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Visual Measurement of a 3-D Plane Pose by a Cylindrical Structured Light

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ABSTRACT – A simple and reliable method for measuring the depth and orientation of a local area of an object surface is proposed. The prototype system consists of a camera, a He–Ne laser, and a beam expander ~~to make,~~ producing cylindrical ~~structured~~ beam. The cylindrical beam ~~structured light~~ is actively projected onto the surface of the object, and the distortion of the light pattern is fitted into ellipse. Without computation of 3–D range data, the depth and orientation of object surface ~~are~~ directly determined by ellipse parameters. In ~~the~~ a noisy enviroment, this method reliably offers 3–D information even ~~though~~ the light pattern is partially missing. The measurement error and its source are discussed and experimental results are shown. Due to ~~the~~ simplicity and reliability, this method may be implemented ~~to~~ for various robotic tasks requiring 3–D information on the ~~between~~ of the relationship robot's end effector ~~and~~ To its task enviroment.

I. INTRODUCTION

Recently, in the robotic field technique for acquiring 3–D information using a visual sensor have been pursued, with increasing demands for advanced and sophisticated tasks that robot has coped with. Most robotic applications, such as deburring task in machining, seam tracking task in welding, and part mating in assembly require accurate determination of the position and orientation of a task surface relative to the robot's end effector. In these applications, a 3–D sensor system is usually attached at the robot end effector measuring a 3–D local pose of a task surface with high speed and high reliability, and robot's end effector tracks a task surface correcting its own pose relative to a task surface.

Many 3–D visual sensing methods have been developed in the past. An overview of the research efforts in this subject area is given in the references[1,2]. The structured light method is often used for quick and reliable acquisition of object's 3–D information and some works have been applied to robot applications[3–13]. The use of the structured light method gives distinct advantages in that the intensity features obtained from the images are well defined and their geometric relationships are simple, depending on the property of the projected light pattern. The light pattern has many kind of shapes such as point, slit, rectangular, and circle for each different purposes. To obtain 3–D information of object, a point light scanner must sweep around object. It takes much time because only one point is measured at a time. If a slit light is used, many points along a line can be measured at a time, and, hence, is widely used[2–4]. Even if the slit light is used, the projected light also sweeps the scene to get the range data about whole surface of object, and the data acquisition, threfore, takes much time. The regular light pattern consisting of a set of points does no need to sweep the scene. It has a regular shape such as rectangular or circle and is distorted by the surface pose of object. This distorted light pattern is the advantage of this method since the 3–D information is contained in the image frame of object' surface. Therefore, the 3–D information of objects surface can be obtained by only analyzing the distorted light pattern. Although this regular light pattern can not provide full information of an object, it can quickly extract the surface information[10–13].

Sugihara [10] proposed a method of projecting regular light patterns such as circles and squares onto object surface to determine the position and orientation of the object surface. He argued that if these patterns contain both vertical and horizontal vectors and can be identified in image, the surface normal can be determined uniquely by processing the distorted regular pattern. Asada et. al[13] proposed a thick stripes pattern using grid projection to obtain a surface orientation map from a single image. The thick stripe includes vertical and horizontal vector and its thickness implies a surface orientation. In the methods using such regular light pattern, however, orthogonal projection is assumed to be an camera model. This assumption is available when the distance between the camera and object is more than 20 times the object size[13]. It is not available for many applications performed by robot end effector since, in this case, the distance between a camera and an object is short. The distortion of regular patterns comes out as the change of pattern size such as thickness, length and width, which is eventually the change of pixel position in image frame. The position of pixel is sensitive to environment noise and is not consistent during image processing. If environment is noisy or a light pattern is partially missed due to occlusion, the accuracy of measurement can not be guaranteed. To overcome noisy enviroment for the above methods, a closed form solution of identifying the surface geometry must be introduced.

More accurate and fast method was proposed for measuring the orientation and position of plane surface. Wei and Gini [11] proposed a structured light method using a circular shaped pattern to identify planar surface. This makes use of the following idea: When a light pattern of circular shape is projected onto an inclined planar surface an elliptic pattern is formed. In this case the end points of ellipse's major axis are interpreted as the orientation and position of the surface. However, the position of the end points in image may not clearly appear or even is unstable in noisy environment. Gordon[12] proposed a light stripe vision method to accurately measure the location of polyhedral objects by utilizing a single frame of video camera output. The solvable geometric condition of this method is given only when the light plane intersects three planes of the polyhedral object. This condition is very restrictive to use this method generally.

