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ELECTROMAGNETIC MEASUREMENT SYSTEM FOR UNDERGROUND TUNNELING ROBOT IDENTIFICATION

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Abstract: This paper proposes a newly developed thin arrayed magnetic receiver system and describes an especially designed 1.3mm thick high sensitive magnetometer. The former enables remote position sensing of underground mobile robots using electromagnetism. It features a sensor sheet spread over the ground above the construction site. The robot position is estimated in high accuracy with its multiple measurement data. The receiver contains the latter. A print-circuit-board photofabrication process has successfuly realized a planar coil. A very thin and high-sensitive magnetometer is prototyeped by adding a built-in amplifier and filter circuit.

Keywords: tunneling robot, magnetometer, electromagnetics, underground, remote sensing print circuit, estimation, ferromagnetic, magnetic flux density, band path filter

1. INTRODUCTION

Underground communication networks are recently being constructed to correspond to the increasing demand for the multimedia applications. The press-in-type tunneling machine is recognized as a useful non-excavation construction technique of telecommunication line conduits. We developed remote controlled robots which construct less than 1 meter diameter tunnels [2]. They travel underground longer than 200m. As this method can suppress the excavation of the road to be minimum, it decreases the traffic jams caused by the construction and prevents an environmental pollution. Because various equipment is laid underground, a further improvement of construction accuracy is required for this non-excavation technique. The construction accuracy depends on the experiences of the skilled operator at this time. To achieve the automatic direction control, we have already proposed the dynamic model of the press-in-type micro tunneling machine [3]. The results confirmed that the automatic control system can construct tunnels much accurately than human operators as long as the robot position data are correctly given. In order to establish tunnels precisely, accurate measurement method of the robot position is indispensable.

Several method are used to measure the robot position such as a laser transit and a gyroscope [4]. The former measures very precisely but is not available to winding route. The latter is expensive and inaccurate due to error of measured data integration.

Another method is to use electromagnetism [5]. The measurement system consists of transmitters and receivers. Relative location between them is estimated by detecting electromagnetic field generated by the transmitters. The robot position measurement system is easily realized if you mount a transmitting coil in the robot and set receiving coils on the ground surface. It has not such fatal defects that were mentioned above, but still has some practical problems. It is necessary to measure and find out the peak of the magnetic intensity above the tunneling robot. Measurement by personnel has risks of traffic accidents or traffic jams, human measurement errors, and long measuring time. Another problem is that the transmitter position cannot be estimated due to the magnetic disturbance caused by closely buried ferromagnetic materials such as steel pipes.

We propose an unmanned measurement system which estimates the tunneling robot position safely, accurately, quickly, and automatically. Its distinctive features are a thin receiver sheet and arrayed multiple sensors. The former makes it possible to be laid even on a busy street. The latter provide sufficient data to compensate magnetic disturbance and estimate the transmitter position.

We also report a very thin magnetometer device which is indispensable to be contained within the sensor sheet. As it is sensitive enough to detect very weak magnetic flux beyond meters of soil, tunneling robot position can be measure precisely.

2. AUTOMATIC NAVIGATION SYSTEM

We are planning to establish the automatic navigator system of the tunneling robot as shown in Fig.1. A transmitting coil is installed in the head of the tunneling machine to emit the 220Hz magnetism. A sensor sheet, laid above the objective route of tunnelling, measures the magnetism and estimates the robot position. An automatic control system creates control commands using the estimated data, and drives hydraulic cylinders to press and steer conduits.

The tunneling machine and driving system were already developed [2], and are now in service controlled by human operators.

The automatic control system is just developed [1], where the optimal regulator and the state observer using Kalman's filter provide control commands. Though it is going to be installed in the actual machines, you cannot expect high improvement of construction performance. That is because the robot position is still measured by human workers. A high accuracy unmanned sensing system is therefore required to complete the automatic navigation system.

The developing sensor system consists of both a transmitting coil mounted on the tunneling robot head and a sensor sheet which contains very thin magnetometer.

3. THIN AND HIGH-SENSITIVE MAGNETOMETER

In order to construct the thin sensor sheet, we have designed thin magnetometer. It is required to measure less than 10nT. It is also desirable to be thin so that a 5mm thick sensor sheet may contain the magnetometer.

There have already been developed magnetic sensors such as winding coils and Hall elements. The former are difficult to be contained within the 5mm thick sheet. The latter are small enough but are not able to give such high sensitivity.

We have designed the magnetometer structureto be manufactured by print circuit board process. A planar coil is created by photofabrication.

