A Rapid 3D Vision Inspection System for Sheet Metal Parts Based on Feature Extraction and Partial Point Clouds

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Abstract. 3D vision inspection of sheet metal parts is usually a time-consuming task and hence not suitable for real-time measurement of 3D geometric features. To address this problem, this work presents an active binocular 3D vision inspection system for rapid measurement of features of sheet metal parts using 2D feature extraction and partial 3D point cloud. The inspection system firstly extracts the feature to be measured from one 2D image, then identifies the homologous points describing the feature on the other 2D image with the assistance of structured light, and lastly computes the 3D coordinates related to the feature measurement to largely reduce computational complexity. The system is applied to a sheet metal parts punching production line to monitor a couple of critical dimensions in real time. The experiment results indicate that it can acquire aperture center coordinate, radius, and aperture distances within 0.1 seconds and with an average error of less than 0.2mm. The proposed system shows the potential for being deployed on mass-production lines to realize rapid 3D measurement for metal sheet parts.

1. Introduction

In automotive manufacturing industry, there has been an increasing demand for real-time inspection of assembly parts for quality control purposes. This is different from Initial Sample Inspection Record (ISIR), which has lower requirement for timeliness and hence can be realized by ordinary 3D scanning method. Due to the time constraint and efficiency requirement of automatic production lines, many factories have turned to 2D vision inspection for these real-time dimension measurements. 2D vision inspection has its advantage in inspection speed, however, its application is limited to the parts with flat surfaces. For many parts in complex 3D shapes such as many sheet metal parts, 2D inspection either generates inaccurate measurements or requires complex settings.

In order to address this problem, many researchers have set out from improving the speed of 3D scanning. Fringe Projection Profilometry (FPP), a widely-used structured light measurement method, is one of the most studied techniques for real-time 3D imaging and measurement [1, 2, and 3]. Zhang and Huang [4], Nguyen et al. [5] used FPP method and the computational power of GPU to improve the speed of 3D measurement. Zuo et al [6] proposed a FPP-based fast-speed 3D measurement method by reducing the number of projection fringes to merely four. Although these methods have greatly enhanced the acquisition speed of 3D point cloud as well as the performance of the regeneration of 3D models, they have not fundamentally simplified the measurement process. No matter what scanning method is
employed, the generation of 3D model from point cloud remains as an unavoidable and time-consuming process in the realization of measurement. As a matter of fact, in many real-time measurement applications the quality control only focuses on a few critical dimensions rather than the entire 3D model of the workpiece. For example, judging if a punching machine produces qualified parts may only require the inspection of the relevant distance of a few critical holes.

The objective of this paper is to introduce a novel real-time 3D measurement system for the critical dimensions of automotive sheet metal parts, which utilizes image feature extraction and structured light measurement to selectively compute only the partial 3D cloud comprising the critical features to improve the speed of measurement. Compared to traditional structured light measurement methods, the proposed system has significantly improved the speed of measurement by directly computing the coordinates from partial point cloud. Not having to generate the entire point cloud and 3D model, this proposed system can bypass a large amount of computation in a 3D measurement. In the combination with two 130fps high-speed cameras, the system can achieve a real-time 3D measurement within 0.1 seconds with an average error smaller than 0.2mm.

2. System configuration and working principles

The hardware part of the system consists of one LG HW300TC projector and two CrashCamTM CC-4010 high speed cameras which can record up to 130 frames per second at resolution 2560x1600 with SSD. The adoption of high speed cameras would significantly reduce the time used to capture the series of pictures when successive fringes are being projected onto the metal sheet parts. The pictures without fringes were used to extract the 2D edges defining the feature to be measured, and the rest pictures with fringes were used to mark the homologous points to generate the 3D point cloud related to this feature. The projector and cameras were fixed on a metal plate and protected by a plastic case to improve the working stability of the system and reduce the error introduced by the move of the optical components.

![Figure 1. Schematic diagram of the system and stereo matching.](image)

2.1. Feature selection and extraction

Instead of capturing the 3D information of an entire sheet metal part, the proposed system uses only the points constituting the feature to be measured and bypasses the irrelevant surface points. The approach results in light computational load and hence quicker response time.

