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AUTOMATIC SURVEYING SYSTEM FOR SHIELD TUNNELING

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ABSTRACT

During shield driving , to survey and control the position of a shield machine is an essential part of the quality control to keep the tunnel alignment within the tolerance . In curved alignment , conventional surveying with a transit and a level is quite time-consuming and often results in steering of a shield machine too late to stay on the design alignment . To overcome this problem , an automatic surveying system has been developed , which works effectively even in a curve(1) . This system consists of a laser measurement unit , a signal processing unit , an I/O unit , a data transmitting unit and four corner-cubes , and calculates the position and the heading of the shield machine by measuring the angles and the distances of each two corner-cubes set on fixed reference points and the shield machine . This paper describes the surveying method , the mechanism and functions of the surveying system, and discusses the surveying accuracy and results of some tests conducted on its performance .

1. Introduction

For shield tunneling , it is important to survey and control the position and the heading of a shield machine in order to achieve high accuracy in tunnel driving . Generally ,the position accuracy of a shield tunnel to be driven is dependent on the frequency and the accuracy of the surveying and also on the timing and the method of the attitude control. An automatic surveying system supplies precise real time data to improve the construction accuracy and to save time for surveying . Therefore , the system plays an important part of the automation of shield tunneling .

For manual survey using optical instruments , it is necessary to transfer a measuring point because reference points or targets cannot be sighted with obstacles in the shield tunnel . As a result , the frequency of surveying increases and hours are idled away at a curved section .

For this reason , an automatic surveying system composed of a laser measurement unit (LMU) , a signal processing unit (SPU) , a I/O unit (IOU) , a data transmitting unit (DTU) and four corner-cubes (CC's) has been developed . LMU transmits a beam to CC's , receives a reflected beam from them , and measures the angles and the distances to them . SPU receives data from LMU and calculates the position and the heading of the machine . Then , SPU sends the outputs of the deviation from the design alignment . The system performs this process automatically .Its characteristics are as follows ;

(1) Since CC set at a measuring point is a kind of prism to reflect a beam in the same direction of incidence, no electric wiring is required , maintenance madé simplified and no large space required for installation.

(2) LMU is very small and can be mounted in a narrow space .

(3) The system adopts the principle of traverse survey and is very reliable . LMU occasionally self-checks its position with regard to the two reference points behind it .

(4) Since the system automatically measures the position of a moved CC in an obstructed view, the inspection survey is easy at a transfer point.

2. Conventional survey and its problem

A transit and a level are used for conventional survey as shown in Fig.1 . It takes a long time at a curved section. As a result, timing to control a shield machine is often missed and the machine cannot keep the design alignment . To solve this problem , automatic drive of a shield machine has been studied and an automatic surveying system has been developed . Generally , the specifications of the system are required to meet the following conditions ;

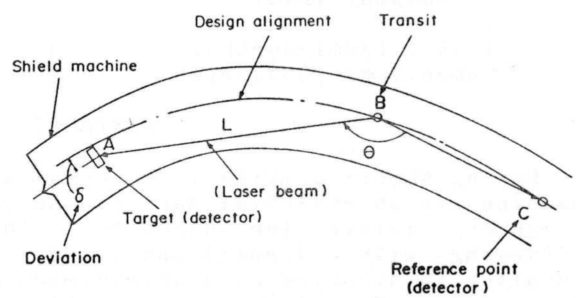


Fig.1 Conventional survey

(1) The design alignment usually includes curves in consideration of the buildings and roads on the ground .

(2) The space to be surveyed is limited and has only one direction .

(3) The measurement distance is generally 300 m to 1000 m .

(4) The survey accuracy varies according to the purpose of a tunnel , but generally 1 to 2 cm maximum . High accuracy is required to measure the distance .

(5) The driving speed of a shield machine is about 2 to 10 cm/min..

3. Present status of automatic surveying system

Various automatic surveying systems (ASS) which have been developed are listed in Table 1 . All the systems are on the market , but have not been in wide use .

Table 1 Various automatic surveying systems

Item	Method	Accuracy	Characteristic
Laser (2)(3)	*Angle measurement by laser scanning *Distance measurement	Equivalent to transit survey	High reliability that is based on conventional survey
Gyrocompass	*Heading measurement *Measurement of unit driving distance	*HDG accuracy: ± 0.1 deg. *Need inspection survey	No need for a space like optical survey
Image processing	*Beam position measurement on image *Distance measurement	Equivalent to transit survey	Basically same as laser method with same or higher accuracy

4. Development of the automatic surveying system

4.1 Principle of survey

Figure 2 illustrates a new surveying and is based on triangulation. It measures the position of a laser measurement unit (LMU) and next , a shield machine on both horizontal and vertical planes.

