DEVELOPMENT OF A LASER SENSOR FOR IN-PROCESS GUIDANCE OF AN INDUSTRIAL ROBOT

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A pilot-type laser sensor for non-contacting distance measurement has been developed, which was aimed at application to in-process guidance of an industrial robot. A laser beam is emitted through a convex lens to an object and the reflected light is collected and focused by the lens. Diameter of its unfocused image is measured using one dimensional CCD-array, from which the distance is determined. Because the way of the beam emission and that of reflected light to the lens are the same, scanning of the beam to follow a path for robot guidance is easy and some geometric constraints, which may arise for a sensor using triangular principle, are removed. Geometric analyses for scanning the beam with a mirror are presented to determine the distance and position of an object point. A simple tracking control theory for the beam to follow a path and give informations about its position to a robot controller has been suggested and analyzed.

Key Words: Non-Focused Image, Non-Contact Distance Measurement, Triangular Principle, In-Process Tracking Control, Describing Function Method

1. INTRODUCTION

It is true that robots which can only repeat processes which are firmly programmed in advance need some careful preparations such as well defined pre-process, positioning and orientation of workpieces. This procurement cost and efforts may offset the advantages of their applications. The equipping of robots with sensors is one of the ways of increasing their flexibility and adaptability, and thus extends their applications(Plander, 1987).

In this paper development of a laser sensor aiming at in-process guidance of an industrial robot has been studied. The sensor measures the true positions(or lines) on which the robot must work(e.g. grooves, edges or etc.) and informs the robot of them.

A pilot-type sensor system is constructed which is based on a simple object-image point relation in a convex lens(Rosler, 1986). The relation between the distances from the lens to the points is the basic theory of the measurement. The principle is considered here and an approach for optimization of the sensor is suggested. Some measurement results are presented and discussed.

Essentially the sensor is a non-contacting distance measurement one. Scanning a laser beam to an object(work-piece) it measures the distance of an object point at which the beam is reflected. Monitoring variations of the distance, that implies monitoring the shape of workpiece, it deduces informations about the true working positions.

The beam is scanned with a mirror which is rotated by a motor controlled by a μ-processor. Some geometric relations for the scanning with a mirror have been analyzed.

A possible approach for tracking control of the sensor to follow a working line in process is suggested and studied.

2. PRINCIPLE

Principle of the sensor is based on the relation between the object and image points for a convex lens as shown in Fig. 1. The relation is written as

$$\frac{1}{g}+\frac{1}{l}=\frac{1}{f} \tag{1}$$

where g and l are distances between the lens to the object and image point respectively, and f the focal length of the lens.

When we set a linear CCD-array sensor at a distance e from the lens, we get an equation

$$W=D\frac{l-e}{l} \tag{2}$$

where W is the width of bright zone in the array, which is the diameter of an unfocused image, and D the diameter of the lens.

From the above Eqs.(1) and (2) the relation between W and g is given as

$$\begin{aligned} W&=D-\frac{eD(g-f)}{gf} \\ &=C_1+C_2\frac{1}{g} \end{aligned} \tag{3}$$

where $C_1=D-eD/f$ and $C_2=eD$, which are constants when the sensor system is built.

Using the above equation, we can measure the distance of the object point g by measuring the width W.

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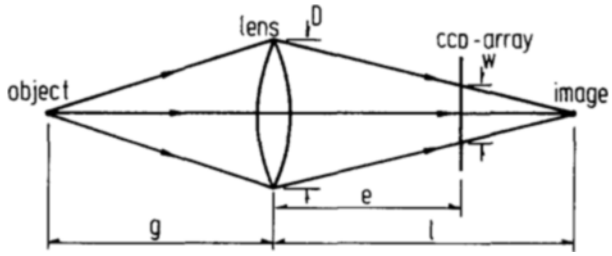


Fig. 1 Principle of measurement

When the sensor is constructed, all the parameters are costants except W and g. Then the following equation is given.

$$\frac{dW}{dg}=-\frac{eD}{g^2} \tag{4}$$

Considering that Eq. (4) denotes the sensitivity of the sensor, it is known that to get increased sensitivity a lens with short focal length and large diameter is preferred and the object point is to be placed near to the focal point and the CCD-array near to the image point. In other words it can be said that the CCD-array is to be placed as far as possible from the lens to get a larger value of e in Eq.(4) and the object point is to be placed near to the focal point of the lens to have a smaller g.