The feature extraction is performed based on the 2D images acquired via the cameras prior to the projection of fringes. There are many feature extraction methods that have been proved effective in different contexts, such as Histogram of Oriented Gradient (HOG) and Local Binary Pattern (LBP). For the purpose of feasibility verification, a simple template matching based method was selected in the experiment so as to focus on the speed and accuracy of the proposed system. An image template containing the feature to be measured was adopted to locate the feature in the captured image via comparing their grayscale distribution, and then the edge of the feature was extracted using canny edge detection.
2.2. Stereo matching

A key procedure in 3D reconstruction based on stereoscope is stereo match, i.e. identify the homologous point on the 2nd camera image given a point on the 1st camera image. Traversing all the pixels on the right camera image to find the homologous point is not only timely expensive, also difficult for textureless surface. To address the above problems, epipolar constraint and structured light techniques were adopted to enable quick and precise stereo matching.

Epipolar constraint converts a two-dimensional search problem into a one-dimensional search problem. According to epipolar geometry, given a point on the left camera image, its homologous point must be on its corresponding epipolar line on the right camera. The epipolar line of a point PL can be identified as the line on the right camera image which is the projection of the spatial line linking the point PL and the focal point of the camera. Searching along epipolar line for homologous point greatly reduces computational load and makes a real-time automatic 3D measurement system possible.

The structured light technique projects one or a group of designed patterns onto an object, so that every pixel captured by the camera can be identified with a unique corresponding code. In the proposed system the maximum min-SW gray code proposed by Gupta et al. [7, 9] and Micro Phase Shifting were employed to generate the patterns. Compared to conventional gray code with a min-SW of 2 pixels, the maximum min-SW gray code uses a min-SW of 8 pixels and 10-bit binary gray code [8]. Due to the larger strip width, the maximum min-SW gray code is more resistant to reflective and scattering surface such as the shining surface of sheet metal parts.

The micro phase shifting method [10] shifts every next projection pattern by a factor of $\frac{2\pi}{N}$, where N is the total number of projection patterns. This method can be described with the following equations:
Where $I$ is the received intensity value from the projection surface, $A^p$ and $B^p$ are projection constants, $x$ and $y$ are projection coordinates, $n = 0, 1 \ldots N$.

The decoding process is shown in the equation 3:

$$\phi(x, y) = \arctan \left[ \frac{\sum_{n=1}^{N} I_n(x, y) \sin \left( \frac{2\pi n}{N} \right)}{\sum_{n=1}^{N} I_n(x, y) \cos \left( \frac{2\pi n}{N} \right)} \right]$$

The key idea of the micro phase shifting method is to project sinusoidal patterns with spatial frequencies limited to a narrow, high-frequency band. The bandwidth and the periods are selected to be so small that for each surface point, both global illumination and defocus effects remain constant over all the captured images. Hence it is more resistant to interreflections and subsurface scattering in 3D measurement.

For $F$ frequencies, the phase recovery requires $F+2$ projection patterns and can be solved using equation 4 and 5.

$$R_n(c) = O(c) + A(c) \cos(\phi_1(p) + (n-1)2\pi/3)$$

$$R_n(c) = O(c) + A(c) \cos(\phi_{n-2}(p))$$

Similar to Guehring’s method [11], the combination of the maximum min-SW gray code and the micro phase shifting code are simultaneously projected onto the surface. The decoding result of the robust maximum min-SW gray code is used to label the integer center of every pixel. The sub-pixel locations are acquired via the decoding result of the micro phase shifting patterns. Then the correspondences are detected by the following steps:

1. For a pixel on the left camera, decode the maximum min-SW gray code and get the pixel number.
2. Decode the micro phase shifting code and get the sub-pixel correspondences.
3. Search along the Epipolar line on the right camera for the pixel number and sub-pixel correspondences.

