Stereo Match of Serial Feature Points on Scanning Laser Beam

T Q Ren, J G Zhu, D W Wang and S H Ye
State key laboratory of precision measuring technology and instrument, Tianjin University, 300072, China
E-mail: renatseatj@eyou.com

Abstract. In 3D contour inspection based on laser scanning, the scanning laser beam provides enough successive features to recover the object surface. It is the key link of completing measurement to determine and match feature points accurately. A method based on epipolar slope-constrain and ray intersection-constraint is proposed in this paper. The centroidal curve is picked as the primitive to be matched. Given one point of left centroidal curve, its corresponding epipolar line on right image plane can be obtained due to epipolar slope-constraint. And the intersecting point of right centroidal curve and right epipolar line is the rough matching point of given point. An exact searching around rough matching point according to ray intersection-constraint is adopted to complete the accurate stereo matching. This method is applicable for field measurement with large data because of its high precision and speed.

1. Introduction
Stereo matching [1,2] is one key problem in stereo vision theory. The goal of stereo matching is to determine one object point’s image coordinates both in left and right cameras. Further more, these image coordinates are used to reconstruct this object point. In visual surface inspection, correct recovery of object surface needs sample points more than Nyquist’s sampling points. It is difficult to obtain sufficient parallax density regarding object’s own texture as feature point. So space encoding technology [3] and laser scanning technology [4] are always used to produce enough feature points. And the latter method is more widely adopted because of simple image processing and obvious feature. However, the scanning laser beam contains plenty of data of serial feature points. So a stable and quick matching algorithm is need to fit measurement system’s request of high matching precision, density and efficiency. Therefore, precise stereo matching method of serial feature points based on epipolar-slope constraint and ray-intersection constraint is proposed in this paper.

2. Matching constraints
2.1. Epipolar slope-constraint.
Epipolar slope-constraint [3] is one of the most important constraints in stereo vision as figure 1 shows us. Points \( o_1 \) and \( o_2 \) are respective center of perspectivity of two cameras. Points \( o_1 \), \( o_2 \) and object point \( p \) can compose one plane called epipolar plane. And the epipolar plane intersects left and right image planes respectively at lines \( p_1 e_1 \) and \( p_2 e_2 \) which are the epipolar lines of projective points \( p_1 \) and
on each image plane. Points \( e_1 \) and \( e_2 \) are the intersecting points of line \( o_1o_2 \) and two image planes. They are called as epipolar points of each image plane. All the epipolar lines belong to the same image plane must intersect at one point \( e \), which is called epipolar center.

**Figure 1.** Epipolar geometrical relationship of cross-placing binocular vision model.

In stereo binocular vision model, left and right camera coordinate frames are defined as \( o_1x_1y_1z_1 \) and \( o_2x_2y_2z_2 \). Given the transition relation of these two camera coordinate frames as follows:

\[
\begin{align*}
\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} &= \begin{bmatrix} r_{21} & r_{22} & r_{23} \\ r_{24} & r_{25} & r_{26} \\ r_{27} & r_{28} & r_{29} \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} + \begin{bmatrix} t_{2x} \\ t_{2y} \\ t_{2z} \end{bmatrix} \\
\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} &= \begin{bmatrix} r_{31} & r_{32} & r_{33} \\ r_{34} & r_{35} & r_{36} \\ r_{37} & r_{38} & r_{39} \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} + \begin{bmatrix} t_{1x} \\ t_{1y} \\ t_{1z} \end{bmatrix}
\end{align*}
\]

(1)