A copper thin film on a plastic plate is etched to create a conductive spiral. This method realized 0.14mm of circuit line width and 0.10mm of distance between circuit lines. When making 50mm x 50mm square circuit, it counts about 100 turns which is 10m circuit length of coil. In order to obtain sensitivity to measure 10nT of magnetic flux density, the sensor device is made of ten layers of the planar coil, whose total thickness is 1.3mm as shown in Fig.2.

The amplifier and the filter circuits are built in the same board as shown in Fig.3. The latter is the band path filter tuned to the transmitter frequency.

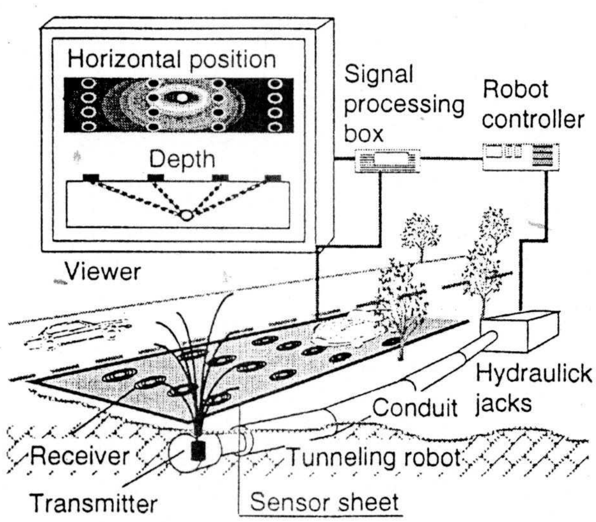

Fig.1 Automatic navigation system.

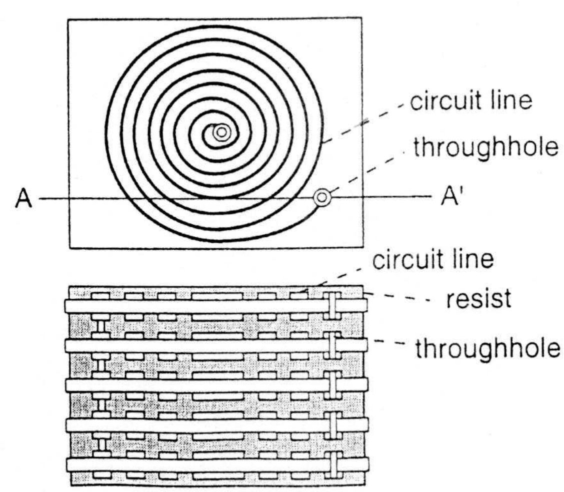

Fig.2 Planar coil.

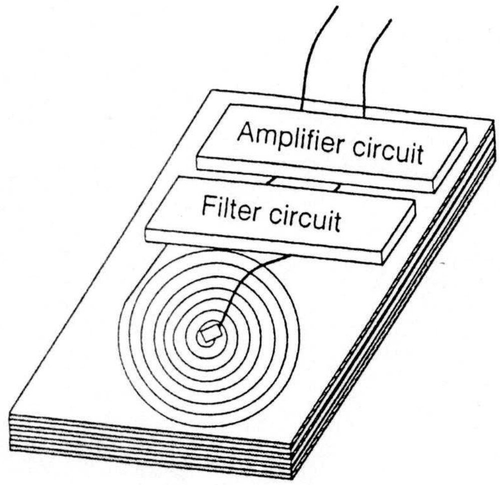

Fig.3 Sensor board.

Experiments are conducted to clarify fundamental performance of the sensor board.

Figure 4 shows the sensor output when the 220Hz alternating magnetic field is generated, where horizontal axis denotes time. The upper graph shows input magnetic flux density, whose maximum amplitude is 200nT. The lower graph illustrates the sensor output.

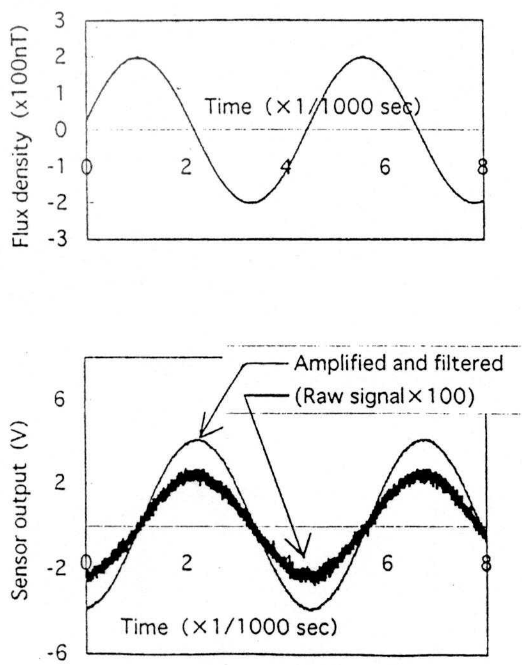

Fig.4 Sensor output signal.