2.3. 3D reconstruction and inspection

The reconstruction of a 3D point from two plane images is based on stereoscope equation. Assuming the following factors are known:

1. The intrinsic parameters of the two cameras, which are the focal length, principal point, pixel size, and distortion coefficient.
2. The extrinsic parameters of the two camera, which are a 3 x 3 rotation matrix and a 3 x 1 translation vector defining the relative location of the right camera with respect to the left camera.

The 3D coordinates of the surface points of the target object, i.e. the point cloud, can then be generated using the intrinsic parameters and coordinate transformation. Let $P$ be a point on the surface of the target metal sheet, $P_1$ and $P_2$ be the projection of point $P$ on the camera $C_1$ and camera $C_2$, $M_1$ and $M_2$ be the projection matrices of the two cameras respectively. The following equations can be yielded:

$$Z_{C_1} = \begin{bmatrix} u_1 \\ v_1 \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11}^1 & m_{12}^1 & m_{13}^1 & m_{14}^1 \\ m_{21}^1 & m_{22}^1 & m_{23}^1 & m_{24}^1 \\ m_{31}^1 & m_{32}^1 & m_{33}^1 & m_{34}^1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (6)$$
The above equation group and the least squares method can be used to solve the spatial coordinate of point P. Then the 3D coordinates of the entire feature can be recovered by solving the spatial coordinates of all the points on it. Finally the inspection can be realized via the computation of spatial equations describing the geometric feature.

3. Experimental results and discussion

In the experiment, the diameter of a punched hole on a type of metal sheet parts was inspected online to monitor if every piece of the metal sheet parts met the assembly requirements and the punching machine was functioning properly. The time consumption of every inspection was recorded and the inspection results were compared to those from a GOMTM ATOS Core 500 3D scanner to get an accuracy comparison. The main steps of the proposed 3D vision inspection method are as follows:

1) Extracted the edge of the punched hole from one captured image
2) Find homologous points on the other image via stereo matching.
3) Reconstruct the 3D coordinates comprising the edge punched hole.
4) Fit a spatial circle to the 3D point cloud acquired from step 3 and compute its diameter. The fitting of a spatial circle to 3D points can be viewed as fitting a sphere and a plane to the 3D points and finding their interception.

Figure 4. One inspection result of the feature (punched hole).

In the experiment, a total of 65 pieces of metal sheet parts were inspected for the diameter of the punched hole. The average inspection time and measurement error is shown as below, with reference to the performance of GOMTM ATOS Core 500 3D scanner.

|                  | Average inspection time (seconds) | Average measurement error(mm) |
|------------------|-----------------------------------|-------------------------------|
| The proposed system | 0.18                              | +0.113                        |
| ATOS Core 500 3D scanner | 962                               | 0                             |
The experimental results show that the proposed system has tremendously improved the inspection time at the cost of a slightly higher average measurement error. The ATOS Core 500 3D scanner is a highly accurate 3D scanner with the highest precision reaching 0.003mm. However, using Core 500 3D scanner for the measurement of one punched hole would involve the manual scanning of the parts (at the absence of a robot arm) and operation of the GOMTM inspect software, which is quite time-consuming and subject to the skill of the operator. Therefore, it resulted in much longer inspection time. In the statistics of the average measurement error, the actual measurements by the ATOS Core 500 3D scanner were assumed as the standard dimensions due to its high measurement precision. The +0.113mm measurement error of the proposed system is acceptable for many applications in the manufacturing of metal sheet parts, and it can be further improved via the adjustment of the edge detection algorithm. The edge detection has a considerable impact on the precision of measurement due to the wall thickness of the punched hole. It is easy to extract the wrong edge from a side view picture of the punched hole.

4. Conclusion
The proposed system bypasses the acquisition of the entire cloud point and the generation of triangle meshes, hence tremendously improves the measurement speed. It has a great potential to be applied to all sorts of production lines for real-time inspection. The performance of the system is subject to the surface of the workpiece to be measured as well as the feature extraction algorithm. The future work would involve the improvement of measurement of performance with workpieces with specular and transparent surface, as well as the extension of measurement to more geometric features.

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