3. DEVELOPMENT OF THE SENSOR SYSTEM

3.1 Construction

Construction of the sensor system developed is shown schematically in Fig. 2. A laser beam is emitted and passes through a beam splitter, a convex lens then changes its direction on a plane mirror surface and then is reflected at a point on the object surface, which is an object point.

A part of randomly reflected light at the object point is collected by the lens and being focused. Before the focusing, the beam splitter changes the direction of light and a CCD-array is placed to measure diameter of the unfocused image. In front of the array a cylindrical lens is placed to increase the intensity of light on the array.

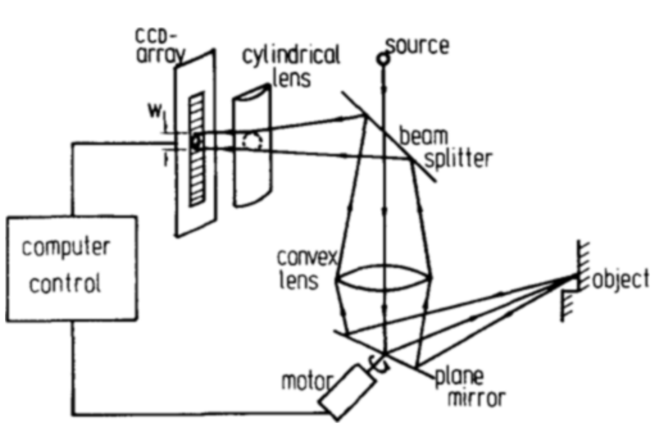


Fig. 2 Structure of the pilot-type sensor system

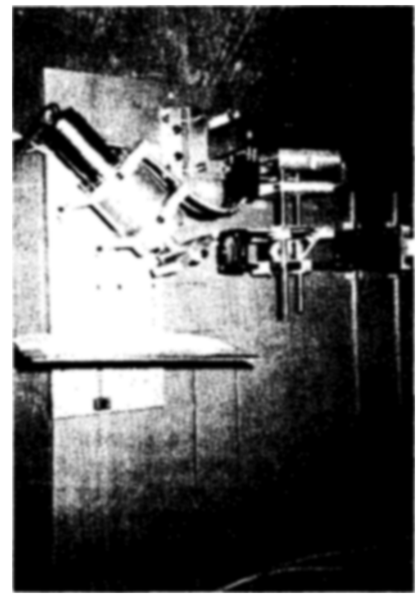


Fig. 3 Photograph of the sensor

The mirror is firmly fixed to a motor shaft. Scanning of the laser beam is done by rotating the mirror of which the normal vector is inclined to the rotating axis of mirror, which corresponds to the motor shaft. The motor is controlled by a computer to do some scanning mode.

A photograph of the pilot-type sensor is shown in Fig. 3.

3.2 Determination of Distance and Position of an Object Point

In Fig. 4 it is shown that an incident beam, denoted by an unit vector $\vec{p}$, is reflected at a point 0 on the mirror surface. An unit normal vector to the mirror surface at 0 is taken as $\vec{n}$. The reflected beam is represented by an unit vector $\vec{p'}$. It is clear that $\vec{p}$, $\vec{n}$ and $\vec{p'}$ are on a same plane and the angles of $-\vec{p}$, $\vec{n}$ and $\vec{n}$, $\vec{p'}$ are the same, from which the following equations are deduced.

$$-\vec{p}\cdot\vec{n}=\vec{n}\cdot\vec{p'} \tag{5}$$
$$-\vec{p}\times\vec{n}=\vec{n}\times\vec{p'} \tag{6}$$

A cartesian coordinates is used. The x-coordinate is taken to be the rotating axis of the mirror, which corresponds to the

