A POSITION AND HEADING MEASUREMENT SYSTEM FOR ROBOTS
-- LASER NAVIGATOR --

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ABSTRACT

This paper describes the development of a position and heading measurement system using for moving robots (we call "LASER NAVIGATOR ") , which is composed of a scanning laser unit (SLU) mounted on a robot and three or more corner-cubes (retro-reflectors) fixed on the ground . A coordinate system and corner-cubes are arbitrarily set on a horizontal plane , and their coordinates have already measured by other survey . SLU measures three angles to each CC from a robot heading and computes the position and the heading of the robot on the coordinate system .

An experimental model (LN-10) has been manufactured , evaluated and fundamental data for a production model were obtained . This time , a production model (LN-11) was produced and tested . It is confirmed that LN-11 satisfies user's requirements ;

(1) Distance range : 50 m maximum
(2) Distance accuracy : $\pm$ 5 cm maximum
(3) Heading range : 360 deg.
(4) Heading accuracy : $\pm$ 0.5 deg. maximum

This navigation system applies to a floor-finishing-robot used in a building under construction .

1. Introduction

Robotics and automation in construction field have spread and a lot of kinds of robots have been developed . In order to control and guide such a robot , it is necessary to measure the accurate position and the heading of the robot . Many types of navigation systems are proposed and some of them are on the market . Based on the method to have been proposed [(1)] , we have developed the system (**LASER NAVIGATOR**) which is composed of a LASER SCANNING UNIT (LSU) equipped on the robot and three or more corner-cubes (CC's) fixed on the ground and measures the position and the heading of the robot .

We have already developed two types of LASER NAVIGATORs , LN-10 and LN-20 . LN-20 which is a high accurate system and is used for a low speed vehicle (e.g. a shield tunnel machine) was confirmed to satisfy user's requirements : position accuracy $\pm$ 2 cm max. and heading accuracy $\pm$ 5 min. max.. [(2)(3)] LN-10 which is an experimental model for a wide use (e.g. AGV) was produced and evaluated ,and the basic data for a production model was obtained . [(4)] This time , LN-11 which is a production model of LN-10 has been developed , evaluated and was confirmed to satisfy user's requirements : distance range 50 m max. , distance accuracy $\pm$ 5 cm max. , heading range 360 deg. and heading accuracy $\pm$ 0.5 deg. max..

This paper describes the principle of the measurement , the hardware and the software ,specifications , results of the evaluation test and the future of LN-11 .

2. Principle of measurement

The theory to calculate the position and the heading of a vehicle is detailed in the reference(1) and the summary of the theory is described here . The coordinate system (XOY) and three reference points (CC1 , CC2 & CC3) are arbitrarily set in a horizontal plane as shown in Fig.1 , and their coordinates CC1(X_1,Y_1) , CC2(X_2,Y_2) and CC3(X_3,Y_3) are well-known . If three angles (θ_1,θ_2 & θ_3) from the vehicle heading to the three reference points are measured , the coordinates (Xv,Yv) and the heading (ψ) of the vehicle are obtained as follows ;

2.1 Position calculation

A vehicle position can be calculated by obtaining an intersection point between two following circles (O_{12} and O_{13}) as shown in Fig.1 .

O_{12} : a circle passing through the vehicle (V) , CC1 and CC2
O_{13} : a circle passing through the vehicle (V) , CC1 and CC3

Now , α and β are defined as follows ;

$$\alpha = \theta_1 - \theta_2 \qquad (1)$$

$$\beta = \theta_1 - \theta_3 \qquad (2)$$

The coordinates of the centers of two circles $O_{12}(X_{12},Y_{12})$ and $O_{13}(X_{13},Y_{13})$ are given by ;

