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Real-time 3D Shape Measurement System based on Single Structure Light Pattern

Jing Xu, Ning Xi, Chi Zhang and Quan Shi

Abstract— **The objective of this paper is to propose a robust one shot structured light pattern for real time 3D shape inspection system. To reduce the influence of inspected part reflectance property and ambient light, the pattern is constructed by using monochromatic light. The corner of the chessboard is utilized as the primitive of the pattern since it can provide highly accurate position. Additionally, the orientation of the corner is used to encode the primitive of the pattern. Compared with ordinary two dimensional patterns, the pattern is developed in one dimension, along the epipolar line so that the search of the corresponding pixels between the projector and the camera is speeded up. Last, experiments were conducted to evaluate the robustness and accuracy of the inspection system using the proposed pattern. The results demonstrate that the system has high accuracy performance.**

I. INTRODUCTION

In automotive industry, there has been an increasing requirement to rapidly measure the 3D shapes of the automotive parts instead of traditional coordinate measurement machine (CMM), one of the contact measurement sensors. The dimensional inspection using CMM is time consuming since the part can only be measured point by point. To overcome such drawback, the non-contact 3D inspection system based on structured light has been successfully achieved in a variety of application. A white light area sensor usually contains two parts, a projector and a camera: the projector is used to put a set of encoded structured light patterns on the part surface such that the camera can decode those patterns for the acquisition of 3D part shape using triangulation measurement technique. The encoded pattern affects all of the measurement performance such as accuracy, precision, point density, and time cost, etc.

Many different structured light pattern codification strategies have been developed [1]. They can be mainly categorized as time multiplexing, direct coding, and spatial neighborhood. The strategy based on time multiplexing is easy to be implemented and can achieve a high accuracy and resolution performance. At present, the Gray Code and Phase Shifting (GCPS) and Gray Code and Line Shifting (GCLS) are widely used in shape measurement system for quality inspection in automotive industry [2]. However,such systems have following main drawbacks: the inspected part must not be moved while the coded patterns are being obtained since the multiply patterns should be projected in sequence. Otherwise the system may acquire incorrect stripe and result in inaccurate 3D shape. Thus, the combination of the space and time in each stripe boundary of patterns is used so that the time consistency and the number of fringe patterns can be reduced. Actually, this strategy is still multi-shot pattern which can not deal with the fast moving part [3]. For this purpose, the method for direct coding based on every point containing the entire codeword in a unique pixel is developed; however, it is very sensitive to the noise because a large range of color values are adopted in such a pattern.

In the strategy of a spatial neighbor pattern , the codeword of each primitive (element) depends on its value and those of its neighbor so that the codeword can be determined in a unique pattern. Therefore, it can be used as one shot pattern for real time 3D shape measurement. The most typical one shot pattern based on spatial neighbor is constructed with stripe pattern [4], [5] (parallel adjacent bands), multiply slits[6], [7](narrow bands separated by black gaps), and sparse dots[8], [9] (separated dots on the black background). The efficient way to encode these patterns is based on color so that pixel codeword can be determined by different colors around it. In practice, the reliability of the color pattern is lower than those from monochromatic light (black and white) pattern because color contrast is affected by inspected object color reflectance and ambient light. To solve this problem, neighbor strategy based on black/white pattern is used for inspection system. However, the number of neighbors increases for encoding each primitive because the possibility of color value for each primitive decreases. To solve such a problem, some authors develop patterns based on the geometrical feature of the primitive instead of color [10], [11]. In this case, the required number of coding length depends on the number of different geometrical features of the primitive.

To satisfy the requirement of the real time measurement for the automotive production lines, the structured light pattern should simultaneously satisfy the robustness, accuracy, and realtime performance. However, the existing patterns have not been achieved in the real-time measurement for automotive parts, such as pillar and windshield. For this purpose, a new structured light is proposed based on spatial neighbor strategy in this paper. The primitive of the pattern is designed with the corner of black/white chessboard which is also called Xpoint. The Xpoint provides more robust and accurate position compared with conventional pattern primitive based on symmetrical symbols such as disc, stripe and so on. The orientation of the Xpoint is used to encode

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the primitive of the pattern. Moreover, the pattern coding and corresponding pixel search are constrained along the epipolar line of the projector and the camera which is implemented in a predefined rectangle window. Thus, it reduces the coding length and speeds up the corresponding pixel search to satisfy the requirement of real time measurement.