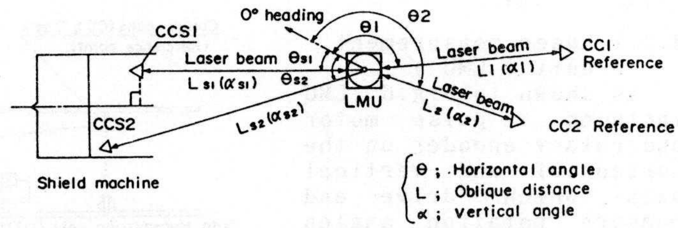


Fig.2 Illustration of developed survey

4.1.1 Calculation of position of LMU

Figure 3 shows a relation between CC's as the fixed references and LMU. The known quantities are as follows ; the coordinates of CC1 (X_1,Y_1,Z_1) and CC2 (X_2,Y_2,Z_2) , and the distance between CC1 and CC2 . The measured quantities are as follows ; the angles from the heading of LMU to CC1 and CC2 , and the distances from LMU to CC1 and CC2 . The coordinates of LMU (Xs,Ys,Zs) can be calculated from these known and measured quantities as follows ;

$$Xs = L_1 * COS(\gamma_1) + X_1 \quad (1)$$

$$Ys = L_1 * SIN(\gamma_1) + Y_1 \quad (2)$$

$$Zs = M_1 * SIN(\theta_{V1}) + Z_1 \quad (3)$$

where

$$L_1 = M_1 * COS(\theta v_1) \quad (4)$$

$$L_2 = M_2 * COS(\theta v_2) \quad (5)$$

$$L_3 = \{(X_1 - X_2)^2 + (Y_1 - Y_2)^2\}^{\frac{1}{2}} \quad (6)$$

$$\gamma_1 = \beta_1 - \alpha_1 \quad (7)$$

$$\alpha_1 = COS^{-1}\left(\frac{L_1^2 + L_3^2 - L_2^2}{2L_1L_3}\right) \quad (8)$$

$$\beta_1 = TAN^{-1}\left(\frac{Y_2 - Y_1}{X_2 - X_1}\right) \quad (9)$$

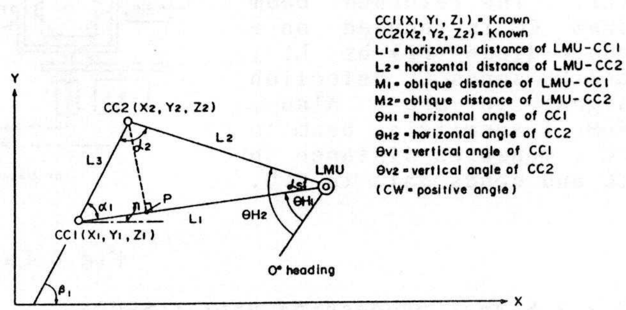


Fig.3 Position of laser measurement unit (LMU)

4.1.2 Calculation of position of shield machine

Figure 4 shows a relation between LMU and CC's (CCS1 & CCS2) mounted on a shield machine . The known quantities are the coordinates of LMU and the measured quantities are the distance and the horizontal and vertical angles from LMU to CC's . The coordinates of CCS1 and CCS2 can be calculated from these known and measured quantities as follows ;

$$Xcs = Lcs * COS\zeta + X_s \quad (10)$$

$$Ycs = Lcs * SIN\zeta + Y_s \quad (11)$$

$$Zcs = Mcs * SIN(\theta sv) + Z_s \quad (12)$$

where

$$Lcs = Mcs * COS(\theta sv) \quad (13)$$

$$\zeta = \theta_0 - \theta_{SH} + \pi \quad (14)$$

$$\theta_0 = \gamma_1 + \theta_{H1} \quad (15)$$

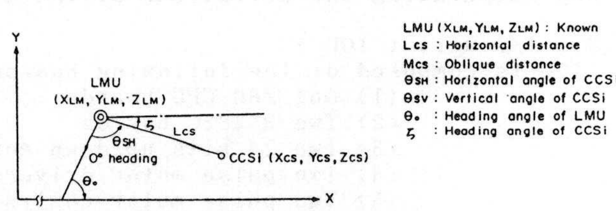


Fig.4 Position of shield machine

4.2 Components of ASS

The automatic surveying system (ASS) which has been developed is composed of a laser measurement unit (LMU) , a signal processing unit (SPU) , an I/O unit (IOU) , a data transmitting unit (DTU) and four corner-cubes (CC's) as shown in Fig.5 .