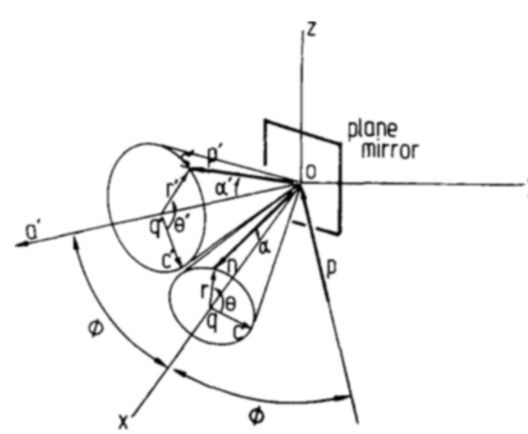


Fig. 4 Geometry of mirror reflection

motor shaft. y-coordinate is on x, $\vec{p}$ plane and z-coordinate is vertical to x, y coordinates. Now the vectors $\vec{p}$ and $\vec{n}$ are written as

$$\vec{p}=-\cos\phi\ \vec{i}-\sin\phi\ \vec{j} \tag{7}$$
$$\vec{n}=\cos\alpha\ \vec{i}+\sin\alpha\ \cos\theta\ \vec{j}+\sin\alpha\ \sin\theta\ \vec{k} \tag{8}$$

where $\vec{i}$, $\vec{j}$, and $\vec{k}$ are unit vectors of x, y, and z coordinates respectively, ϕ the angle between $\vec{p}$ and $\vec{i}$, and α the angle between $\vec{n}$ and $\vec{i}$.

When the mirror rotates, the vector $\vec{n}$ makes a real cone (i. e. cross-section normal to the cone axis is a circle) with the cone angle α and the cone axis corresponding to $\vec{i}$. Draw a vector, $\vec{r}$, connecting the center of base circle, q, and the vector $\vec{n}$ on the circle. As the mirror rotates, the vector $\vec{r}$ also rotates. The vector $\vec{c}$ is taken as a reference, which is $\vec{r}$ when it is on x-y plane. Now the rotation angle of the mirror is expressed by θ which is the angle between $\vec{r}$ and $\vec{c}$. As the mirror rotates the reflected beam $\vec{p'}$ also makes a cone with a cone angle α' and a center axis denoted by an unit vector $\vec{a'}$, which is expressed as

$$\vec{a'}=\cos\phi\ \vec{i}-\sin\phi\ \vec{j} \tag{9}$$

The cone angle α' is found from an equation

$$\cos\alpha'=\frac{\vec{p'}\cdot\vec{a'}}{|\vec{p'}|\cdot|\vec{a'}|} \tag{10}$$

from the Eqs. (5)~(8), $\vec{p'}$ is expressed with the defined parameters ϕ, α and θ as

$$\begin{aligned}\vec{p'}&=(\cos\phi\ \cos2\alpha+\sin\phi\ \cos\theta\ \sin2\alpha)\ \vec{i}\\&+(\cos\phi\ \sin2\alpha\ \cos\theta+\sin\phi\ \sin^2\alpha\ \cos2\theta-\sin\phi\ \cos^2\alpha)\ \vec{j}\\&+(\cos\phi\ \sin2\alpha\ \sin\theta+\sin\phi\ \sin^2\alpha\ \sin2\theta)\ \vec{k}\end{aligned} \tag{11}$$

Substitution of Eqs.(11) and (9) into (10) gives

$$\alpha'=\cos^{-1}(\cos2\alpha+2\ \sin^2\phi\ \sin^2\alpha\ \sin^2\theta) \tag{12}$$

The parameters ϕ and α are fixed for a built sensor system and θ is measured from the motor during rotation.