Raw signal of the sensor is 0.02V maximum sinusoidal wave as drawn by the bold line, which contains high frequency noise. The solid line indicates final output of the sensor board. The signal is passed through the 220Hz band path filter and amplified to 4V maximum.

The band path filter is designed to cut frequency off other than 220Hz from the signal. It functions as the experimental results shown in Fig.5, where the horizontal axis expresses frequency and the vertical one indicates gain. The 70Hz rectangular wave is intentionally given as the input signal in order to clarify characteristics of the filter. The broken line shows the power spectrum of the input signal. The solid line indicates the power spectrum of the sensor output. It is assured that the band path filter successfully permits the only frequency of the transmitter signal.

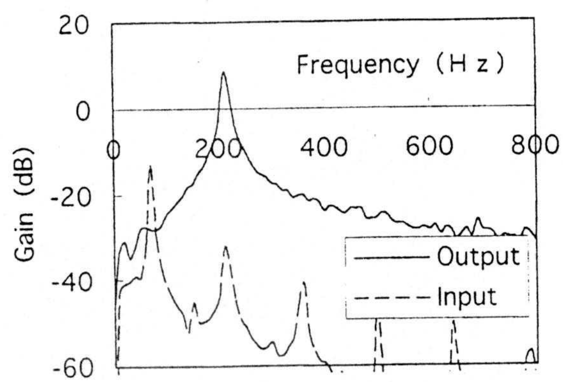

Fig.5 Filtering characteristics.

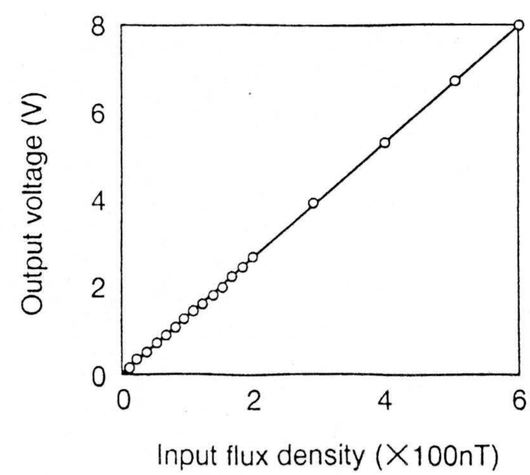

Fig.6 Sensor output voltage.

The sensor output is measured with respect to the magnetic field amplitude. Magnetic flux density is changed from 10 to 600nT. The output voltage of the sensor is linear to the input magnetic flux density and shows good resolution as shown in Fig.6, where the horizontal axis indicates magnetic flux density and the vertical one expresses the sensor output voltage.

4. MAGNETIC POSITION-IDENTIFICATION SYSTEM

The prototype magnetic position-identification system is designed as shown in Fig.7 using the thin sensor device mentioned above. The 63 sensor boards is arranged in 7 x 9 array and contained within a 5mm thick rubber sheet. The sensor sheet covers 1.6m x 1.6m areas. Each sensor board is protected from crash by aluminum thin container box.

A transmitting coil is installed in the head of the tunneling robot which travels underground at 3 to 5m deep. As the coil is mounted on the gimbal mechanism, the coil axis always points the vertical. Because the coil is driven by 220Hz AC voltage, it creates 220Hz alternating magnetic field. When the sensor sheet is laid on the ground above the robot head, it detects flux which reaches the ground surface.

Some experiments were carried out to confirm the system's faculties.

A planar distribution of magnetic field intensity was at first measured in the air by the gauss meter. The measurement plane was determined at 1m apart from the transmitting coil. The vertical component of the magnetic flux density within 0.4m x 0.4m was as shown by 25 measurement points in Fig.8, where the transmitter was just under the origin. Note that this figure illustrates only a quarter of the measurement plane, and the others have the same configurations. It was confirmed that the vertical magnetic intensity shows hilly-shaped axis-symmetry, whose peak is on the origin.

The sensor sheet was next evaluated its ability by laid on the same plane. Figure 9 shows the experimental results concerning nine measuring points, where the magnetic intensity of almost every point coincides with that by the gauss meter of the correspondent point given in Fig.8.