$$(X_{12},Y_{12})=(X_1+P_1,Y_1+Q_1) \qquad (3)$$

$$(X_{13},Y_{13})=(X_1+P_2,Y_1+Q_2) \qquad (4)$$

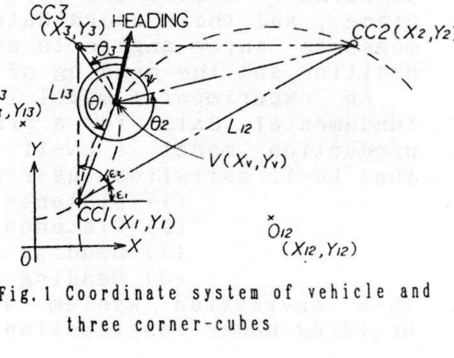

Fig.1 Coordinate system of vehicle and three corner-cubes

where

$$(P_1\ ,\ Q_1)=\left\{\frac{L_{12}\,\mathrm{SIN}\,(\alpha-\varepsilon_1)}{2\,\mathrm{SIN}\,\alpha}\ ,\ \frac{L_{12}\,\mathrm{COS}\,(\alpha-\varepsilon_1)}{2\,\mathrm{SIN}\,\alpha}\right\} \qquad (5)$$

$$(P_2\ ,\ Q_2)=\left\{\frac{L_{13}\,\mathrm{SIN}\,(\alpha+\varepsilon_1+\varepsilon_2)}{2\,\mathrm{SIN}\,\beta}\ ,\ \frac{-L_{13}\,\mathrm{COS}\,(\alpha+\varepsilon_1+\varepsilon_2)}{2\,\mathrm{SIN}\,\beta}\right\} \qquad (6)$$

As the coordinates of CC1 , CC2 and CC3 are already known , the following values can be calculated ;

L_{12} : distance between CC1 and CC2
L_{13} : distance between CC1 and CC3
ε_1 : included angle between X-axis and L_{12}
ε_2 : included angle between CC1-CC2 and CC1-CC3

From equations (3) and (4) , the equations of the circles O_{12} and O_{13} are given by ;

$$O_{12}:(Xv-X_1-P_1)^2+(Yv-Y_1-Q_1)^2=P_1{}^2+Q_1{}^2 \qquad (7)$$

$$O_{13}:(Xv-X_1-P_2)^2+(Yv-Y_1-Q_2)^2=P_2{}^2+Q_2{}^2 \qquad (8)$$

By solving the equations (7) and (8) , the vehicle position is ;

$$(Xv,Yv)=\{X_1+K*(Q_2-Q_1)\ ,\ Y_1-K*(P_2-P_1)\} \tag{9}$$

where

$$K=\frac{2(P_1Q_2-P_2Q_1)}{(P_2-P_1)^2+(Q_2-Q_1)^2} \tag{10}$$

2.2 Heading calculation

After obtaining the vehicle position (Xv,Yv) , the vehicle heading can be calculated by following equation ;

$$\psi=\pi+\tan^{-1}\left(\frac{Y_v-Y_1}{X_v-X_1}\right)-\theta_1 \tag{11}$$

3. Operation of production model LN-11

LN-11 is composed of a laser scanning unit (LSU) and three or more corner-cubes (CC's). Equipments associated with LN-11 are a host computer and a power supply of a robot . CC is a kind of prism and has the characteristic of reflecting a beam in the same direction of incidence . LSU which includes a laser emitter/ receiver,a horizontal laser scanning mechanism , a signal processor,etc., measures three angles from a vehicle heading to three CC's and calculates the vehicle position and heading .

A host computer and a power supply on a moving robot is connected to LSU . The host computer transmits initial data and control signals as the positions of corner-cubes , the initial position of the robot , etc. at initial mode , and receives the position and heading signals and the operation monitoring signals from LN-11 .

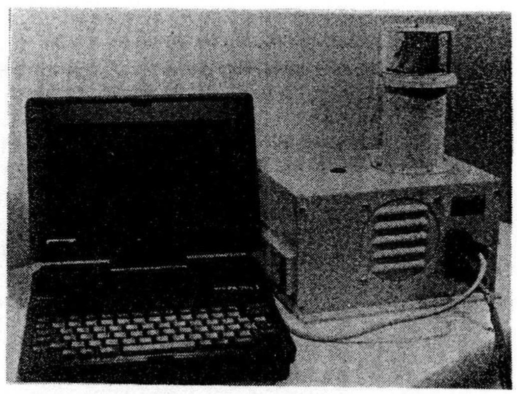

Fig.2 LN-11 and lap-top computer for evaluation

3.1 Hardware of LN-11

Figure 2 shows the external appearance of LN-11, and Fig.3 shows the system block diagram .

