INTELLIGENT DRIVING CONTROL SYSTEM

-Automated Driving Management and Control System Using Optimum Control Theory-

Teruhisa AWATA (awata@ansl.ntt.co.jp)
Koichi YOSHIDA (yoshida@ansl.ntt.co.jp)
Hidenori HINO (hino@ansl.ntt.co.jp)

NIPPON TELEGRAPH AND TELEPHONE CORPORATION
Access Network Service Systems Laboratories

1-7-1 Hanabatake, Tsukuba-city, Ibaraki, 305-0805, JAPAN

Abstract: To realize the all NO-DIG (trenchless method) operation of conduit installation, NTT developed the microtunneling method “ACEMOLE” allowing long-distance and curved installations and promoted use of this method. NO-DIG method is not widespread in construction works because its construction cost is not economically compared with open-cut method. We developed new ACEMOLE to solve these problems drastically and realize NO-DIG entirely. Especially position-detection system using fiber-optic gyroscope and intelligent driving control system using optimum control theory make possible to control microtunneling machines accurately without operators skills and to disseminate NO-DIG technology smoothly.

Keywords: NO-DIG(trenchless method), microtunneling robot, fiber optic gyroscope, directional control, Kalman filter

1 Introduction

NTT has independently developed and promoted the microtunneling robot ‘ACEMOLE’ as a technology for laying electronic communications conduits. The application of the ACEMOLE has expanded to take in other pipe and conduit-laying operations, such as water and sewage pipes and electric power cables. This technology has now laid 677 km of conduit, but costs are high, numerous technological problems have been encountered and the level of NO-DIG operations have reached their limit. Cost reduction is the major prerequisite for increasing the application of this NO-DIG method. Another important agenda is the improvement of microtunneling machine position detection and control technology, to enable flexible response to varying road shapes, operation in areas with a high concentration of underground facilities and high-accuracy long-distance and curved route driving. Accurate control of the microtunneling machine requires a system which accurately monitors the position and posture of the machine, predicts changes in driving status and machine behavior with changes in external conditions, and determines control guidelines on the basis of an overall judgment of status. However, depending on the form of the route being driven and the driving distance, there are certain restrictions on present position detection technologies. Problems may occur with the accuracy and continuity of measurements, or measurements may not be able to be taken in real time. In addition, human error on the part of the operator or the application of control with an inaccurate understanding of changes in external conditions can cause trouble, and this trouble can spread without being corrected. It is necessary to prevent or reduce the occurrence of trouble originating in human error and external factors to achieve the smooth spread of NO-DIG method.

NTT has therefore developed continuous high-precision position detection system to enable real time position detection without restrictions over the entire driving course and driving distance using optic fiber gyroscopes. In addition, to further prevent the occurrence of trouble and enable higher-accuracy execution, an Auto-navigation system has also been developed. The introduction of these technologies enables inexperienced operators to control the microtunneling machine at the same level as experienced operators, prevents the occurrence of various types of trouble which have occurred in execution up to the present, and has improved the accuracy and efficiency of driving operations. This paper will give an outline of the overall makeup of the ACEMOLE system, and will then discuss the high-precision continuous position detection system. After this, the makeup and component technologies of the Auto-navigation system will be discussed. The paper will conclude with a discussion of the results of test operations.

2 Auto-navigation System

2.1 Outline of ACEMOLE System

Fig. 1 shows the entire system configuration of the microtunneling ACEMOLE robot controlled by the system described in this paper. The ACEMOLE system shown here uses dynamic press-insertion, in which vibration of the front of the microtunneling machine liquefies the surrounding soil face to reduce face resistance and the machine advances under thrust provided by jacking machine. This system lays pipes of a fixed length in succession. The machine's driving direction is controlled by an inbuilt hydraulic jack, which moves the front of the machine head up and down and left and right.