4.2.1 Laser measurement unit (LMU)

As shown in Fig.6 ,LMU includes a pulse motor and rotary encoder on the horizontal and vertical axes which drive and measure rotation angles of the axes . A He-Ne laser transmitter and a electro-optical distance meter (EDM) are mounted on the inner horizontal axis . The laser beam is reflected at right-angle prisms and is emitted outwards through a beam expander (BE) , a holed mirror (M1) and a lens (L1) . The returned beam from CC is focused on a photo-diode (PD) by L1 , and PD sends CC detection signal to SPU . Also , EDM transmits a beam to CC , measures distance to CC and sends data to SPU.

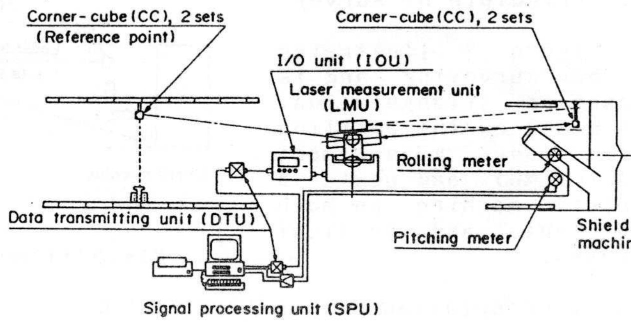


Fig.5 Illustrated system composition

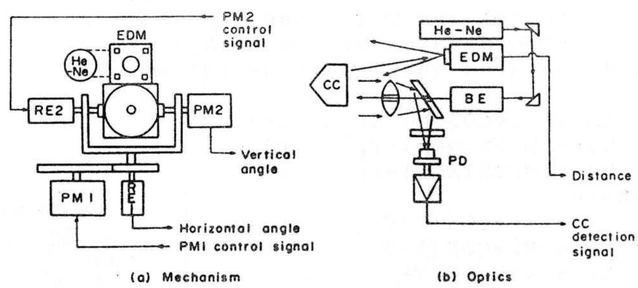


Fig.6 Laser measurement unit (LMU)

4.2.2 Signal processing unit (SPU)

SPU is a conventional personal computer which is composed of a CPU with floppy disk drives , a keyboard , a CRT and a printer . SPU performs the following main functions ;

(1) Calculating the included angle between CC's using angle data .

(2) Calculating the position and the attitude of LMU and the shield machine .

(3) Memorizing the positions of each CC and transmitting the command of laser scanning range to LMU

(4) Memorizing the design alignment , comparing it with surveying data , and calculating the deviations of the distance and the heading .

4.2.3 I/O unit (IOU)

IOU is composed of the following boards ;

(1) One Z80 CPU board
(2) Two RS232C boards
(3) Two 24 bits up/down counters
(4) Two pulse motor drivers
(5) Two pulse motor controllers

Two pulse motor controllers and drivers control two motors mounted on the horizontal and the vertical axes of LMU . The outputs of the rotary encoders on each axis are sent to two up/down counters . Z80 CPU reads the outputs at CC detection signal and measures the horizontal and vertical rotation angles of the laser beam . Two RS232C boards are connected to SPU and the electro-optical distance meter (EDM) .

4.2.4 Data transmitting unit (DTU)

DTU uses a modem which is on the market because the distance between SPU and IOU may be over 1 km .

4.2.5 Corner-cube (CC)

CC is a kind of prism to reflect a beam in the same direction of incidence .

4.3 Method of surveying

4.3.1 Mounting of components

LMU is set behind a shield machine and at a place where CC's on the machine and the fixed points can be seen through free space .

Two CC's are mounted on the machine and other two CC's are set at the fixed reference points behind LMU . CC's on the machine are set back and forth for some distance along the fore-aft axis of the machine ,and the heading of the machine can be calculated .

4.3.2 Searching of CC

Figure 7 shows a system flow chart of the developed automatic surveying system . A laser beam of LMU should be launched to the center of CC so that LMU can measure the angle and the distance to CC . For this purpose , some area including CC is decided , and the beam is scanned within the area to find the center of CC .The beam scans horizontally from the upper left side of the area , then vertically for some distance at the upper right side of the area and , again , scans horizontally in the opposite direction .

When the beam strikes CC and it is returned , LMU can find CC . Because the shield machine moves slowly ,the data are not different from the previous data too much.If the previous data are used as the center of the scanning area,the CC to be measured must exist in the area , and the area should be set larger than the estimated change of the data .