The system was then tried to use on the actual construction site. A transmitting coil was installed in a tunneling machine, and placed at 3m below ground. Its position was previously surveyed. Therefore the sensor sheet was set so that its center was right above the transmitting coil, only for this experiments.

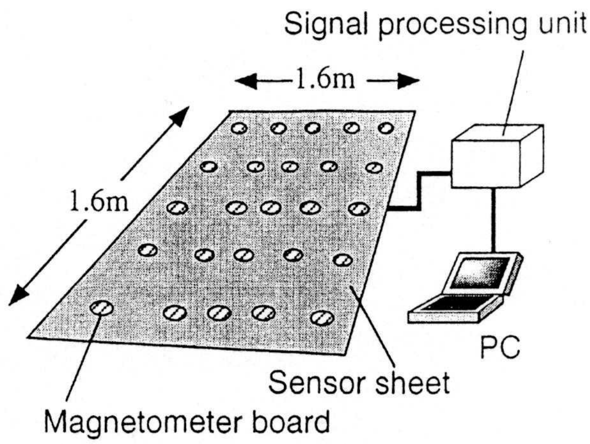

Fig.7 Magnetic receiver system.

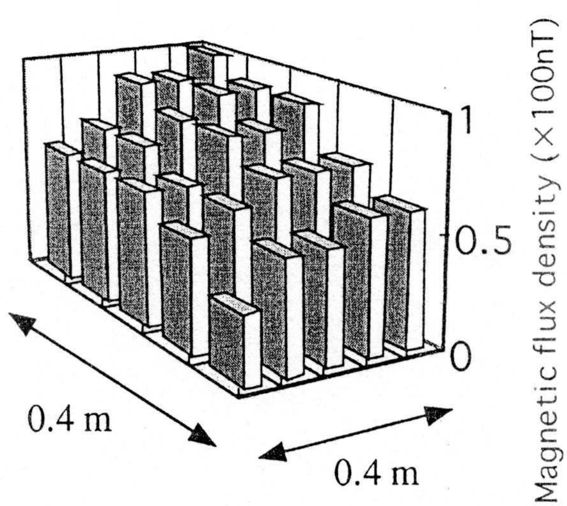

Fig.8 Magnetic intensity by gauss meter.

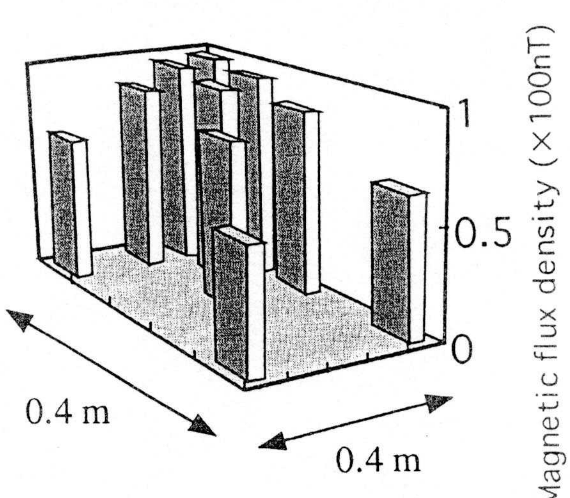

Fig.9 Magnetic intensity by sensor sheet.

There were nothing that disturbed the magnetic field such as steel pipes but soil between the transmitting coil and the sensor sheet. The sensor output is illustrated in Fig.10. It is disclosed that the same intensity pattern as in the air is obtained even across soil as thick as 3m. The maximum magnetic intensity was also confirmed to certainly appear just above the transmitting coil.

Because the practical design cannot allow the sensor sheet to be closely filled with plenty of sensor boards, it is not often the case that the transmitting coil happens to be located directly under one of the sensor boards. That is why we studied the intensity peak estimation method using multiple data. The method is available not only when you find out the vertex of the intensity distribution surface from sparse sensor data, but when you compensate the magnetic field disturbed by ferromagnetic materials which stays among the magnetic flux.

At the beginning of estimation, a polynomial is assumed as the envelope of the magnetic intensity. Its coefficients are next determined according to the sensor data so as to fit the polynomial surface with the magnetic field configuration as shown in Fig.11. The transmitter position is finally defined by the position where the polynomial takes the maximum.

Experiments of estimation was conducted using 16 sensor data. The sensor sheet is placed so that one of the sensor boards was directly above the transmitting coil as illustrated in Fig.12, where the black spot denotes the transmitter position and the white ones express other sensor boards. Data of the sensor boards except for the black spot one are used for estimation. Estimation errors were 7.2mm and 3.4mm along the both axes as shown in Table 1.