This paper presents a simple and reliable method for measuring a local plane pose by a cylindrical structured light which has a circular cross sectioned shape containing the vertical and horizontal vector. When projecting the cylindrical structured light on a plane, different elliptical patterns are obtained, depending on the plane poses[14]. Ellipse light pattern is taken perspectively by a camera and the characteristic of the pattern uniquely determines the

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plane pose. Utilizing such properties, this paper mathematically derives an ellipse equation from geometric relationships between an ellipse pattern and a plane pose. The derived ellipse parameters simultaneously determine a position and orientation of a plane, which are estimated by fitting ellipse pattern on image to the ellipse equation. The least square approximation for estimating ellipse parameters are robust against environment noise, even though partial ellipse contour is missed. Therefore, this method is fast in image processing and reliable even with noisy environment. In addition, the proposed method takes the perspective projection as a camera model, so that this method is available for measuring an object near a camera. We show the performance of the proposed method through the experiment and computation results.

II. THE SENSING PRINCIPLE

A. Sensing coordinate system

As shown in Fig.1, three coordinate frames are chosen to effectively describe the ellipse pattern projected on a target plane. They are the projector coordinate frame, the image coordinate frame and the object coordinate frame. The relationship between these coordinate frames may be effectively represented by a *homogeneous transformation matrix*, a 4x4 matrix containing orientation and position information. The subsequent analysis adopts the use of this homogeneous transformation to represent the configurations of three coordinate frames. As shown in the figure, the image coordinate frame has the origin on the image plane of a camera. The ${}^{I}Z$ axis is aligned along the principal ray of the camera, and the image plane (u,v) coincides with the plane $({}^{I}X, {}^{I}Y)$.

Referring to the figure, the projector coordinate frame {L} is defined as follows : Rotate {I} about ${}^{I}Z$ by angle ϕ, and subsequently translate along ${}^{I}X$ by d. Here, ϕ and d are called the view angle and the base distance, respectively. The projector coordinate frame {L} has the origin on the principal ray of the structured light beam, and the projector is positioned along the ${}^{L}Z$ axis of the projector coordinate frame {L}. The configuration of the projector coordinate frame {L} can be described by the transformation matrix relative to the image coordinate frame {I} as follows:

$$ {}^{I}_{L}T = \left[\begin{array}{ccc|c} \multicolumn{3}{c|}{\text{ROT}({}^{I}Y,\phi)} & \text{TRANS}({}^{I}X,d) \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \qquad (2.1) $$

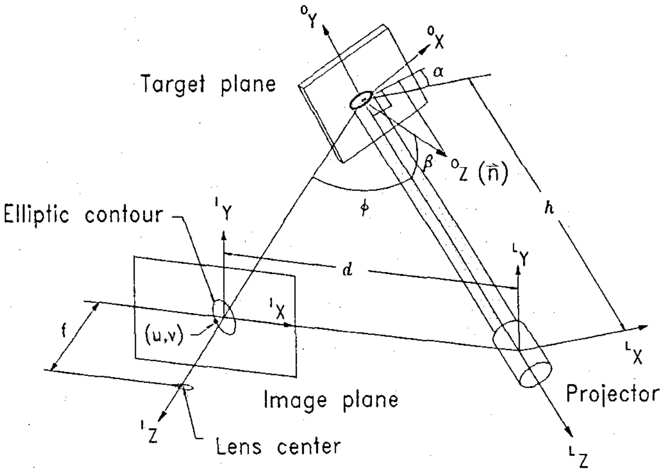


Figure 1. The sensing coordinates system

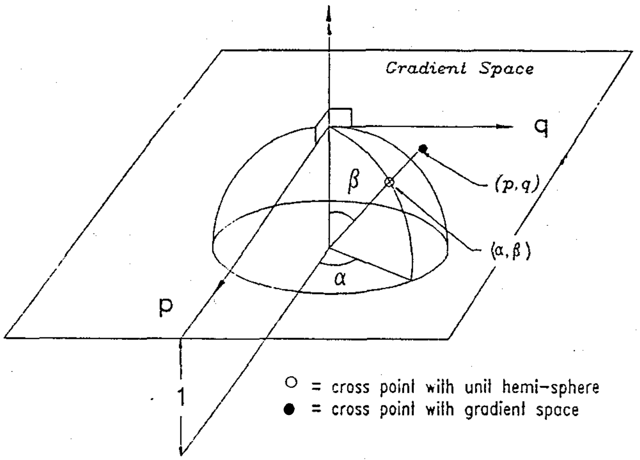


Figure 2. Gradient space $(p,\ q)$ and angle $(\alpha,\ \beta)$

where ${}^{I}_{L}T$ describes the frame {L} with respect to the frame {I}.