The cone made by the reflected beam $\vec{p'}$ may not be a real cone. At the end point s' of $\vec{p'}$, a line is drawn normal to the cone axis $\vec{a'}$ and the cross point is denoted by q'. A vector $\vec{r'}$ is defined by connecting q' and s', which corresponds the vector $\vec{r}$. At point q', an unit vector $\vec{c'}$ is drawn which is perpendicular to the axis $\vec{a'}$ and is on the x-y plane, which corresponds to the vector $\vec{c}$. An angle between $\vec{r'}$ and $\vec{c'}$ is denoted by θ', which is determined by

$$\cos\theta'=\frac{\vec{c'}\cdot\vec{r'}}{|\vec{c'}|\cdot|\vec{r'}|} \tag{13}$$

where

$$\vec{c'}=\sin\phi\ \vec{i}+\cos\phi\ \vec{j} \tag{14}$$
$$\vec{r'}=\vec{p'}-\cos\alpha'\cdot\vec{a'} \tag{15}$$

From the Eqs. (11)~(15), the equation below is obtained.

$$\theta'=\cos^{-1}\{\frac{1}{\sin\alpha'}(\sin2\alpha\cdot\cos\theta-\sin2\phi\cdot\sin^2\alpha\cdot\sin^2\theta\} \tag{16}$$

As shown in Fig. 5, a normal distance h of an object point is defined as that from 0 to Q', which is

$$h=g_2\cdot\cos\alpha' \tag{17}$$

where g_1 and g_2 are the distances from the point 0 to the lens and to the object point respectively, i.e., The position of an object point is defined by θ' in Eq. (16) and R' which is

$$R'=g_2\cdot\sin\alpha' \tag{18}$$

As a result the determination of position of an object point may be stated as follows. The width W and rotation angle of mirror θ are measured from the CCD-array and motor respectively. The Eq. (3) (or calibration table which relates W and g) gives the value of g. Since g_1 is a constant g_2 is obtained and α' is determined from Eq. (12). Thus the position of an object point is defined by θ' from Eq. (16), R' from (18) and h from (17).

3.3 Test Results

Using the pilot-type sensor, some measurement tests have been done. The parameters of the sensor system are shown in Fig. 6.

To investigate the effects of surface conditions of objects three different surfaces are taken. They are white paper, steel surface with gray painting and a machined steel surface without painting and with a certain rust.

