = \cos\alpha \cos\beta$, $r_{21} = -\sin\alpha \cos\beta$, $r_{31} = \sin\beta$

$r_{12} = \sin\alpha \cos\gamma + \cos\alpha \sin\beta \sin\gamma$

$r_{22} = \cos\alpha \cos\gamma - \sin\alpha \sin\beta \sin\gamma$, $r_{32} = -\cos\beta \sin\gamma$

$r_{13} = \sin\alpha \sin\gamma - \cos\alpha \sin\beta \cos\gamma$

$r_{23} = \cos\alpha \sin\gamma + \sin\alpha \sin\beta \cos\gamma$, $r_{33} = \cos\beta \cos\gamma$

Translation vector $T=[T_x, T_y, T_z]^T$ shows the position relation of the camera with respect to the world coordinate system.

(2) Transform from 3D camera coordinates $P_c(x, y, z)$ to ideal retinal coordinates $P_u(X_u, Y_u)$ in ideal pinhole model:

$$X_u = f\frac{x}{z}$$

$$Y_u = \sigma f\frac{y}{z} \qquad (2)$$

where f is the effective focal length. σ is the aspect ratio.

(3) Transform from ideal retinal coordinates $P_u(X_u, Y_u)$ to pixel coordinates P(u, v):

$$u = X_u N_x + u_0$$

$$v = Y_u N_y + v_0 \qquad (3)$$

Its (u_0, v_0) expresses the pixel coordinates of image centre O_i; N_x and N_y express the number of pixel contained in unit distance of image plane.

Transform from object 3D world coordinates (X_w, Y_w, Z_w) to pixel coordinates (u, v) shows the imaging process of 3D object in single camera. This process is irreversible, that is, it can't determine 3D spatial position of object uniquely from pixel coordinates (u, v). However, based on triangulation principle, it's known that two (or more) images in two (or more) different positions can determine the 3D spatial position $P_w(X_w, Y_w, Z_w)$ of object uniquely.

For two views, as showed in Figure 2, to integrate the camera model of image pair, we can obtain mathematical model as following:

$$B\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = D \qquad (4)$$

Then, we can obtain the least squares solution of $P_w(X_w, Y_w, Z_w)$ as following:

$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = (B^TB)^{-1}B^TD \qquad (5)$$

B and D contain all the camera intrinsic and extrinsic parameters corresponding to these image pair.

3.3 Camera Calibration

For precision measurement of an object in space to acquire more accurate 3D world coordinates from their 2D image coordinates, the camera calibration with higher accuracy must be obtained first to establish an exact relationship between 3D world coordinates and their corresponding 2D image coordinates as seen by the computer. Once this relationship is established, 3D information can be inferred from 2D information and vice versa.

Camera calibration is the process of determining camera intrinsic parameters and/or extrinsic parameters. The intrinsic parameters characterize the inherent optical and geometrical properties of the camera, including focal length, image centre, image scaling factor and lens distortion coefficients. The extrinsic parameters of a camera indicate the 3D position and orientation of the camera frame relative to a certain world coordinate system, such as rotation and translation. In the ideal situation, the user calibrates the camera's intrinsic parameters using a calibration pattern before taking the images of the scene to be reconstructed.

Many techniques and studies concerning camera calibration have been presented in the last few years. Most of these camera calibration techniques iterate by minimizing the discrepancy between the real position in pixels of a 2D image point (obtained from image segmentation) and the calculated projection of the 3D object point on the image plane (obtained by using the camera model).

In this paper, given a set of matched calibration points with their 3D positions in the world coordinates $[X_{wi}, Y_{wi}, Z_{wi}]^T$ and their 2D projections in the image coordinates $[u_i, v_i]^T$ obtained from known markers, camera calibration can be realized by minimizing the distance between the imaged points and the modeled projections, with the least squares solution and iteratively optimizing the intrinsic and extrinsic parameters of the camera model by downhill simplex method of Nelder and Mead.

The complete calibration process consists of three steps:

(1) the determination of initial estimates;

(2) the camera calibration itself;

(3) the accurate localization of the markers in the image plane.

Steps 2 and 3 are repeated until convergence is reached.

3.4 3D Point Data Acquirement

A point in a calibrated image back projects to a ray in the 3D space. Two corresponding points in two separate images define two rays that lie in the same plane. Intersecting these two rays result in the reconstruction of a 3D point.

Based on multi-image photogrammetry, a user-friendly semiautomatic surface measurement process consists of six steps.

(1) Mark manually some key points, interested points of a few special targets on the object to make them visually outstand from the background. Some specifically designed markers are distributed around the object as well.

(2) Take digital photographs of the object from different angles with ordinary digital camera.

(3) Load these high resolution scale image files into DPD (Digital photogrammetry Digitizer) system.

(4) Calibration camera with some calibration points and corresponding calibration data.

(5) Followed by an automatic camera pose recovery step, click the corresponding markers in image pairs with mouse on GUI (Graphical User Interface) of DPD system to establish corresponding relationship respectively.