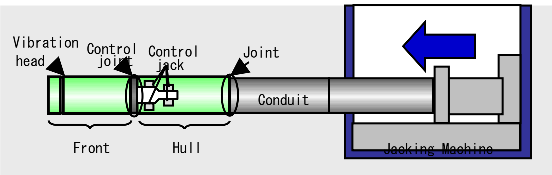

Figure 1: Schematic of a microtunneling robot

2.2 Position Detection System

Fig. 2 shows the horizontal and vertical position detection systems. Up to the present, horizontal position detection has relied on a laser target system: a laser beam produced by a laser theodolite is detected by a light-sensitive target in the microtunneling machine, and the displacement of that beam from the base line (laser beam) is determined. An Electromagnetic method is also used, in which receivers above ground detect a magnetic field induced by a transmission coil built into the microtunneling machine, enabling the machine's absolute position to be determined. However, the laser targeting method can only be used over straight sections, and the magnetic method used on curved routes requires the operator to stop driving in order to take above ground measurements, resulting in discontinuous position data. The magnetic method also cannot be used near magnetic bodies, under riverbeds, etc. An optic fiber gyroscope system was developed to provide a solution to these problems. Vertical position is detected using a Hydraulic pressure differential method enabling relative depth to be detected in real time, using the difference between a standard liquid pressure and the pressure detected by a pressure sensor in the microtunneling machine.

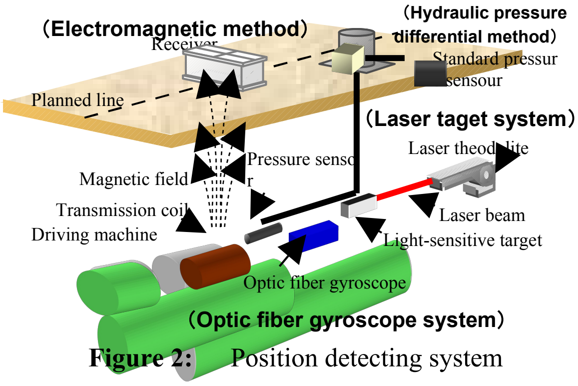

Figure 2: Position detecting system

2.3 Outline of Optic Fiber Gyroscape System

Optic fiber gyroscopes have a broad range of application, but are chiefly utilized in the inertial measurement of direction and posture in space and the measurement and control of rotation. These gyroscopes were utilized in a newly developed system for microtunneling machine position detection as a means of solving the problems delineated above. Optic fiber gyroscopes continuously detect the angular velocity of a moving body. relative change in the angle can be found by integrating the angular velocity, and therefore the horizontal position of the machine can be continuously calculated from the driving distance using the starting point of driving as a base. Horizontal position y is found using the following equation, where Ω is angular velocity and x is driving distance:

$$y(x) = \int_x \int_t \Omega \, dtdx \qquad (1)$$

Below is a simple discussion of the Sagnac effect (the principle of measurement with optic fiber gyroscopes). We will consider the optic system shown in Fig. 3. The beam of light produced by the light source is split into left and right beams by a beam splitter. These beams then enter circular optic fiber loops. After being propagated through these loops, the beams are reintegrated at the same beam splitter. If the loops have remained still, the left and right beams will have traveled a path of exactly the same distance, and the time required for the beams to arrive at the beam splitter will be the same. However, if the optic fiber loops are rotated in one direction at angular velocity Ω , then the distance traveled by the two beams will differ, and there will be a difference in propagation times. This time differential is expressed as

$$\Delta t = \frac{2rL}{c^2}\Omega$$

where L is the length of the fiber, r is the radius of the fiber, and c is the speed of light.

(2)

The time differential Δt for propagation of the left and right beams is proportional to the angular velocity of the rotation of the optic fiber loops, Ω . Calculation of angular velocity utilizes the fact that the propagation time differential for the left and right optic fiber loops Δt found in equation (2) becomes $\Delta \theta$, the phase difference between the left and right beams, as shown in equation (3).

$$\begin{aligned}\Delta \theta &= \omega \Delta t = (2\pi / \lambda) c \Delta t \\ &= \frac{4\pi rL}{c\lambda}\Omega \qquad (3)\end{aligned}$$

Here, ω is the angular frequency of the light source.

Utilizing equation (3) to find phase difference $\Delta \theta$ enables the rotational angular velocity Ω of the fiber optic loop to be determined. In addition to the use of angular velocity Ω when calculating horizontal position, this parameter is also used as important machine posture data in the Auto-navigation system described in the next section.

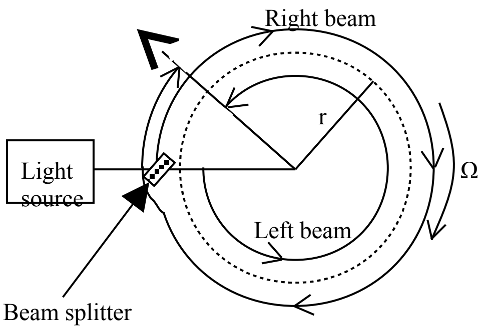

Figure 3: Principle of Sagnac effect

2.4 Outline of Auto-navigation System

The Auto-navigation system detects the machine’s position and posture, predicts behavior and provides control. Fig. 4 shows an image from the Auto-navigation system screen. The screen shows 0 m for both horizontal and vertical position. On the left (the negative side), we see data detected to present and values predicted on the basis of the machine behavior model (to be discussed in the next section). On the right (the positive side), we see the optimum value of correction of machine direction to be applied based on model parameters estimated to present, and results of a simulation of machine displacement in response to this correction.