A CCD-array with 2048 elements is used. Some typical

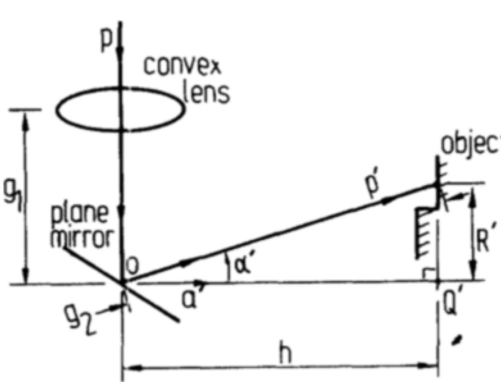


Fig. 5 Position and distance of an object point

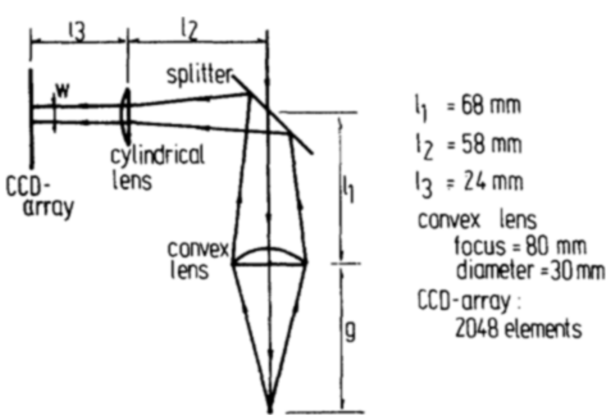
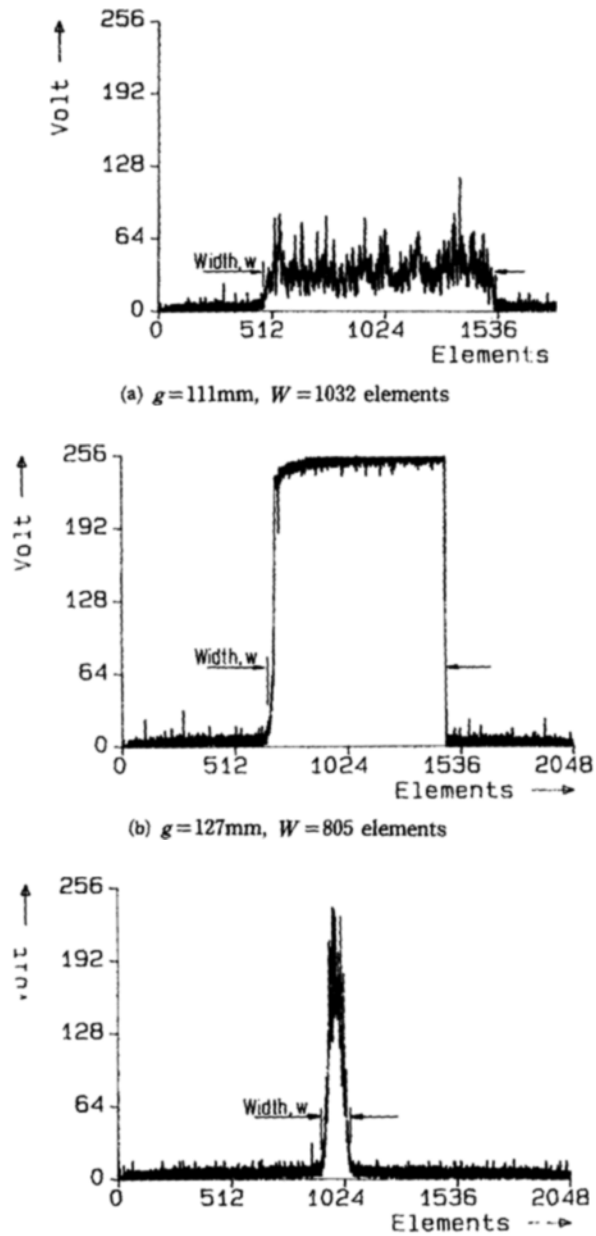


Fig. 6 Parameters of the sensor system for test



(a) $g=111$mm, $W=1032$ elements

(b) $g=127$mm, $W=805$ elements

(c) $g=171$mm, $W=136$ elements

Fig. 7 Some typical patterns of signal from CCD-array Object surface : white paper

signals from the array are shown in Fig. 7. In the figures the horizontal axis is the elements and vertical axis is the signals from the elements, which are related to the intensity of light on them. As shown in the figure, three typical patterns of signal were observed according to the the distance g. Fig. 7(a) shows a signal with wide width, W, and low light intensity, Fig. 7(b) with saturation and Fig. 7(c) with a peak at the center of the width.

The test results are drawn in Fig. 8. It is shown that the curves meet the W-g relation in Eq. (3). In the range of $g<$ 135mm the effects of surface conditions were larger than those in $g>$135mm. It is observed that the width, W, read from the CCD-array varies even at a constant distance. Some unstable signals were observed when $g=127$ and 131mm which may attribute to mal-function of the CCD-array.

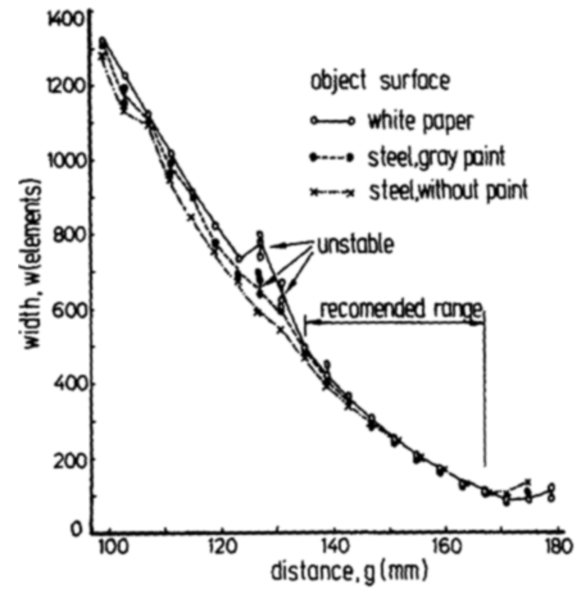


Fig. 8 Distance-width curves of the test results

In the range of $135<g<171$mm the effects of surface conditions were small and rather stable signals were obtained. This range of distance is recommended as a measuring range of the sensor. In this range the reapeatability(variation of measurement at a constant distance) was about 0.8mm, which may not be enough for some jobs. It is observed that the measurement is varied with the surface conditions and the amount was similar to the reapeatability.