The remaining sections of this paper are arranged as follows: in section II, the one shot pattern design is described. The calibrations of sensors and system are given in section III. In section IV, the accuracy and reliability of the measurement system are tested. The conclusion is given in section V.

II. ONE SHOT PATTERN DESIGN

A. Epipolar Geometry

A typical triangulation-based 3D shape inspection system based on active vision using the structured light pattern consists of a CCD (Charged Couple Device) camera and a DLP (Digital Light Processor) projector as shown in figure 1. Once the correspondence problem is solved using the structured light pattern, the surface point of the measured part shape can be reconstructed.

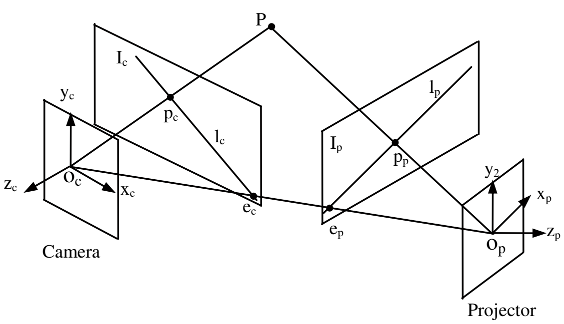


Fig. 1. The epipolar geometry of the inspection system

In such a system, a projector can also be regarded as an inverse camera for it projects images instead of capturing them. Hence, the epipolar geometry in stereo vision can be utilized as one constraint of the pattern designed and correspondence search. Considering the case shown in figure 1, P is a point on the surface of inspected part; p_c and p_p are the projections of the point P on the camera image plane I_c and the projector image plane I_p, respectively. Additionally, O_c and O_p are the focal points of the camera and the projector, respectively. Each focal point projecting onto other image plane forms two image points e_c and e_p, named epipolar or epipolar point. Therefore, P, p_c, p_p, O_c, O_p, e_c and e_p are coplanar. The plane is known as epipolar plane. The intersection of the epipolar plane with the image plane I_c and I_p are called the epipolar line and denoted by l_c and l_p , respectively. Thus, the corresponding points , p_c and p_p are constricted by [12]:

$$p_c^T \cdot F \cdot p_p = 0 \qquad (1)$$

where F is the fundamental matrix. The two corresponding epipolar lines l_c and l_p satisfy:

$$l_c = F\left[e_p\right]_\times l_p \qquad (2)$$

Where $\left[e_p\right]_\times$ denotes 3×3 skew symmetric matrix. If $e_p = \begin{bmatrix} e_1 & e_2 & e_3 \end{bmatrix}^T$, then the corresponding skew symmetric matrix can be represented as:

$$\left[e_p\right]_\times = \begin{bmatrix} 0 & -e_3 & e_2 \\ e_3 & 0 & -e_1 \\ -e_2 & e_1 & 0 \end{bmatrix}$$

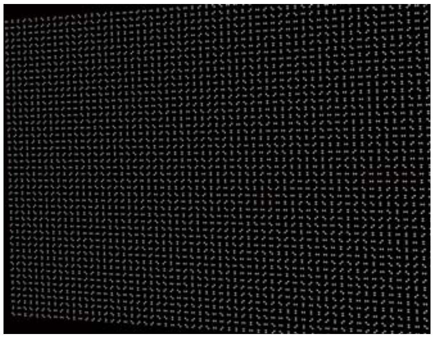
Once the fundamental matrix is calibrated, the camera and projector image plane can be divided by a serial of epipolar line. Then, the structure pattern is developed along each epipolar line. As a result, the pattern design and the correspondence problem are both reduced from the traditional 2D search (the whole image) to 1D search problem (along the epipolar line). Thus, the algorithm will be significantly accelerated compared with the conventional strategies.