Accurate detection of microtunneling machine position and posture are essential for directional control of the ACEMOLE. This is an important element in the application of control and has an effect on driving accuracy. The optic fiber gyroscope system described in Section 2.3 is able to gather high-precision position data in real time; conditions in the machine behavior model can therefore be accurately estimated online, and the optimal value of control can be determined by feedback of these conditions, enabling high-accuracy directional control.

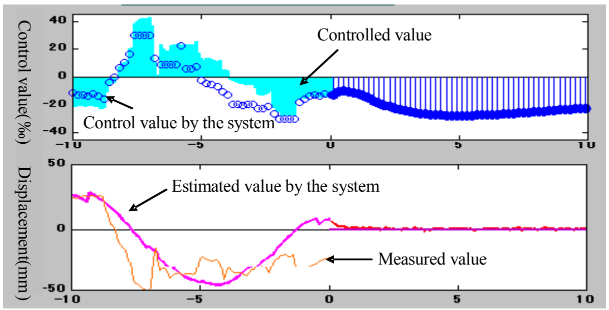

Figure 4: Screen shot

2.5 Machine Behavior Model

Because horizontal and vertical motion is independent and mutual interference does not occur, models of each direction have been designed. Because the characteristics of the machine's motion in the horizontal and vertical directions can be expressed in identical behavior models, this model will be explained using Fig. 5, which defines machine position and posture in relation to the microtunneling machine base line.

Changes in machine posture ($\Delta\theta$) are defined by the linear sum of noise components which are unrelated to past head angle (including current head angle) and directional control. This can be expressed as follows:

$$\theta[k+1] = \theta[k] + \sum_{i=0}^{nb-1} b_i \eta[k+1-i] + \omega[k] \qquad (4)$$

Here, k is the positive increase in unit driving length L_p for each length driven, $\eta[k+1-i]$ is L_p*i(m), value of past directional control conducted before the present, b_i is the weighting factor for value of directional control, and ω represents noise components.

If the angle of the rear of the microtunneling machine as measured against the base line is taken as following the angle of the front of the microtunneling machine at L_f(m) only, it can be expressed as the following:

$$\theta_r[k] = \theta[k - nd] \qquad (5)$$

where nd is L_f/L_p rounded to a whole number. The change in displacement X_h of the section of the microtunneling machine receiving directional control for each driving length can be expressed

$$X_h[k+1] = X_h[k] + L_p\theta[k] \qquad (6)$$

Until now, it has been impossible to directly detect θ in the horizontal direction and it has been necessary to use a kalman filter adapted to the machine posture model given as equation (4) and the position and posture detection method being used to estimate X_h and b_i from equation (4). However, because the optic fiber gyroscope system has enabled direct detection, it has now become possible to construct a more accurate model.

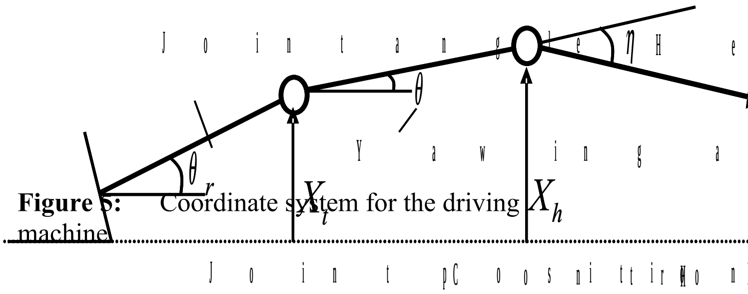

Figure 5: Coordinate system for the driving machine

2.6 Optimum Feedback Control

We will now consider directional control conducted using the equations described above. Equations (4), (5) and (6) are used to newly define the posture vector X.

$$X[k] = \begin{bmatrix} \theta[k] \\ \theta[k-1] \\ \vdots \\ \theta[k-nd] \\ \cdots\cdots\cdots \\ \eta[k-1] \\ \vdots \\ \eta[k-nb+1] \end{bmatrix} \qquad (7)$$

nb in equation (7) is an integer greater than 2. Next, a feedback gain K which satisfies equation (8) is sought.

$$\eta[k+1] = \eta[k] - \boldsymbol{KX}[k] \qquad (8)$$

K is designed on the basis of the principle of harmonizing speed of convergence with value of correction. This has made it possible to closely control the progress of the microtunneling machine underground, and to rapidly correct deviations from the base line.