From the spatial geometrical relationship, the left and right epipolar point can be obtained:

\[
\begin{align*}
& e_1 \left( \frac{t_{2x}}{t_{2z}}, f_1, \frac{t_{2y}}{t_{2z}} \right), e_2 \left( \frac{t_{1x}}{t_{1z}}, f_2, \frac{t_{1y}}{t_{1z}} \right). \\
& \text{Moreover, any line passed } e_1 \text{ with slope } k_1 \text{ in left image plane must have a matching line passed } e_2 \text{ with slope } k_2 \text{ in right image plane. The transition relation of } k_1 \text{ and } k_2 \text{ can be given by:}
\end{align*}
\]

\[
\begin{align*}
k_1 &= \frac{t_{2x} \cdot (r_{24} + r_{28}k_2) - t_{2y} \cdot (r_{27} + r_{28}k_2)}{t_{2x} \cdot (r_{27} + r_{28}k_2) - t_{2z} \cdot (r_{21} + r_{22}k_2)} \\
k_2 &= \frac{t_{1x} \cdot (r_{34} + r_{38}k_1) - t_{1y} \cdot (r_{37} + r_{38}k_1)}{t_{1x} \cdot (r_{37} + r_{38}k_1) - t_{1z} \cdot (r_{31} + r_{32}k_1)}
\end{align*}
\]

(3)

(4)

Epipolar geometrical relationship provides a local constraint condition for binocular vision matching. Considering the error of structural parameter of visual sensor, the hunting zone of matching point can be restricted within a small region around a line section.

2.2. Ray-intersection constraint.

Showed as figure 2, two cameras compose a cross-placing binocular measurement model. Points and \( o_2 \) are cameras’ optical centers. Coordinate frames \( o_1x_1y_1z_1 \) is the left camera coordinate frame, and \( o_2x_2y_2z_2 \) is the right camera coordinate frame. \( P_1 \) and \( P_2 \) are left and right image coordinates of object point \( P \). If \( P_1 \) and \( P_2 \) are matching points to each other, imaging lines \( o_1P_1 \) and \( o_2P_2 \) must intersect at object point \( P \). From the perspective model of camera, the 3D coordinates of image point \( p(X, Y) \) in cameral coordinate frame can be descript as \((X_0, Y_0, f)\), where \((X_0, Y_0)\) is the ideal image coordinates and \( f \) means the effective focal length of camera. Points \( o_2 \) and \( P_2 \) can be unified into left camera coordinate frame when the transition relationship of two cameras is calibrated. So the straight line equations of \( o_1P_1 \) and \( o_2P_2 \) in left coordinate frame can be obtained. Further more, the distance \( d(o_1P_1, P_1) \),

\[
\text{where } d(o_1P_1, P_1) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}.
\]
of spatial lines $o_1P_1$ and $o_2P_2$ can be achieved from their equations. With a view to error of sensor’s structural parameter, an appropriate threshold $\Delta d$ is need. The two lines can be considered as intersection when $d(o_1P_1, o_2P_2) \leq \Delta d$.

![Figure 2. Schematic diagram of ray-intersection constraint.](image)

The true measurement process is from two-dimensional image coordinates data to three-dimensional coordinates. The three-dimensional coordinates of object point are unknown before getting the corresponding matching image points. So the imaging ray can be only represented by optical center $o(0,0,0)$ and image point $p(X_0, Y_0, f)$. Left image point $P_1$ is corresponding to a line section in right image plane due to the analysis to epipolar-slope constraint. Any point $P_2$ of this line section meets the intersecting condition of $o_1P_1$ and $o_2P_2$. So under the condition of image points known only, lines $o_1P_1$ and $o_2P_2$ intersecting in object space is just the necessary condition of $P_1$ and $P_2$ matching each other.

3. Realization of matching

The first step of stereo matching is to determined proper feature point. To the scanning laser beam with obvious image feature, centroidal method [5] takes on the merit of direct-viewing, simple calculation and high precision. So the centroidal point of scanning laser beam can be considered as primitive to be matched. Showed as figure 3, point $P_1$ is selected from left centroidal curve as the candidate point. Its matching point $P_2$ must lies on the centroidal curve of right scanning laser beam. Point $P_2$ can be determined as the intersecting point of right epipolar line $E_2$ corresponding to $P_1$ and centroidal curve of right scanning laser beam due to the epipolar-slope constraint.