The repeatability and dependency on the surface conditions may attribute to the CCD-array. Since the signal from the array element depends on the intensity of light and the exposure time, the signal is to be varied with different surface conditions which cause variations of the light intensity on the elements.

4. TRACKING CONTROL

Consider that a robot must work following a line of edge. The sensor is mounted on the robot body and informs the robot controller of the true positions of the line as shown in Fig. 9. In the figure, $\theta'(t)$ is an angular position of the object point and $\theta_0'(t)$ that of the true position. If the mirror rotates only in one direction, informations of two points on the line will be taken for one revolution, which may be too late for some jobs. The acquisition speed of informations will be increased if the mirror rotation is controlled such that its direction is reversed at every instance when the object point passes through the line. In Fig. 9 the arrow shows the tracking mode of the beam(i.e., movement of the object point) by the control. Monitoring the variation of $h(t)$ of the object point, it is informed whether the point passes through the line or not. At an instance when the point passes through the line, a command is given to the motor to reverse its direction and data of the positions of the object point, R', θ', h, are stored as a true working positions and sent to the robot controller. This control action is shown as a flow chart in Fig. 10.

A block diagram is shown in Fig. 11 for the analysis of the control. In the figure θ_0 and θ are the motor angles corre-

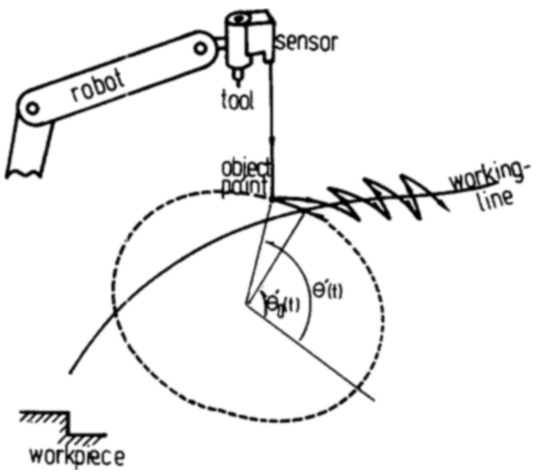


Fig. 9 Tracking mode of the beam

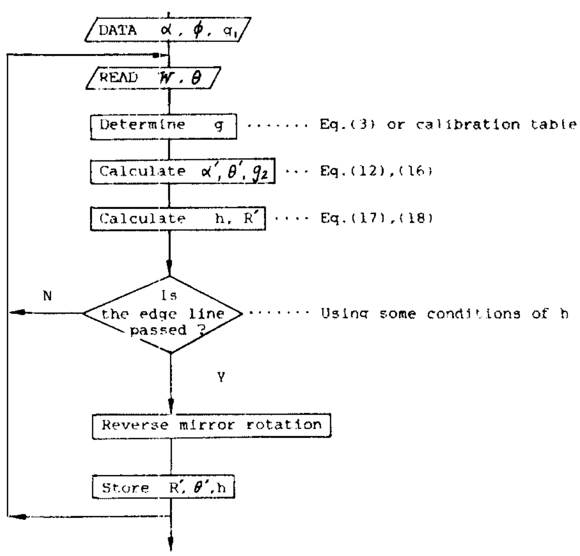


Fig. 10 Flow chart of the tracking control

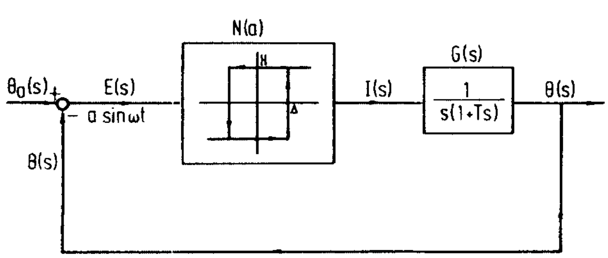


Fig. 11 Block diagram of the control

sponding to θ_0' and θ' respectively. $E(s)$ is a Laplace transform of an error $e(t)=\theta_0(t)-\theta(t)$ and $I(s)$ is that of current $i(t)$ to the motor. In real control action there exists a time delay between the instance when the object point passes through the line and that of commanding to reverse the direction of motor rotation due to processing time of controller. Thus the command is given after a certain amount of angle has been rotated already from θ_0. This fact is considered in Fig. 11 by adopting a delay Δ. The delay will be smaller with lower motor speed and faster process of control.