2.7 Auto-navigation System Flow

Fig. 6 shows the composition of the Auto-navigation system. The utilization of a model of microtunneling machine behavior (Fm) which expresses the value of directional control η (k) and the motion characteristics of the microtunneling machine in response to changes in position and posture mean that current machine status can be estimated online. Feedback of these estimates enables the optimal directional correction controller (K) to calculate the value of correction η (k+1) to be applied next. This online estimation enables the appropriate value of control to be exerted to maintain the microtunneling machine head on the planned line in response to current position and posture, surrounding soil quality, etc., and future machine status to be predicted.

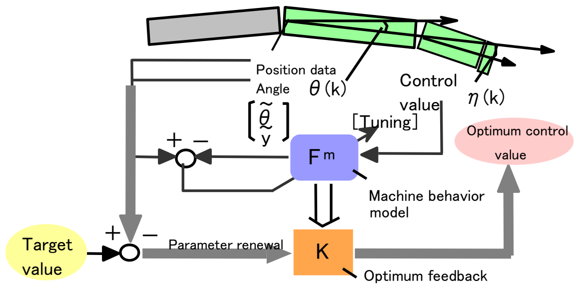

Figure 6: Composition of Auto-navigation system

3 Test Results

To verify the effectiveness of the system, proving trials were conducted using an actual machine. The machine was placed in a homogeneous stratum of 3 m in width and 40 m in length, and driving commenced from a depth of 2 m. Figs. 7 and 8 show actually measured values and values estimated by the system for horizontal and vertical directions respectively. The horizontal axes show data sampled at L_p = 10 cm.

Values predicted by the system are compared with values measured in the horizontal direction using the magnetic method (capable of measuring absolute position in this direction) and in the vertical direction by the liquid pressure differential method. The results of directional control conducted on the basis of optimum values calculated by the system showed less than ± 30mm difference between values predicted by the system and actually measured values, proving the effectiveness of the model and the algorithm.

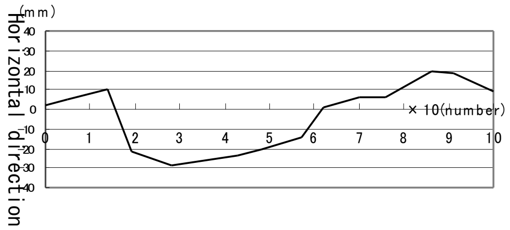

Figure 7: Values estimated by the system and measured values by electromagnetic method

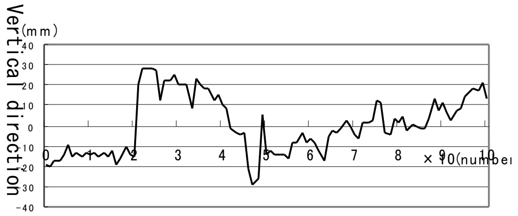

Figure 8: Values estimated by the system and measured values by Hydraulic differential method

4 Conclusions

A high-accuracy Auto-navigation system has been developed for conduit microtunneling machines using the dynamic press-insertion method. The system utilizes a machine behavior model which displays motion characteristics in response to correction of microtunneling machine direction. This has enabled optimal feedback control based on the model and estimates of position and posture of the microtunneling machine, both of which are difficult to directly monitor. Use of an optic fiber gyroscope for horizontal position and posture detection has enabled estimates of machine status to be made at a higher level of accuracy. The introduction of this system has increased the efficiency of execution management and optimized driving control, leading to the following benefits:

(1) Homogeneous and high-accuracy execution is possible irrespective of the level of experience and skill of the operator.

(2) Rapid and accurate driving control has increased the level of driving efficiency achieved to date.

(3) The problem of shortage of skilled operators has been solved, and the period and costs required to train operators have

been reduced.
(4) These results will aid in the diffusion of NO-DIG method.

The results reported in this paper have demonstrated the effectiveness of the newly developed technology. To increase the spread of NO-DIG method in the future, it will be essential to continue to improve the technology in this way. These technologies have been developed for the ACEMOLE system, but the broad applicability and potential for future development of the system mean that we can expect that it will be possible to construct similar systems reflecting machine characteristics for other driving methods.

5 REFFERENCES

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