The object coordinate frame {O} is located on a target plane and its configuration is dependant on the pose of a target plane. The object coordinate frame {O} can also be defined by performing a series of transformations on the projector coordinate frame {L}. First rotate {L} about ${}^{L}Z$ by angle α, then rotate about ${}^{L}Y$ by angle β,and then translate along ${}^{L}Z$ by h. Therefore, the relationship between the object coordinate frame {O} and the projector coordinate frame {L} can be represented by

$$ {}^{L}_{0}T = \left[\begin{array}{ccc|c} \multicolumn{3}{c|}{\text{ROT}({}^{L}Z,\alpha)\ \text{ROT}({}^{L}Y,\beta)} & \text{TRANS}({}^{L}Z,h) \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \qquad (2.2) $$

where ${}^{L}_{0}T$ describes the configuration of frame {O} with respect to frame {L}. In this case, the normal of the target plane may be represented as

$$ \begin{aligned} {}^{0}z = \vec{n} &= p\,\vec{i} + q\,\vec{j} + \vec{k} \qquad (2.3) \\ &= (\cos\alpha\ \tan\beta)\ \vec{i} + (\sin\alpha\ \tan\beta)\ \vec{j} + \vec{k} \end{aligned} $$

where p and q are the non-dimensional parameter of *gradient space*[16]. We can use a sphere to represent a surface normal vector with angles $(\alpha,\ \beta)$. But, there are some ambiguities. If β is zero, the surface normal is the same for any α. Fig.2 shows the relation between *gradient space* (p,q) and the orientation angles $(\alpha,\ \beta)$. Similarly, the transformation from {O} to {I} is obtained by

$$ {}^{I}_{0}T = {}^{I}_{L}T\ {}^{L}_{0}T \qquad (2.4) $$

Perspective transformation is used to approximate the manner in which an image is formed in viewing a three dimensional world. We simply use the pin hole model for perspective transformation as

$$ M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & {}^{1}/f & 1 \end{bmatrix} \qquad (2.5) $$

where M is the perspective transformation matrix and f is the focal length of a camera[15]. Then, the relationship between an arbitrary point $({}^{0}x, {}^{0}y, {}^{0}z)$ defined in the object coordinate frame {O} and its corresponding image point (u, v) is expressed by

$$\begin{bmatrix} u \\ v \\ z \\ k \end{bmatrix} = M \begin{bmatrix} {}^{I}x \\ {}^{I}y \\ {}^{I}z \\ 1 \end{bmatrix} = M\, {}^{I}_{0}T \begin{bmatrix} {}^{0}x \\ {}^{0}y \\ {}^{0}z \\ 1 \end{bmatrix} \qquad (2.6)$$

where $\boldsymbol{k}$ is the scale factor.

B. The ellipse equation in the image plane

When the cylindrical structured light is projected on a target plane located at distance h from the origin of the {L}, having nomal vector $\vec{n} = (p, q, 1)$ of equation (2.3), a bright elliptic shape is formed on the surface of the plane. The ellipse equation on this plane surface is described with respect to the object coordinate frame {O} as :

$$\frac{1}{\sqrt{p^2+q^2+1}}\, {}^{o}x^2 + {}^{o}y^2 = r^2\,, \qquad {}^{o}z = 0 \qquad (2.7)$$

where r is the radius of the cross section of the cylindrical light beam.