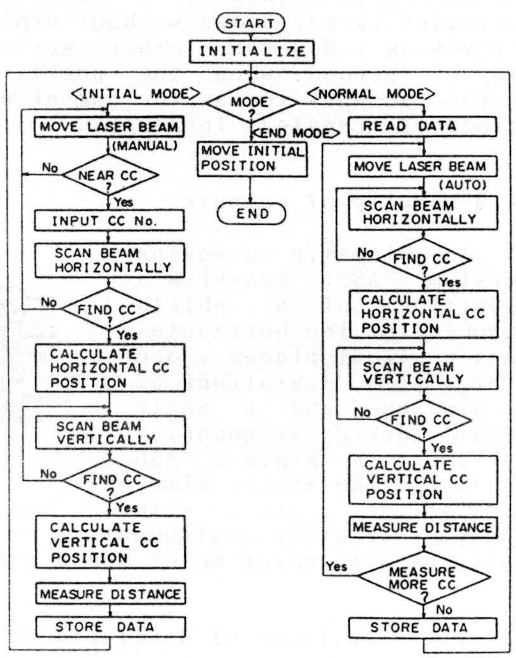


Fig.7 System flow chart

At the initial mode or transfer, the center of the scanning area should be indicated by operating a keyboard of SPU and guiding a laser beam , but at the normal mode , the laser beam automatically scans only two CC's on the shield machine using the previous data indicated by SPU ,and SPU transmits the data of the position and the heading of the machine at every measurement . At the inspection mode , the position of LMU is checked by operating the keyboard and scanning two CC's at the fixed reference points behind LMU at segment erection .

After the angle to CC in the horizontal plane is measured by horizontal scanning , a laser beam is fixed at the horizontal angle and a vertical angle is measured by vertical scanning . Then , the beam is fixed at the vertical position and a distance is measured by an electro-optical distance meter .

4.3.3 Transfer of LMU and CC

As shown in Fig.8 , when the view is obstructed between LMU and the shield machine or the reference point during shield driving , LMU or CC at the reference point behind the LMU should be transferred forward in sequence . A new setting point of LMU or CC can be any place and is automatically surveyed by the system itself after setting . The conditions of the transfer occur at the following occasions ;

(1) obstructed view between a shield machine and a LMU
(2) obstructed view between LMU and a reference point

In the case of (2) occurs when LMU is moved forward at the case of (1) , CC at the reference point must be transferred before LMU is moved . For the case of (1) , LMU is reset at any place where an unobstructed view is obtained , and the position of LMU is surveyed by measuring CC's at the reference points . In the case of (2) , one of two CC's at the reference points , which is farther from the LMU ,is reset at any place with an unobstructed view , and its new place is surveyed by using LMU and the other CC . The above procedure is repeated , and the transfer is performed without other surveying . However , other survey may be needed when the position error accumulates as the number of times of transfers increases.

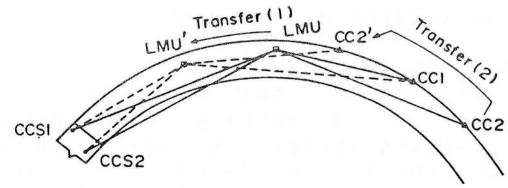
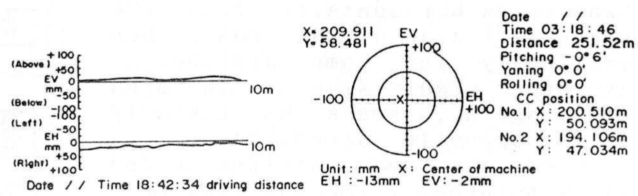


Fig.8 Illustration of transfer

4.4 Display of outputs

An automatic surveying system (ASS) measures a position of a shield machine at the horizontal and vertical planes , and calculates deviations of a distance and a angle from a design alignment . As shown in Fig.9 , ASS displays the date , time, deviations , etc . with outputs of other instruments such as a pitching meter and a rolling meter.