To simplify the corresponding point search in the image plane for camera and projector and let the epiploar lines uniformly distribute on the projector image plane, the line connecting the optical centers of the camera and projector (baseline) should be parallel to both the scan lines of the image plane for the camera and projector (in other words, the epipolar lines are parallel to horizontal image axes). For this purpose, we can firstly roughly adjust the relative position and orientation between the projector and the camera based on the result of calibration. Then, the two image planes can be further rectified. The rectified images can be regarded as acquired by the optical device rotated with respect to the original one [13]. Figure 2 illustrated the one-shot pattern in projector image plane and in the rectified image plane. The epipolar line in the former plane is not parallel to the scan line one such that the primitive projected is not in horizonal direction. However, the primitive in the latter one is in horizonal direction, resulting in simplification of the image processing. Hence, the pattern design and identification are both in rectified plane.

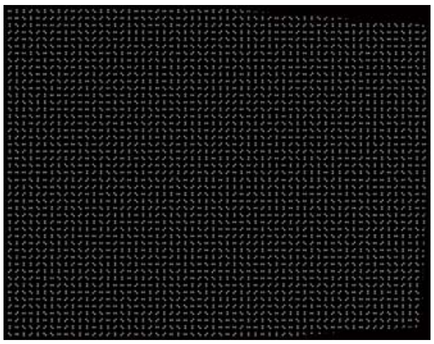
B. Pseudorandom sequence

The patterns based on spatial neighbor can be generated by brute-force algorithm to obtain the desired characteristics without any mathematical background. In general, it is not optimal and robust. Thus, some authors developed the pattern based on the well-known type of mathematical sequence, De Bruijn sequence. A De Bruijn sequence of order m over an alphabet of q symbols is a circular sequence of length q^m length that contains each substring of length m exactly appears once[14].

Similarly, a pseudorandom sequence is a length of $q^m - 1$ circular sequence without the subsequence formed by 0, where q is a prime or a power of prime[7], [14]. Then, any substring of length m also exactly appearing once according to its window property. The pseudorandom sequence is generated by a primitive polynomial with coefficients from the Galois field $GF(q)$



(a)



(b)

Fig. 2. Image rectification: (a)projection image ; (b) rectified image

$$h(x) = x^m + h_{m-1}x^{m-1} + \cdots + h_1 x + h_0 \quad (3)$$

This polynomial defines a feedback shift register as shown in figure 3, where the boxes contain the elements of $GF(q)$ named $a_{i+m-1}, \cdots a_i$, then feedback path then forms [14]

$$a_{i+m} = -h_{m-1}a_{i+m-1} - h_{m-2}a_{i+m-2} + \cdots + h_1 a_{i+1} - h_0 a_i \quad (4)$$

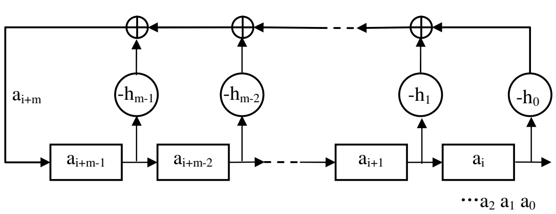


Fig. 3. The pseudorandom sequence generator

The Galois field $GF(q)$ elements are expressed as

$$\mathrm{GF}(q) = \left\{0, 1, A, A^2, \ldots A^{q-2}\right\} \quad (5)$$

Some primitive polynomials are shown in Table .I [14].

In our paper, along epipolar line of the projector image plane, we use the feedback path defined by the primitive polynomial $h(x) = x^3 + x^2 + x + A$ over $\mathrm{GF}(4) = \left\{0, 1, A, A^2\right\}$ with $A^2 + A + 1 = 0$ and $A^3 = 1$

TABLE I

PRIMITIVE POLYNOMIAL OVER GF(Q)

deg(m)	q=3	q=4	q=8
1	$x+1$	$x+A$	$x+A$
2	x^2+x+2	x^2+x+A	x^2+Ax+A
3	x^3+2x+1	$x^{+}x^2+x+A$	x^3+x+A
4	x^4+x+2	$x^4+x^2+Ax+A^2$	x^4+x+A^3
5	x^5+2x+1	x^5+x+A	$x^5+x^2+x+A^3$

Along each epipolar line, a pseudorandom sequences with length of 63 is generated. One of them is shown as: 110312223221020213100220123331 332030321200330231112113010132300

C. Primitive Design

Design a good primitive of the pattern is critical important for achieving accurate correspondence with optical triangulation technique, especially one shot method. The primitive design should satisfy the following constraints in our paper:

(a) Monochromatic light;

(b) Robust and accurate detection.