A laser diode is driven by an automatic power control circuit (APC). The laser beam is collimated by a lens (L1) and passes through a cylindrical shaft. Then ,it reflects horizontally at a mirror (M1) and is launched outside after expanded vertically by a cylindrical lens (L2) so that the beam can certainly strike CC regardless of the vehicle attitude . The returned beam from CC is reflected at mirrors (M2 and M3), and is focused on a photodiode (PD) through an interference filter (IF). Mirrors (M1 and M2) and a lens (L2) are mounted on the shaft , and the beam is horizontally scanned with the shaft rotation . PD transmits a CC detection signal to a signal

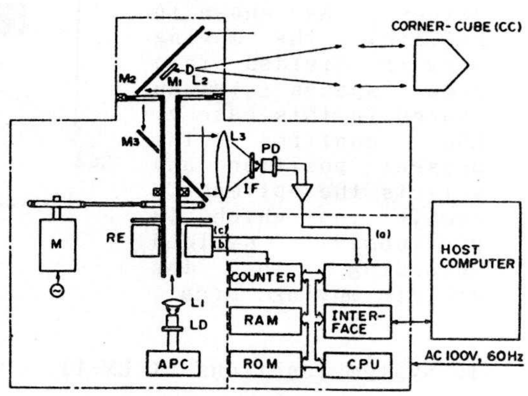

Fig.3 System block diagram

processor (SP). An incremental rotary encoder (RE) is also mounted on the cylindrical shaft which is driven by an AC motor, and sends an angle signal and a reference signal to SP.

3.2 Software of LN-11

Figure 4 shows the schematic system flow chart of LN-11. The signal processor (SP) of LSU receives initial data like positions of three CC's from the host computer and stores them after checking. The laser beam begins to scan, and angle signals from the zero reference signal of RE to each CC detection signal are sent to SP and checked. SP confirms the present area and selects the optimum CC combination within stored ones and the position and heading can be calculated by three angle data.

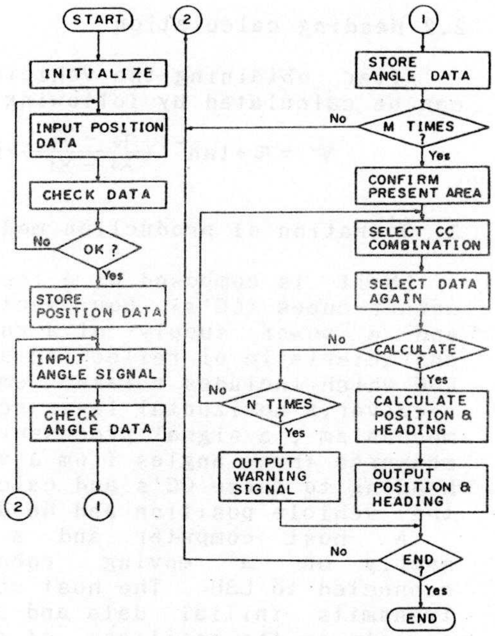

Fig.4 System flow chart

3.3 Consideration for obstacles

As shown in Fig.5(a), if obstacles like pillars are in a vehicle moving area, it may occur that three angle data cannot be obtained according to some condition. Therefore, many CC's are set on the moving area as shown in Fig.5(b) (eight CC's in this case), and it becomes possible that three or more CC's data can always be obtained. As many CC data are obtained in this case, it is important to select the optimum CC combination so that the position and heading errors may become the minimum values. As shown in Fig.5(b), the moving area is divided into some spaces (sixteen spaces in this case). LSU confirms the present position and selects the optimum CC combination which is previously decided according to the vehicle moving area.

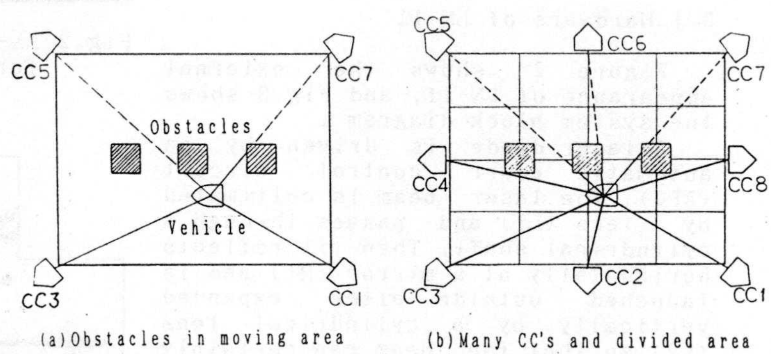

Fig.5 System optimization

4. System functions of LN-11

LN-11 has the following two main system functions;

(1) Measurement function
(2) Operation monitoring function

4.1 Measurement function

LN-11 has a function to measure a position and heading of a vehicle as described in chapter 3 .