Given a left image point $p_1(X_1,Y_1)$, the slope of line $p_1e_1$ on left image plane can be resolved by:

$$k_1 = \frac{Y_1 - Y_{e_1}}{X_1 - X_{e_1}} \quad (5)$$

$k_2$, the slope of line corresponding to point $P_1$, can be obtained by formula (4). Further more, the planar equation of this line on right image plane can be gained due to the known conditions of slope $k_2$ and point $e_2$. The centroidal curve of scanning laser beam is not standard curve. It can not be expressed by an accurate equation. So the intersecting point can not be resolved directly. The image planar equation of $E_2$ can be abbreviate as $f(X_2, Y_2)=0$. Traversing the whole centroidal curve, the intersecting point is the point making following equation come into existence.

$$\left| f(X_{p_2}, Y_{p_2}) - f(X_2, Y_2) \right| = Min \quad (6)$$
The scanning laser beam is successive in vertical direction. Centroidal method of picking feature point just works in scanning direction. And the minimum resolution in scanning direction is one pixel. In addition, object surface imperfection is likely to cause fracture of scanning laser beam, which leads no matching point at fracture. So the mathematical point from formula (6) is only rough matching point at most, even false matching point. On the other hand, the physical size of image plane is limited. The epipolar point must lies far away from the real image plane, which leads to unparallel direction of epipolar line and centroidal curve of scanning laser beam. This means one exclusive intersecting point. So, linear interpolation can be done with appropriate pace \( \Delta p \) in a small neighborhood of the rough matching point along centroidal curve. Considering the adjacence of rough matching point and accurate matching point, a span of two pixels can be adopted. And the accurate matching can be accomplished by using ray-intersection constraint as criterion at the interpolative point fitting formula (6) best. When the parameters of camera and sensor are fixed, smaller values of \( \Delta p \) and \( \Delta d \) mean higher matching precision.

4. Conclusion

In contour inspection based on visual method, matching of feature points is one key link which influences the final measurement accuracy. At the same time, plenty of data to be operated make it to be the most time-consuming link. Centroidal method of feature picking can reach precision of sub-pixel, even higher level, because of the simple feature and the well controlled image with high-quality. It can be ensured at the level from 0.02 to 0.03 pixels. So, when the camera parameters and sensor parameters are fixed, matching algorithm becomes the main factor influencing the matching precision.

A matching experiment (\( L \) is approximate 700mm, \( \Delta p \) is 0.1 pixel and \( \alpha \) is approximate 15 ) is done to match a pair of successive laser beams in vertical direction getting by digital camera Basler-A101f (1300×1030 pixels). Table 1 intercepts matching results of ten pairs of continuous points. In this method, \( \Delta d \) is an important reference of matching precision. In fact, \( \Delta d \) is an enlargement expression of matching precision, where the enlargement factor \( \alpha \) is concerned with structural parameters of sensor and working distance L. Enlargement factor \( \alpha \) is about 15 in this experiment. Tracking results of the whole laser beam show that maximum \( \Delta d \) is no more than 0.6 pixel. And the matching process costs less 3 seconds.

| Serial number | Candidate points of left image plane(X,Y) | Matching point in right image plane(X,Y) | \( \Delta d \) (pixel) |
|---------------|------------------------------------------|------------------------------------------|----------------------|
| 1             | (172.00,4.00)                            | (246.50,132.28)                          | 0.58                 |
| 2             | (171.89,5.00)                            | (246.41,133.33)                          | 0.47                 |
| 3             | (171.90,6.00)                            | (246.50,134.25)                          | 0.44                 |
| 4             | (172.12,7.00)                            | (246.91,135.33)                          | 0.36                 |
| 5             | (172.00,8.00)                            | (247.00,136.34)                          | 0.51                 |
| 6             | (172.00,9.00)                            | (246.98,137.39)                          | 0.47                 |
| 7             | (172.00,10.00)                           | (246.96,138.42)                          | 0.49                 |
| 8             | (171.50,11.00)                           | (246.48,139.06)                          | 0.11                 |
| 9             | (171.50,12.00)                           | (246.55,140.17)                          | 0.12                 |
| 10            | (171.50,13.00)                           | (246.61,141.14)                          | 0.08                 |
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