Taking the monochromatic light into account, the symbol should not contain color coding information. Hence, the symbol with geometrical feature will be adopted, instead of the traditional color based coding patterns. The image feature should be accurately extracted and solve the problem of shadows and occlusions. The center symmetry symbol, such as circle, disc etc, is widely used for fringe pattern and the intensity centroid of the symbol is regarded as the symbol location. However, a partial occlusion affects the centroid position. In this paper, the strategy determines the symbol location with the corner of high contrast checkerboard. Thus, the portions of the Xpoint region hidden by smudges or occlusions are disregarded, with no significant impact on accuracy as shown in figure 4.

Fig. 4. The comparison of different primitives

Additionally, the disc in an image dose not contain any geometrical information other than its center's location. Xpoint has both a location and an orientation. This additional characteristic usually is used to discriminate the different symbol in the epipolar line. As shown in figure 5, the red arrow denotes the orientation of the symbol and the corresponding code. The angle between the principle axis of the symbol and the epipolar line are 0, $\pi/4$, $\pi/2$, $3\pi/4$ and the corresponding codes are 0, 1, 2, 3, respectively.

Moreover, misleading bright reflection spots are more often naturally found in a measurement environment than

Xpoints. Therefore it is easy to remove the noise caused by bright spots when using the Xpoints as the primitive.

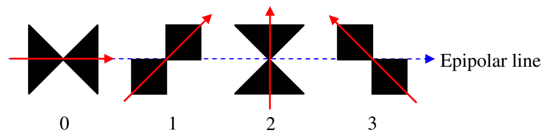
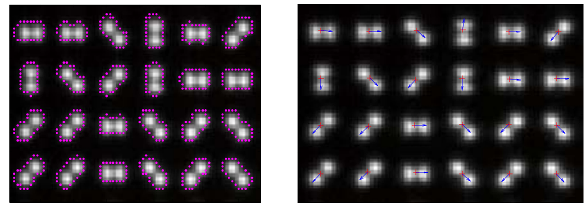


Fig. 5. The primitives design



(a) (b)

Fig. 6. Image processing: (a) contour extraction; (b) location and principal axis identification

D. Pattern Detection and Identification

Once the pattern is projected on the scene, a single frame is captured by the camera. The image processing is simple because the primitives are designed on the black background and separated enough. Given the inspected surface are locally smooth and a strong gradient in the image intensity around the symbol boundary, the contour of the symbol is easily detected and can be implemented in real time. Additionally, it is less sensitive to reflectivity variation and ambient illumination than threshold based segmentation. Consequently, the moment and principal axes method is adopted to recognize the primitive. The moment of geometrical primitive is represented as:

$$M_{jk} = \int_{-\infty}^{\infty} x^j y^k f(x,y) dxdy \tag{6}$$

The coordinates of the mass center are denoted as:

$$X_m = M_{10}/M_{00}; Y_m = M_{01}/M_{00} \tag{7}$$

A central moment is basically the same as the moment just described except that the values of x and y used in the formula are displaced by the mean values

$$CM_{jk} = \int_{-\infty}^{\infty} (x - X_M)^j (y - Y_m)^k f(x,y) dxdy \tag{8}$$

The angle between the principal axes and x axes is :

$$\alpha = \frac{1}{2} acr\tan\left(\frac{2CM_{11}}{CM_{20} - CM_{02}}\right) \tag{9}$$

Hence, the mass center of the counter is detected by (7) and is regarded as the initial rough location of the Xpoint. Then, the fine location of the Xpoint is determined by the Harris algorithm within a local region for corner detection. Consequently, the principal axes is extracted by (9). In fact, two perpendicular axes can be extracted, long axis and short axis. The long axis is regarded as the principal axis. Then directions of the principal axis and the epiploar line are compared to determine the symbol. If difference between the principal axis and the epiploar line is lower than an experimentally predefined threshold, then this primitive is determined. The image processing for the pattern with 5×5 primitives as shown in figure 6.

Once each primitive along the epipolar line is determined, the codeword of this primitive depends on its value and both left and right neighbor values. For example, if one primitive value is 2 and its left and right neighbor values are 1 and 3, then its codeword can be calculated as $1 \times 4^2 + 2 \times 4^1 + 3 \times 4^0 = 27$.