Since the light pattern generated by the structured light beam lies on the target plane, the z component value of the pattern with respect to the object coordinate frame is zero. Thus, using the equation (2.5), a point on the light pattern can be converted to a corresponding point in the image coordinate frame. Suppose that a point on the object plane has the corresponding image point (u,v,0). Then, the point in the object coordinate frame, $({}^{o}x, {}^{o}y, 0)$ can be obtained by

$$\begin{aligned} {}^{0}x &= (u\, b \cos\alpha + v\, b \sin\alpha \cos\phi - h \cos\alpha \sin\phi)/a \\ {}^{0}y &= \{-u\, b \sin\alpha \cos\beta + v\, b\, (\cos\phi \cos\alpha \cos\beta - \sin\phi \sin\beta) \\ &\qquad + h \sin\alpha \cos\beta \sin\phi\}/a \end{aligned} \qquad (2.8)$$

where the parameters a and b are defined by

$$\begin{aligned} a &= (\cos\phi \cos\alpha \cos\beta - \sin\phi \sin\beta) \cos\alpha + \sin^2\alpha \cos\phi \cos\beta \\ b &= (\, d - h \cos\phi + f\,)/f\,. \end{aligned}$$

From the equations (2.7) and (2.8), the ellipse equation in the image coordinate frame can be described by

$$u^2 + w_1 v^2 + w_2\, u\, v + w_3\, u + w_4\, v + w_5 = 0 \qquad (2.9)$$

where
$$\begin{aligned} w_1 &= \cos^2\phi + (p^2+q^2) \sin^2\phi - 2\, p \sin\phi \cos\phi \\ w_2 &= 2\, q \sin\phi \\ w_3 &= -\,2\,\left(\frac{d - h \sin\phi}{fh \cos\phi + 1}\right) \\ w_4 &= 2\, q \sin\phi\,\left(\frac{d - h \sin\phi}{fh \cos\phi + 1}\right) \\ w_5 &= \frac{r^2(\cos\phi - p \sin\phi)^2 - (d - h \sin\phi)^2}{(fh \cos\phi + 1)^2} \end{aligned}$$

As can be seen from the above, the ellipse parameters w_i (i=1, 2, 3, 4, 5) are the functions of the parameters p, q, ϕ, h, d, f and r. Among these, the ϕ, d, f and r may be fixed by some known constant values. Therefore, as shown in equation (2.9), the target plane produces various ellipse contours on the image according to its own pose(p, q, h).

The w_1 and w_2 represent the shape of ellipse contour in 2-D image which is the ratio of two axes and the slant angle. These are functions of the orientation of a target plane, and independent of a target plane's position. The w_3 and w_4 are terms fromed due to the deviation of an ellipse center from center point of 2-D image. The w_3 is a function of a target plane's position and is independent of a target plane's orientation. The w_4 is a function of both position and orientation of a target plane. The w_5 is related with the size of ellipse contour and is a function of both position and orientation of a target plane.

Among five ellipse parameters, the w_1 and w_2 can determine a target plane's orientation, and the w_3 can determine a target plane's position. The w_4 and w_5 are redundant information of a target plane pose.

C. The determination of plane pose

The least square approximation for estimating the ellipse parameters in eq.(2.9) is used. Let the error of fitting an ellipse contour to eq.(2.9) as follows

$$e_i = u_i^2 + w_1 v_i^2 + w_2\, u_i v_i + w_3\, u_i + w_4\, v_i + w_5 \qquad (2.10)$$

where u_i and v_i are the coordinate values of each point on ellipse contour. The estimator to minimize the sum of the square of this error is

$$W = (H^t\, H)^{-1}\, H \qquad (2.11)$$

where
$$\begin{aligned} W &= (\hat{w}_1, \hat{w}_2, \hat{w}_3, \hat{w}_4, \hat{w}_5)^t \\ H &= (\Sigma v_i^2, \Sigma u_i v_i, \Sigma u_i, \Sigma v_i, \Sigma 1) \\ V &= (-\Sigma u_i^2 v_i^2, -\Sigma u_i^3 v_i, -\Sigma u_i^3, -\Sigma u_i^2 v_i, -\Sigma u_i^2) \end{aligned}$$

The estimated parameters $\hat{w}_1$ and $\hat{w}_2$ determines directly orientation of the target plane as the following,

$$\begin{aligned} p &= \left[\frac{1}{\tan\phi \sin\phi}\sqrt{\hat{w}_1 - \hat{w}_2^2/4}\,\right] \\ q &= \frac{\hat{w}_2}{2\sin\phi} \end{aligned} \qquad (2.12)$$

The parameter $\hat{w}_3$ directly determines the position of the target plane as

$$h = \frac{\hat{w}_3\,(d+f)}{\hat{w}_3 \cos\phi - 2f\sin\phi} \qquad (2.13)$$

IV. EXPERIMENTS

Series experiments are performed to verify the proposed method. The first part deals with the case of occluded light patterns, and the second part the error characteristics.