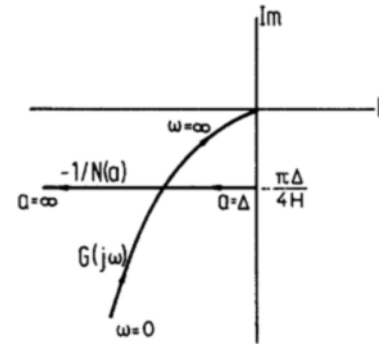


Fig. 12 Curves of $G(j)$ and $-1/N((a))$

Transfer function of the motor, $G(s)$, is assumed as

$$G(s)=\frac{1}{s(1+Ts)} \tag{19}$$

where T is a time constant of the motor. The error $e(t)$ is assumed as a harmonic with an amplitude, a, and frequency, w. Using a describing function method the transfer function of the relay, $N(a)$, is given as(Atherton, 1981).

$$N(a)=4H(a^2-\Delta^2)^{1/2}/a^2\pi-j4H\Delta/a^2\pi,\quad a>\Delta \tag{20}$$

where $j=\sqrt{-1}$.
The characteristic equation of the control system is obtained as

$$1+N(a)\ G(s)=0 \tag{21}$$

The curves $-1/N(a)$ and $G(jw)$ are drawn in a complex plane in Fig. 12. It is known that for any system parameters there exists a cross-point. This implies that a limit cycle always takes place which is reasonable when considering the control action.

The amplitude and frequency of the limit cycle are determined by the values of those of the cross point.

Stability condition of the limit cycle is examined by a Loeb criterion.

$$\left(\frac{\partial U}{\partial w}\cdot\frac{\partial Q}{\partial a}-\frac{\partial V}{\partial w}\cdot\frac{\partial P}{\partial a}\right)\Bigg|_s>0 \tag{22}$$

where U, V, P and Q are defined as

$$G(jw)=U(w)+jV(w) \tag{23}$$
$$C(a)=-1/N(a)=P(a)+jQ(a) \tag{24}$$

From the Eqs. (19), (20), (23) and (24), the Loeb criterion is written as

$$w^2+\frac{1}{3a^2}>0 \tag{25}$$

which is always satisfied, thus implies that the limit cycles which arise in the control are always stable.

In Fig. 12 the cross point moves in a manner that with decrease of Δ and increase of H the amplitude of limit cycle, a, is decreased and the frequency, w, is increased. It is noticed that a small amplitude gives a small error in measuring the true working positions and larger frequency gives more data in a certain time, thus improves resolution of the measurement.

5. CONCLUSIONS

A pilot-type laser sensor for non-contacting distance measurement is developed using non-focused image of a convex lens. The principle is based on a distance relation between object-image point of the lens. The application was aimed at in-process tracking control of an industrial robot.

From some test results, it is convinced that it can be used as a distance measurement sensor with wide range.

Advantages of the sensor comparing with one using a triangular principle(Lee, et al., 1987, Shiraishi, 1979) may be the facts that

—It is simple to scan the beam with a mirror to follow a path(Ruoff, 1987).

—The line of beam emission to an object and that of reflected light to CCD-array is the same.

This may overcome some geometric constraints which may arise for a sensor using triangular principle.

Besides weakness of the sensor may be pointed out as follows.

—The repeatability may not be enough for some jobs.

—The measurement varied with surface conditions of objects.

The following subjects are suggested for further study.

—Development of a stable sensor element to detect light intensity with good repeatability.

—Compact design of the sensor system.

—Method to increase data processing speed for accurate tracking control

—Method of normal beam emission using a normal lamp to replace the laser, which reduces its cost.

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