When each codeword of the primitive on the epipolar line of the camera image is obtained, the corresponding pixel matching will be performed. The leftmost primitive on the camera image plane is selected as the matching window to find the corresponding primitive on the projector image plane. Then the matching windows both on the camera and projector image plane are shifted to the next primitive. The procedure will be performed by a recursive search algorithm until all corresponding primitives are found out. A diagram of recursive search algorithm is shown as figure 7.

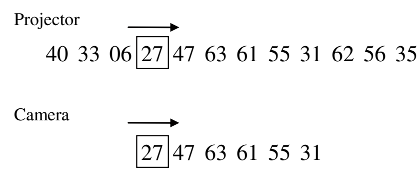


Fig. 7. The corresponding primitives matching

The corresponding pixels in the projector and the camera satisfy the epipolar constraint (1). Whereas, the detected corresponding pixels might not exactly satisfy (1) due to the uncertainty of image processing. To solve such a problem, the modified pixels satisfying (1) are calculated through minimizing the sum of square distance:

$$E = \left\|x_c - x_c'\right\|^2 + \left\|x_p - x_p'\right\|^2 \tag{10}$$

where x_c', x_p' are the optimal locations in the camera and projector image plane. More details can be referred to [16].

III. CALIBRATION

The accurate reconstruction of the 3D shape requires the proper calibration of each component used in the structured light system. In our system, a camera is denoted using a pinhole model due to the slight distortion of the lens. Thus, the coordinate transformation from the world frame to the image frame can be expressed as:

$$sI = AFX \tag{11}$$

where $I = [r, c, 1]^T$ is the homogeneous coordinate of the pixel in the image frame; $X = [x, y, z, 1]^T$ is the homogeneous coordinate of the corresponding point in the world frame; s is a scale factor; F is the extrinsic parameters representing the rotation and translation between the camera frame and world frame; A is the camera intrinsic parameters matrix and can be written as: $A = \begin{bmatrix} \alpha & \gamma & r_0 \\ 0 & \beta & c_0 \\ 0 & 0 & 1 \end{bmatrix}$. where r_0 and c_0 are the coordinate of the principle point; α and β are focal length along the r and c axes of the image plane; γ is the parameter representing the skew of the two image axes.

The camera can be calibrated using a chessboard placed in different positions and orientations described as Zhang [17]. To ensure that the camera can recognize the fringe patterns projected in the area of checkboard during the projector calibration, the flat checkerboard is a red/blue checkerboard with size $15 \times 15mm$ rather than black/white one.

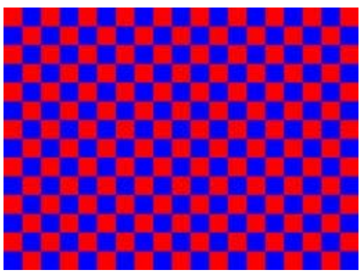


Fig. 8. Checkerboard for calibration

Similarly, a projector can also be considered as an inverse camera since it shoots images instead of capturing them [18]. Thus, once the coordinates of point in the world frame and that in the projector plane are known, the calibration can be achieved using the same strategy for camera calibration. Therefore, a series of vertical and horizontal GCLS fringe patterns are projected onto the checkerboard and the phase distribution of the Xpoint in the projector image plane can be obtained through the images captured by camera. Then the projector can be calibrated as camera calibration.

Fig. 9. The vertical and horizontal patterns

The next step is to calibrate the entire structured light inspection system. For this purpose, a uniform world frame for the camera and projector is established base on one calibration image with xy axes on the plane and z axis perpendicular to the plane as shown in figure 10. In addition, the coordinates of the corresponding pixels on the camera and projector image planes are also used to calibrate the fundamental matrix and rectify the epiploar line.

IV. EXPERIMENTS AND RESULTS

The experiment setup is composed of a projector (PLUS V339), a monochromatic camera (SONY XCD X 710) with the resolution 768×1024pixels, equipped with a convex lens (FUJINON TV LENS) and a commercial computer as shown in figure 11.