A. System setup

The experiments are conducted using a prototype system schematically shown in Fig. 3. The apparatus includes a beam expander which makes a point light source a cylindrical beam, a 7mW He-Ne laser beam source whose position is fixed relative to a C.C.D. camera, and a SCARA type robot used with a tilting device to allow the target plane to have 5 degrees of freedom motion. The projector, camera and robot are mounted on a precision cast iron bed whose surface roughness is 0.002mm. Also, a commercial image processing system is installed to digitize the ellipse image and an IBM PC/AT is used to implement the image processing algorithm.

In the experiment, the following features are remained as followings are fixed : (1) the base distance d between the origins of the projector coordinate frame and the image coordinate frame at 373mm, (2) the focal length f of the C.C.D. camera at 16mm, (3) the radius r of the cylindrical structured beam at 21mm, (4) the view angle ϕ of the

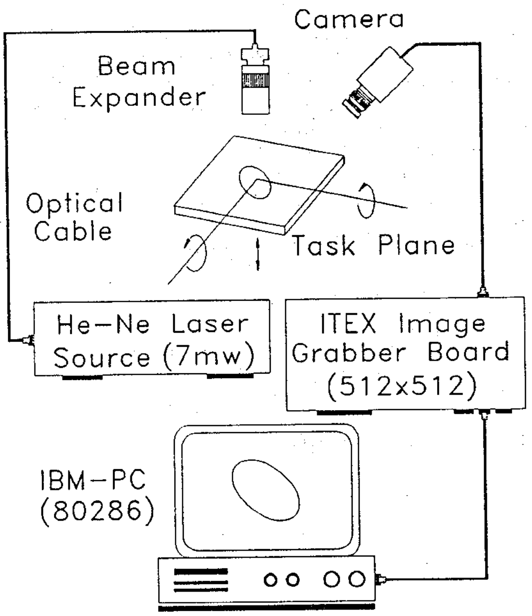


Figure 3. The Experimental Setup

camera relative to the projector at 45o, and (5) scale factor k in eq.(2.2) is 68.8.

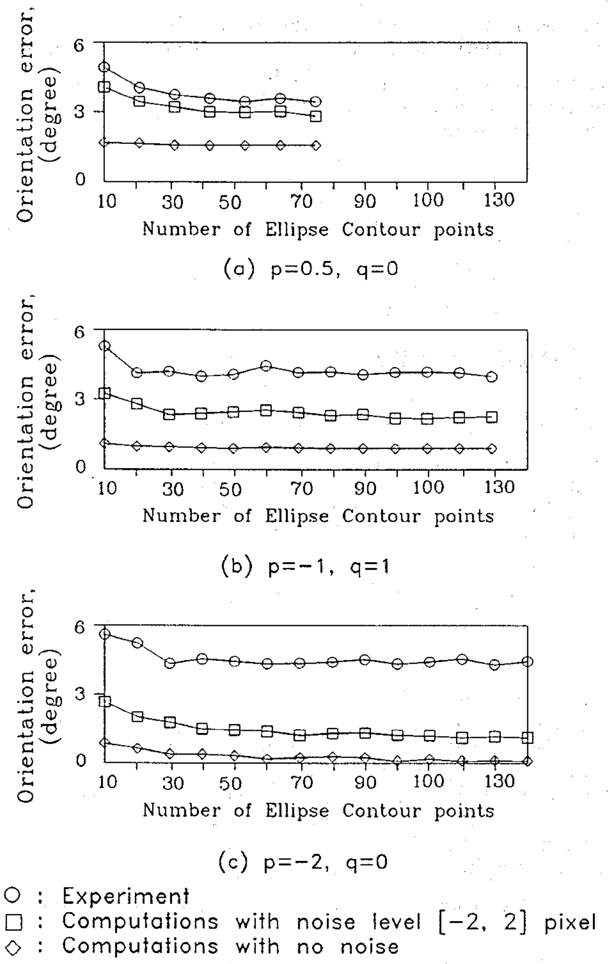
B. Image processing

Since the light intensity of the ellipse pattern is very high, a binary image including clearly defined elliptical pattern can easily be created by a single valued thresholding. Then, by processing the binary image using spatial domain technique, the ellipse contour can be extracted. To remove irregular noises on the image the shrinking and expanding algorithm is used. The coordinate values of the ellipse contour are continuously determined as a 3x3 window template with 8–connectivity tracks around the boundary of elliptical pattern. Having obtained the coordinate values of elliptical contour, the ellipse parameters are estimated using least square method.