(6) Computation of their 3D coordinates of these points in the PDA (Point Data Acquisition) system. The output is high accurate 3D point sets.

4 B-spline Surface Model Reconstruction

B-spline surfaces are widely used to model free-form shapes in product design and manufacturing due to their interesting properties, such as the ability to handle large surface patches, local controllability and also the ability to represent analytical features. A B-spline surface is the tensor product function defined by the equation:

$$S(u, v) = \sum_{i=0}^{n}\sum_{j=0}^{m} N_i^{\,p}(u) N_j^{\,q}(v) P_{i,j} \qquad (6)$$

where $P_{i,j}$ is an array of $(n+1)\times(m+1)$ control points and $N_i^p(u)$ is the *i*th B-spline basis function of degree *p*, defined recursively as

$$N_i^0(u) = \begin{cases} 1 & if\ u_i \le u < u_{i+1} \\ 0 & otherwise \end{cases}$$

$$N_i^p(u) = \frac{u-u_i}{u_{i+p}-u_i} N_i^{p-1}(u) + \frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}} N_{i+1}^{p-1}(u)$$

on a knot vector

$$U = \{\underbrace{0,\dots,0}_{p+1},\ u_{p+1},\dots,u_{r-p-1},\ \underbrace{1,\dots,1}_{p+1}\}$$

$N_j^q(v)$ is defined analogously.

Let $Q_1,\dots, Q_N$ be the reconstructed 3D points. Assume uniform knot sequences, for any fixed degree *p* and *q*, we solve the least square problem:

$$\min_{P_{i,j}} \sum_{i=1}^{N} \left\| Q_i - S(u_i, v_i) \right\|^2$$

for the control points $P_{i,j}$. Here $(u_1, v_1),\dots, (u_N, v_N)$ are the parameterization of the data points.

5 Tool Path Generation

The proposed approach is summarized in the flowchart shown in figure 3. It briefly includes seven steps [22].

(1) In reconstructed parametric surface in the u, v plane, holding one parameter constant defines an iso-parametric curve. If one of the parameters reaches zero or one, the curve becomes exactly one of the boundary curves surrounding the surface. If both parameters are held constant, a point is specified on the surface patch.

(2) Calculate the forward-step size with given tolerance, e. The forward-step size is the maximum distance between cutter contact (CC) points on the current tool path in which deviation does not exceed given tolerance, e.

(3) Convert the forward-step size form the physical domain into the parametric domain in order to calculate the next CC point.

(4) Convert CC points to cutter location (CL) points in order to reduce machining errors.

(5) Calculate side-step, g with given scallop height, h. When the parameter value of an iso-parametric curve reaches one at the end of current curve, side-step (g), should be calculated for the next tool path. The sidestep size is the maximum distance between two adjacent tool paths in which maximum scallop height is expressed.

(6) Convert side-step from the physical domain into the parametric domain in order to generate the next tool path.

(7) Convert CC points to CL points to store the points as a CL data file.

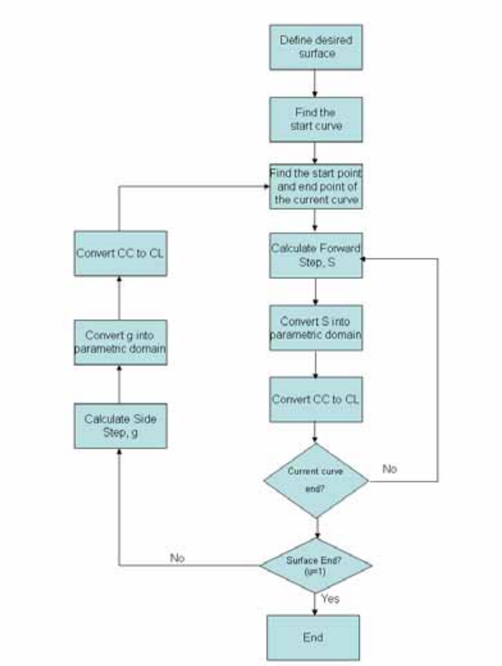

Figure 3. Overall procedure of tool path generation

6 Implementation

Based on upper solution, an experimental prototype of photogrammetry based 3D digitization, B-spline surface model reconstruction, and tool path generation for mechanical products manufacturing has been developed based on Open CASCADE kernel. Experiments show that the method is applicable for reverse modeling of freeform objects with moderate accuracy requirements. Therefore, the presented schema is a valid alternative to laser scanning techniques and coded light-based triangulation approaches with an important reduction of the hardware costs and time. Figure 4, 5, and 6 illustrate the main processes of photogrammetry based digitization. Figure 7, 8, 9 and 10 illustrate an example of point cloud, B-spline surface model reconstruction and tool path generation.