(a) Locus of machine (b) Deviation of machine

Fig.9 Display of automatic surveying system

5. Specifications of developed ASS

5.1 Dimensions

(1) Laser measurement unit(LMU): 1set, 325(W)*370(H)*390(L)mm, 25kg
(2) Signal processing unit(SPU): 1set, personal computer, NEC PC-9801
(3) I/O unit (IOU) : 1set, 430(W)*258(H)*430(L)mm, 5kg
(4) Data transmitting unit(DTU):2sets, 170(W)*62(H)*242(L)mm,1.3kg/set
(5) Corner-cube(CC) :4sets, 70(Dia.)*60(L)mm,0.3kg/set

5.2 Main parts

(1) Electro-optical distance meter : Sokkisha, RED mini 2
(2) Laser : Melles Griot , He-Ne laser 3 mW
(3) Rotary encoder : 4 seconds/pulse
(4) Pulse motor : 13 seconds/pulse
(5) Corner-cube : 1 arc second for reflection accuracy
(6) CPU & software in IOU : Z80 & assembler

5.3 System

(1) Measurement distance range : 150 m maximum
(2) Measurement angle range : 360 deg.(horizontal),± 5 deg.(vertical)
(3) Position accuracy : ± 1 cm maximum
(4) Measurement time : 30 seconds approximately
(5) outputs : Deviations of distance and heading
(6) Power supply : AC 100V , 50/60 Hz

6. Evaluation of developed ASS

6.1 Ground test

A ground test was performed to obtain horizontal angle errors , vertical angle errors and position errors before an installation test .

6.1.1 Horizontal angle error

LMU was placed as shown in Fig.10 and measured 45 degrees included angle of two CC's set with a transit . The mean and the standard deviation of errors were -11.2 and 2.5 arc seconds respectively . Test results are in compliance with design values .

6.1.2 Vertical angle error

LMU was placed as shown in Fig.11 and measured one degree included angle of two CC's set with a transit . The mean and the standard deviation of errors were -5 and 3.1 arc seconds respectively . Test results are compliance with design values .

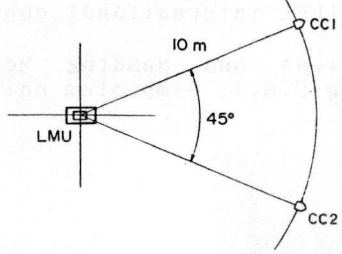


Fig.10 Horizontal angle error test

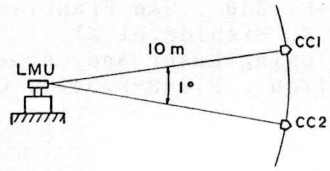


Fig.11 Vertical angle error test

6.1.3. Distance error

Since an electro-optical distance meter on the market is used , tests were not performed . The accuracy is ± 5 mm on the catalog .

6.1.4 Position error

The system position outputs were compared with those by transit survey .The test pattern is shown in Fig.12 . The position errors were X=1,Y=13,Z=-1 for LMU and X=5 ,Y=18 ,Z=19 for CCS . The test results comply with design values .

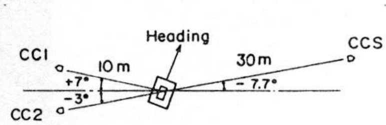


Fig.12 Position error test

6.2 Installation test

An installation test will be done at a shield tunnel construction for subway during this year .

7. Conclusion

The automatic surveying system we have developed has a characteristic that only two corner-cubes set on the shield machine and two reference points are required without a need of electrical wiring to the machine and the points . The evaluation test performed on the ground demonstrated that the test results satisfy the design values . An installation test will be done during this year .

The following future improvements will be considered ;

(1) As the laser measurement unit (LMU) includes a He-Ne laser , LMU is a little large and heavy . LMU will be made smaller and lighter by using a laser diode . Fig.13 shows a photograph of LMU to be removed its covers .

(2) The hardware of LMU is optimized and angle errors are compensated by the software of SPU in order to improve the position accuracy .

8. Acknowledgment

Authors would like to thank T . Tsumura and M . Hashimoto , University of Osaka Prefecture for technical assistance .

9. References

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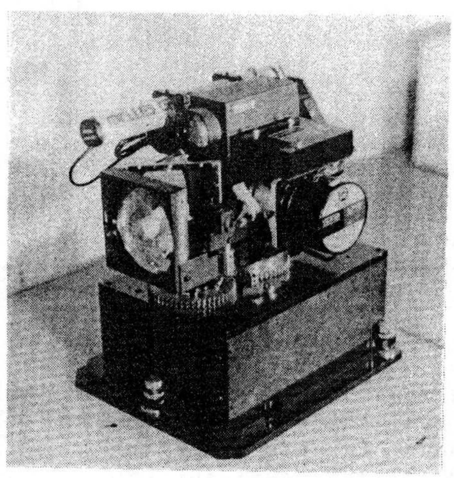

Fig.13 Laser measurement unit