C. Results and Discussion

Fig.4 shows measurement error as the number of ellipse contour points for least square estimation. The number indicates the degree of occlusion in the ellipse contour. The maximum number is the case that the full ellipse contour is used for calculation. Experimental results are compared with the computation results. All results are conducted for three diffrent orientations of a target plane and three different noise level. In the computer simulation, we generate ellipse contour points (u_i, v_i) of a target plane by eq.(2.9), and add random noise to them. The maximum point numbers of each ellipse contours for three orientations are different because the sizes of each ellipses are different. All results are average of 20 trials and its variances are small enough to ignore. In this figure, the errors remain in the same level after 30 number of data which is about one–third of full ellipse contour. Conclusively, although an ellipse contour is occluded and just some pieces of ellipse contour exists, our method can offer accurate measurements. This is a natural result because the ellipse equation, eq.(2.9), is a closed form solution for measuring a target plane pose.

Fig.5 shows the computation results of error characteristics. To examine the noise effect, for the same random noise we calculate measurement errors by varying p from –2 to 1 with 0.5 interval, and q from –3 to 3 with 0.5 interval. The measurement errors are not uniformly distributed because the sensitivities of estimated ellipse parameters to the noise are different according to the



(a) p=0.5, q=0

(b) p=−1, q=1

(c) p=−2, q=0

Figure 4. The Measurement Errors as ellipse contour points

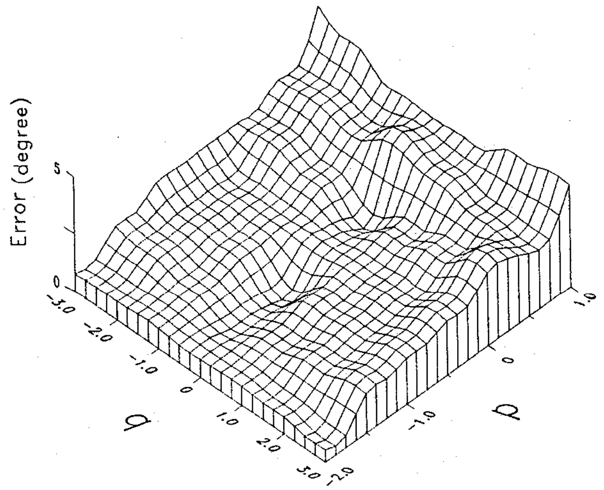
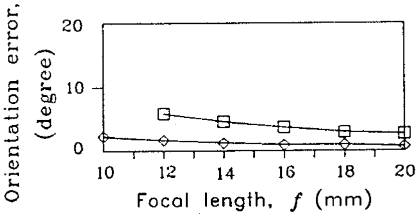
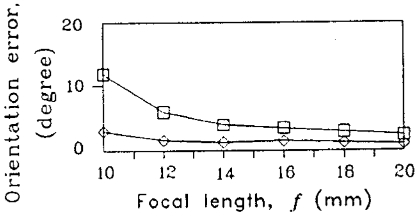


Figure 5. The computation error due to random noise (noise = [–2, 2] pixel, ϕ = 45°, f = 16mm, d = 520cm, r = 12cm)

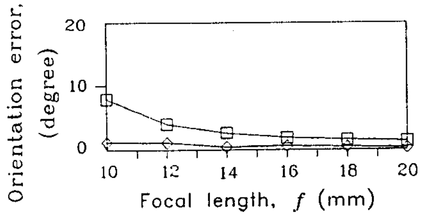
orientation of a target plane. It is difficult to show analytically the sensitivities because eq.(2.11) is nonlinear least square estimator. The general trend is that the errors increase as p and q are close to 1 and 0, respectively. This is why the sensitivities are very high around $p=1$ and $q=0$. There are many sources of errors, such as surface condition of a target plane, image quantization error and bad environments light condition, etc. The overall effect of all sources comes into the uncertainty of ellipse contour on the image. If this uncertainty is uniformly distributed on the image, it does not affect adversely on our method because least square method is used for estimating the ellipse parameres. Fig.6 shows the experimental results of error characteristics. The error trend is somehow different with the computational results. In the computation, as p increases, the error tends to decrease. But, at $p>1.5$ the errors of the experiment are larger than those of the computation. This is why the target plane used in the experiment does not have perfect Lambertian surface. If the target plane inclines too much ($p>1.5$), so its normal direction is wide from the camera direction, the light intensity of ellipse contour received by the camera decreases. The ellipse contours having low intensity are easily contaminated by noise.