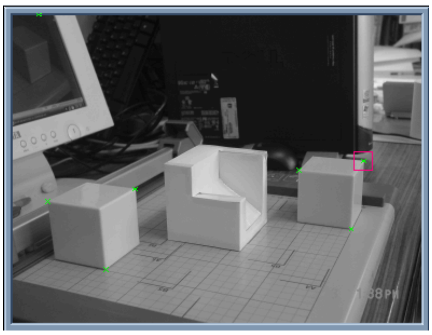

Figure 4 Camera calibration

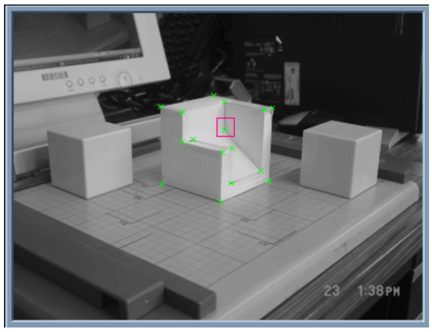

Figure 5 3D points marking

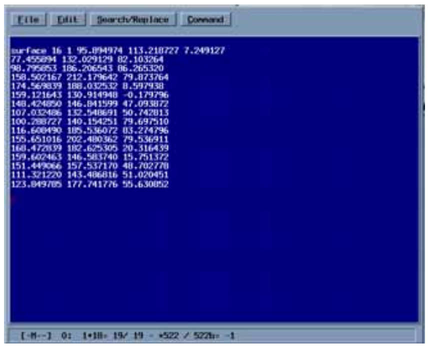

Figure 6 3D points coordinates data

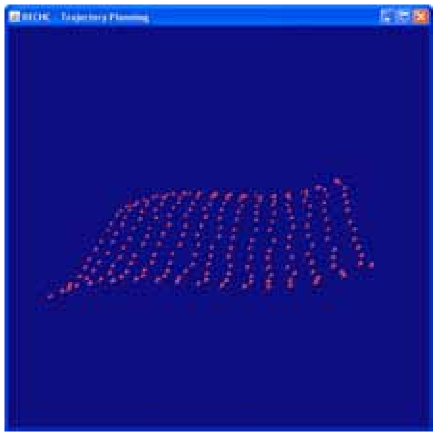

Figure 7 Point cloud

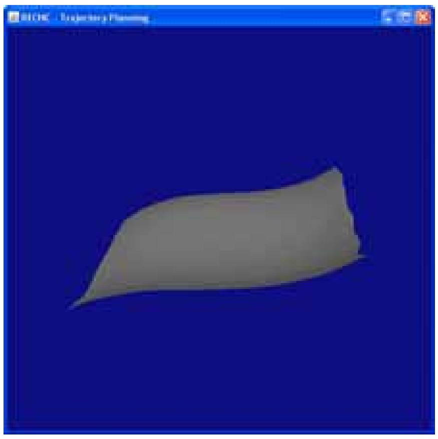

Figure 8 B-spline surface

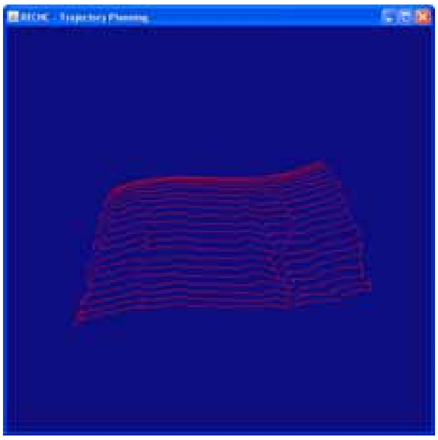

Figure 9 Tool path

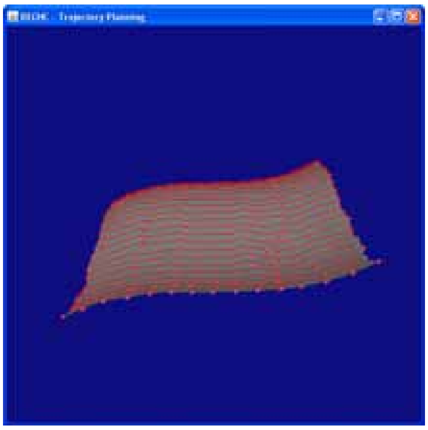

Figure 10 Point cloud, B-spline surface and Tool path

7 Conclusion

To bring a practical application of reverse engineering (RE) in small and medium enterprises (SMEs), this research explores a photogrammetry based strategy to obtain sampled 3D point clouds from a set of photographs, B-splines surface model reconstruction, and tool path generation for manufacturing. Experiments show that the method is applicable for reverse modeling of freeform objects with moderate accuracy requirements. Therefore, it can be concluded that the presented schema is a valid alternative to laser scanning techniques and coded light-based triangulation approaches with an important reduction of the hardware costs and time.

This work is currently under development. There still is room to improve and extend this experimental system. For example, camera calibration should be more precise. We are also attempting on increasing the automation level and improving the quality of the extracted 3D data with advanced computer vision techniques, based on manufacturing features as geometric primitives.

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