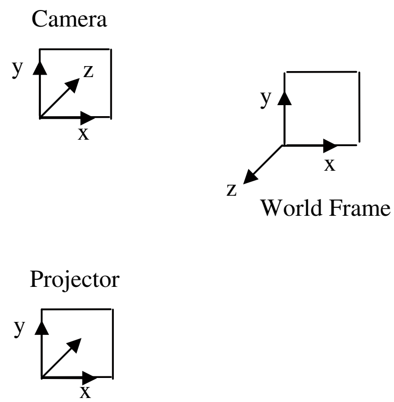


Fig. 10. World coordinate system

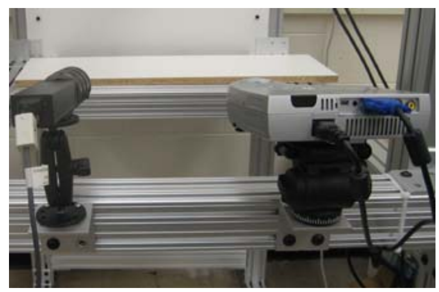
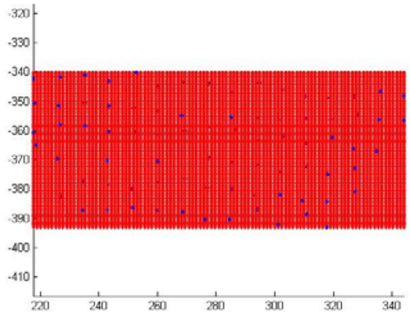


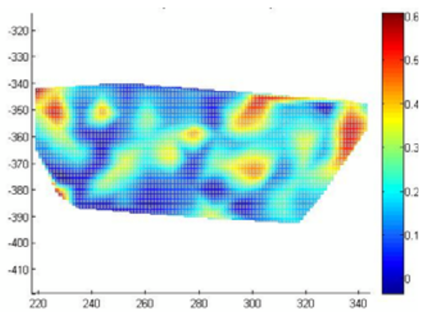
Fig. 11. Experiment setup

The first experiment is to evaluate the inspection system accuracy. The 3D shape inspected by the proposed structured light pattern and the real 3D coordinate of the part is compared. The one shot pattern is projected onto a flat plane. The 3D coordinate of the plane is obtained from the single distorted pattern observed by the camera. Then the set of 3D point is used to fit an ideal plane using linear square method; the distance between the measured points and the plane is regarded as the inspection system error which can be expressed as a color-coded error map as shown in figure 12. The measured point cloud is used to validate the measurement accuracy. The average values of the error deviate 0.23mm. The results are significantly influenced by the system calibration and the Xpoint detection.

The second experiment is conducted to validate the efficiency of the proposed pattern and the detection and decoding algorithm described for the complicated part inspection, a pillar. The pattern is projected on a pillar and detection and decoding algorithm are utilized to construct the 3D shape of the pillar. Figure 13(a) and (b) show the point cloud of the measured pillar and corresponding error map.



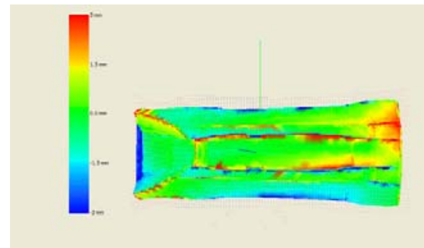
(a)



(b)

Fig. 12. The flat plane measurement: (a) point cloud; (b) error map

(a)



(b)

Fig. 13. Result for a measured pillar: (a) inspected pillar; (b) error map

V. CONCLUSION

This paper proposed an approach for real time 3D shape measurement based on structured light. To solve the correspondence problem between the camera and the projector, a one shot structured light pattern is presented. The concept of one shot projection of pseudo-random sequence along the epipolar line is introduced to accelerate the pattern identification. A robust primitive for the pattern based on the Xpoint is developed since the Xpoint can provide a highly accurate position for the primitive. Besides, the orientation of the primitive is used to encode the pattern. Moreover, the structured light pattern is designed using monochromatic light which will reduce the affection of the ambience light and the part reflection. However, the limitation for this inspection system is the low density of the measured point cloud. The reason is that the primitive needs several pixels to form one code. Another drawback of this method is that both projector and camera images need to be rectified, which reduces the valid inspection range and further reduces the density of point clouds. The high density online pattern will be studied for complicated shape inspection in the future.

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