4.2 Operation monitoring function

LN-11 has the following operation monitoring functions to improve system reliability , and transmits a warning signal to a host computer whenever any defect is detected .

(1) RAM check : RAM is checked by inputting and reading out some number at initialization of CPU .

(2) Self position check : LSU compares the calculated position with the starting position data from the host computer at initial mode , and automatically begins to operate if the difference is within a tolerance . If not so , a warning signal is sent .

(3) Output check : A output from LSU is always compared with the previous one , and the operation continues if the difference is within a tolerance .

(4) LD temperature check : LD operating temperature is always controlled at 20 deg. C. with a closed loop circuit composing of a thermistor and a peltier cooling in order to guarantee the LD long life , and a warning signal is sent if the temperature is over 50 deg. C. .

(5) LD operation check : LD output power is always monitored and a warning signal is sent if the power fails .

(6) Scanning speed check : As scanning speed has relation to not only performance but safety , it is always monitored . If it decreases , a warning signal is sent .

(7) Power supply check : Inner power supply (+5V & $\pm$12V) of LSU is monitored whether it operates within a tolerance $\pm$ 10 % .

(8) CPU operation check : Time intervals of one cycle of CPU are counted by a timer,and a warning signal is sent if it is over some value.

(9) CC angle check :A measured CC angle is compared with the previous CC angle , and if the difference is over some expected value , a warning signal is sent .

5. Specification of LN-11

5.1 Components of LN-11

(1) Scanning laser unit (SLU) : 1 set , 220(W)*380(H)*305(L) mm , 12kg
(2) Corner-cube (CC) : 3 sets or more, 76(W)*90(H)*63(L) mm, 0.5kg/set

5.2 Main parts

(1) Laser diode (LD) : wave length 830nm , output 60mW
(2) LD beam pulse frequency : 1 MHz
(3) Rotary encoder output : 10,000 pulses/rev.
(4) CPU : two Z80B's
(5) CC reflection accuracy : 15 arc seconds

5.3 Performance

(1) Position range & accuracy : 50 m maximum , $\pm$ 5 cm maximum
(2) Heading range & accuracy : 360 deg. , $\pm$ 0.5 deg. maximum
(3) Vehicle speed : 1 km/hr maximum
(4) Vehicle turn rate : 20 deg./sec. maximum
(5) Vehicle pitch & roll : $\pm$ 1.5 deg. maximum
(6) Horizontal scanning speed : 1,800 r.p.m.

(7) Output format : RS-232C
(8) Output interval : 100 msec.each
(9) Software : CP/M-80 Assembler
(10) Power supply : AC100V , 50/60 Hz , 1A maximum
(11) Safety : Class 1 laser product

6. Evaluation of LN-11

LN-11 was set in sequence on sixteen points at a area (12.9m * 9.6m) which were centers of each space described in section 3.3 , and each position and heading were measured statically . The outputs were compared with the values surveyed by a transit and a tape-measure and also , with the error simulation , which is performed with two included angles (α and β indicated by equations (1) and (2)) to be added ± 6 minutes error as the CC setting error and the encoder resolution .

6.1 Position error

The test results of the position error are shown in Table 1 and Fig.6. The mean values and the standard deviations of errors are as follows ;

(1) Mean values of errors :

$$\delta\bar{x} = -9 \text{ mm} , \delta\bar{y} = -15 \text{ mm}$$

(2) Standard deviations of errors :

$$\sigma\delta x = 16 \text{ mm} , \sigma\delta y = 17 \text{ mm}$$

Also , Fig.6 shows the error simulation , and the good agreement between the measured values and the error simulation is obtained .