(a) p=0.5, q=0



(b) p=−1, q=1



(c) p=−2, q=0

□ = Computation with noise level [−2, 2]
◇ = Computation with no noise

Figure 7. The measurement error as focal length of the camera

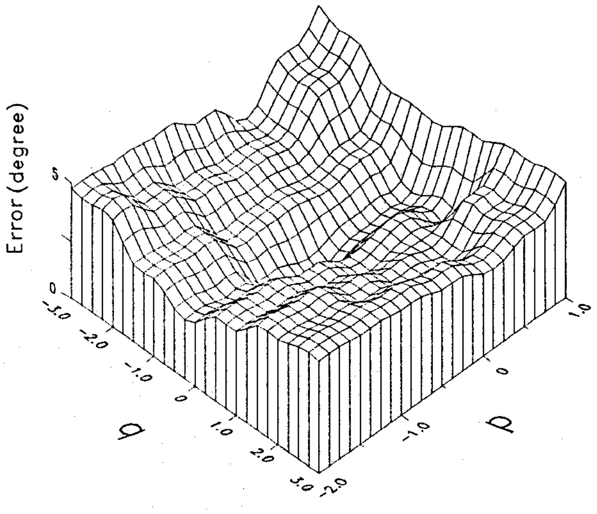


Figure 6. The measurement error in the experiment (ϕ = 45°, f = 16mm, d= 520cm, r = 12cm)

These errors can be overcome by enlarging the image of ellipse, provided that we change the focal length of the camera and the radius of cylindrical beam. Fig.7 shows the computation results as the focal length of the camera. As the focal length increases, the image of ellipse enlarges and the errors reduce significantly.

In the above experiments, we do not deal with the case of varying the position of a target plane. Although the position of a target plane is different, the experimental results are similar. Because, as the position of ellipse varies, the shape change of ellipse is negligible and the center position of ellipses on the image just varies. Table.1 is the experimental results for varying the position of a target plane. The errors remain within ±0.4mm which is a corresponding distance to one pixel at h=520mm. The position measurement of a target plane is very accurate.

Table 1. Comparison of the measurement and actual distance of target plane (p=0, q=0)

Distance = Distance between the orgins of
the object and projector coordinate
Error = (Actual) − (Measured)

Actual values	Measured values	Errors
Distances (mm)	Distances (mm)	(mm)
470.00	470.60	−0.60
480.00	480.50	−0.50
490.00	490.00	0.00
500.00	500.00	0.00
510.00	509.92	0.08
520.00	519.64	0.36
530.00	529.42	0.58
540.00	539.19	0.81
550.00	548.95	1.05
560.00	558.78	1.22
570.00	568.46	1.54

V. CONCLUSION

A simple method for measuring the position and orientation of a target plane in 3-D is developed by utilizing some suitably defined geometric properties of cylindrical structured light. The projection of cylindrical structured light on a target plane always results in an elliptic pattern whose shape is determined by plane pose and system's geometric relation. Ellipse equation is derived from the geometric relationship between the target plane and the sensor system and its parameters directly determine target plane pose. The proposed method gives some advantages; i) It can determine simultaneously the position and orientation of a target plane requiring only a single image frame. Therefore, the computational burden involved with the determination of plane pose may be greatly relived. ii) System set up is simple. The cylindrical beam is easily implemented by beam expander and a point light source. iii) This method is robust against noisy environment. Althogh ellipse pattern is not fully detected, this method can offer reliably information. Experimental results verified the performance of the presented method.

The presented method may directly be applied to a certain class of robotic tasks which requires the robot's end effector to maintain a predefined pose relative to the task surface. Further, since a polyhedron consists of several planes and edges, different plane poses result in different ellipse contours and thus the proposed method may easily be extended to the 3-D identification of polyhedral objects.

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