Table 1 Results of peak estimation.

Cordinates	X	Y
Transmitter position	- 0.10m	0.10m
Estimated summit	- 0.1072m	0.966m

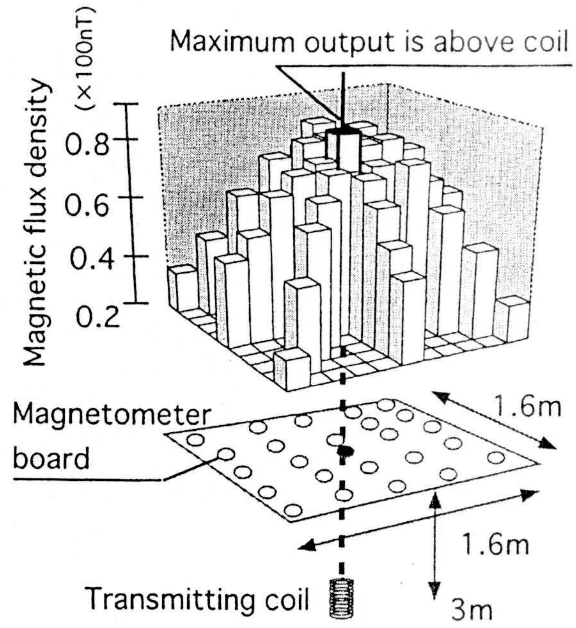

Fig.10 Experimental results on site.

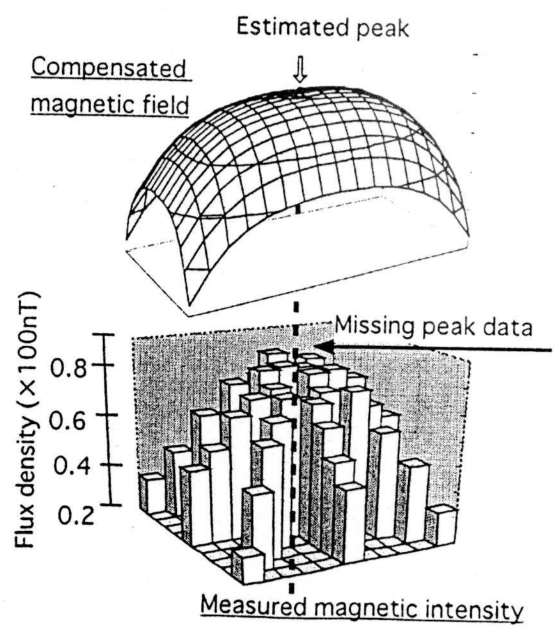

Fig.11 Estimation of configuration.

5. CONCLUSIONS

An automatic sensing system for tunneling robots has been studied. An arrayed magnetic receiver system is proposed first. It consists of a sensor sheet containing thin magnetometer boards, and is used spread over the ground above the construction site. The robot position is estimated in high accuracy with its multiple measurement data even when the magnetic field is disturbed by steel pipes. The prototype has been made and experienced to prove the system has enough performance.

A 1.3mm thick high-sensitive magnetometer is next developed. A planar coil is successfuly manufactured through a print circuit board photofabrication process. Experiments have confirmed that the magnetic sensor device with a built-in amplifier and filter circuit is suitable to the automatic sensing system. The newly developed magnetometer also seems to be available to other puposes.

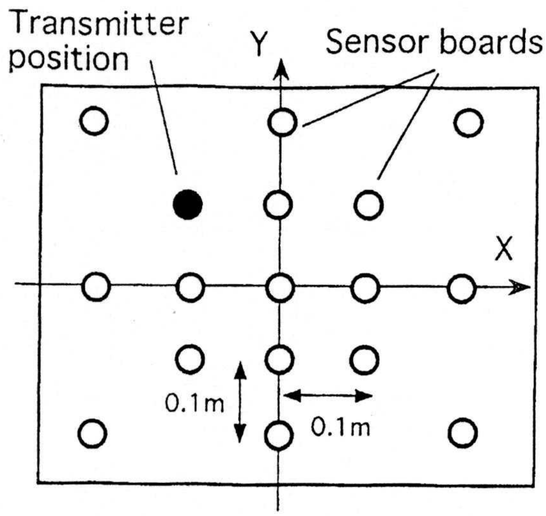

Fig.12 Experiments of peak estimation.

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