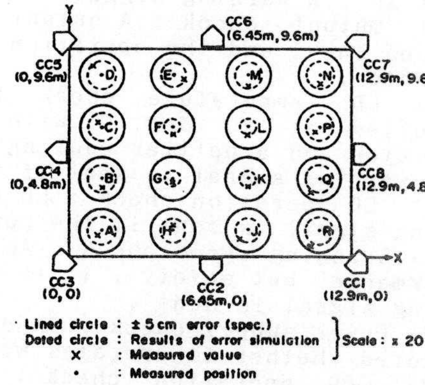

Fig.6 Position error

Table 1 Test result of position error (unit:mm)

T.point	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R
X error	-18	-3	-15	-28	29	2	-3	-2	-26	-4	-1	-3	2	-12	-27	-33
Y error	-16	-22	16	19	-10	-18	-9	11	-24	-21	-21	-25	-22	-14	-37	-41

6.2 Heading error

The test results of the heading error are shown in Table 2 and Fig.7 . The mean values and the standard deviations of errors are as follows ;

(1) Mean values of errors :

$$\delta\bar{\psi} = -6 \text{ minutes}$$

(2) Standard deviations of errors :

$$\sigma\delta\psi = 14 \text{ minutes}$$

Also , Fig.7 shows the error simulation , and the relatively good agreement between the measured values and the error simulation is obtained .

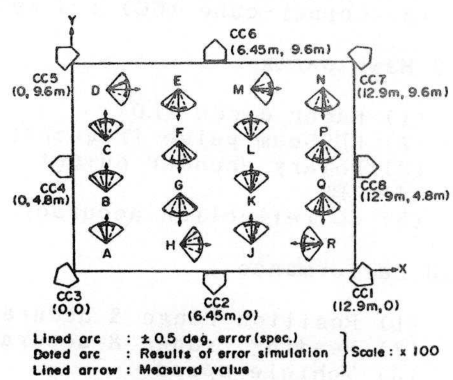

Fig.7 Heading error

Table 1 Test result of heading error (unit:min.)

T.point	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R
ψ error	-13	-22	-19	-12	19	-20	-28	-21	10	5	-2	7	-7	3	4	-5

6.3 Installation test

LN-11 is installed in a floor-finishing-robot (FFR, Manufacturer : Mitsubishi Heavy Industry , User : Obayashi Corporation) and is used as a navigation sensor . The robot moves within a tolerance versus a specified track and the availability of LN-11 is confirmed . Figure 8 shows FFR which installs LN-11 .

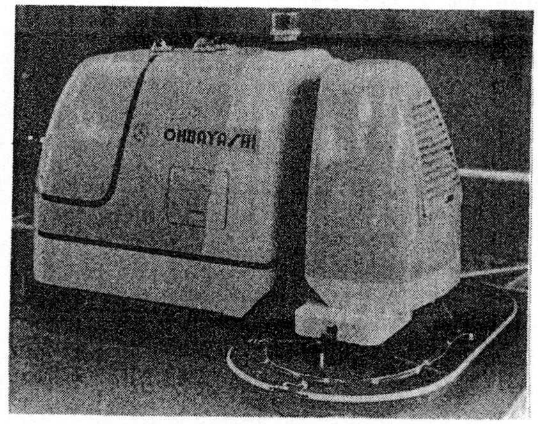

Fig.8 LN-11 on floor-finishing-robot

7. Conclusion

LASER NAVIGATOR can give the accurate position and heading informations to a vehicle by using a scanning laser unit equipped on the vehicle and simple ground support equipments (corner-cubes) . LN-11 to be a production model for general purpose is manufactured, evaluated and confirmed to satisfy user's requirements ;

(1) Position range : 50 m maximum
(2) Position accuracy : ± 5 cm maximum
(3) Heading range : 360 deg.
(4) Heading accuracy : ± 0.5 deg. maximum

Also , LN-11 is installed in a floor-finishing-robot and its availability is confirmed .

In future , the following improvements are planned .

(5) Maximum vehicle speed : 1 km/hr ⟶ 10 km/hr
(6) Maximum vehicle pitch and roll : ± 1.5 deg. ⟶ ± 3 deg.
(7) Accuracy : position ± 5 cm ⟶ ± 1 cm
heading ± 0.5 deg. ⟶ ± 0.1 deg.

8. Acknowledgment

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9. References

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