Decision Process of a Control Limit for Micro-tunnelling Robots

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ABSTRACT

In this paper, we derive a procedure to design a control limit for Micro-tunnelling Robots. The main problem to design the control limit is that the relation between the trajectory of the Micro-tunnelling Robot and the work quality is unknown. We accordingly make a mathematical model for simulation experiment to know the relation. From the simulation experiment and real data, we can get that the work quality is better than the trajectory of the Micro-tunnelling Robot. The relation is that the work quality is better than the trajectory of the Micro-tunnelling Robot. Finally, we propose a procedure to design the control limit for the Micro-tunnelling Robot.

1 Introduction

The number of research and development and construction works of Construction Robots has increased nowadays. This situation is due to continuous effort of researchers. Furthermore the accuracy of Construction Robot's work comes to adapt to inspection criteria. This reason is as follows. The ability of control devices becomes high owing to the development of control computer system and its application software. The application software is depend on inspection criteria. This implies that the first thing to do is to set a control limit. It is easy to decide the control limit if the relation between the action of the Construction Robot and the work quality is clear.

Let us consider an example of this. The work quality is almost equal to the trajectory of the blade when we use a dozer. This implicitly indicates that the control limit is set less than inspection criteria for dozer's works.

On the other hand, it is not easy to decide the control limit for Micro-tunnelling Robots. There are two reason of this. One reason is that there does not exist a common inspection criterion. Another reason is that the relation between the work quality and the trajectory of The Micro-tunnelling Robot is not clear.

In this paper, the author reports the way to decide the control limit for Micro-tunnelling Robots.

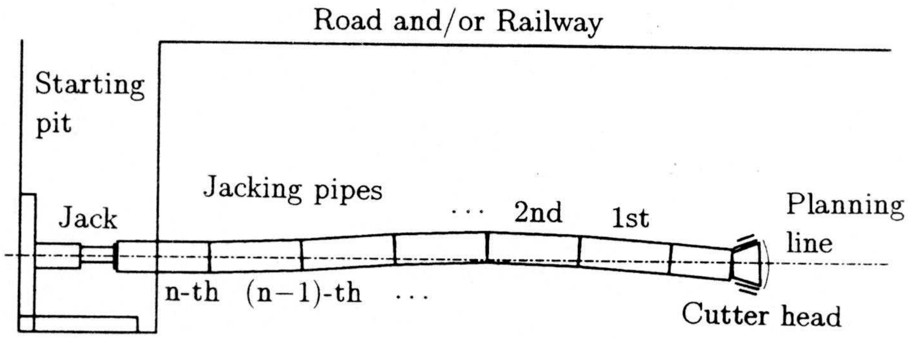

Fig.1. An illustration of the micro-tunnelling system.

Table 1. The result of questionnaires about the criterion for the work quality with Micro-tunnelling Robots

		∼ 20[mm]	∼ 30[mm]	∼ 50[mm]	51[mm]∼	None or Otherwise
Vertical	Control limit	45%	24%	15%	0%	16%
	Allowable error	1%	9%	38%	0%	52%
Horizontal	Control limit	44%	24%	16%	0%	16%
	Allowable error	0%	5%	10%	24%	61%

By the way, an illustration of the Micro-tunnelling Robot is shown in Fig.1. The Micro-tunneling Robot installs a pipeline, when we install the pipeline without cutting over the road. The jacks push into the Micro-tunnelling Robot with jacking pipes into the ground from a starting pit.

This paper consists of three points. Firstly, the author sets a temporary inspection criterion from a fact-finding. A mathematical model described by a stochastic differential equation is derived from a balance of forces and geometrical relations of the Micro-tunnelling Robot and installed pipes secondly [1)]. Finally, the relation between the trajectory of the Micro-tunnelling Robot and the work quality is obtained by a simulation experiment with the mathematical model and real data.

2 Inspection Criteria

In 1988, Public Works Research Institute, Ministry of Construction, obtained information through a questionnaire. The questionnaire was send to 140 cities and all construction companies and makers who made and/or used Micro-tunnelling machines.

Results of the questionnaire are shown in Table 1 and Table 2. From these tables, we can get the following conclusions.

Table 2. The result of questionnaires about the object of Micro-tunnelling Robots

	Number of construction works	Construction length [m]
Sewerage pipelines	3022 (90.4%)	521270 (96.8%)
Otherwise	321 (9.6%)	1750 (3.2%)

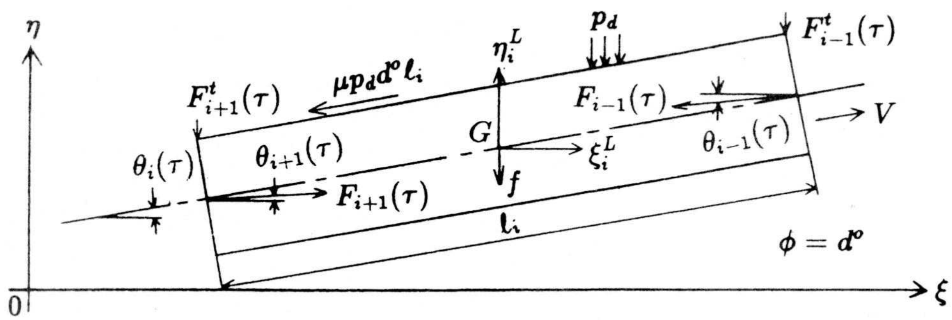

Fig.2. Geometry and force balance of the ith jacking pipe.

1. Control limits are smaller than allowable errors.
2. Construction works almost pass inspections if the pipeline's deviation from the planning line is less than 30[mm] of vertical and less than 50[mm] of horizontal.
3. Micro-tunnelling Robots are almost used to install sewerage pipelines.

We set temporary inspection criteria to ± 30[mm] of vertical and ± 50[mm] of horizontal in consequence of conclusions.

3 Mathematical Model

From Table 2, we consider the only vertical direction. This is because the accuracy of the vertical direction is more important than that of the horizontal direction for sewerage pipelines.

Now, we set the following assumptions to derive a mathematical model which describes motions of the Micro-tunnelling Robot and jacking pipes.

Assumption 3.1 *The motion of the Micro-tunneling Robot and jacking pipes are limited to the vertical plane.*

Assumption 3.2 *Assume the damping modulus and the spring modulus of are constant, i.e.,*

$$D = \text{const.}, \quad K_S = \text{const.} \tag{1}$$

where τ is the time, ξ and η are global axes, and the pushed pipes are regarded as the rigid bodies.

Assumption 3.3 *Assume* $\theta_i(\tau)$ $(i=1,2,\cdots,n)$ *are sufficiently small, i.e.,*

$$\sin\theta_i(\tau) \cong \theta_i(\tau)\ ,\quad \cos\theta_i(\tau) \cong 1$$

Now, we put vectors $z(i,\tau)$ and $z_n(\tau)$ as follows.

$$z(i,\tau) \triangleq \left[\theta_i(\tau), \dot{\theta}_i(\tau), \eta_i(\tau), \dot{\eta}_i(\tau), \frac{K_S V}{m_i}\int_{t_n}^{\tau}\theta_i(s)ds + \frac{K_S}{m_i}\eta_i(t_n) - \frac{f}{m_i}\right]' \quad (i=0,1,\cdots,n) \tag{2}$$

$$z_n(\tau) \triangleq [z'(0,\tau), z'(1,\tau), \cdots, z'(n,\tau)]' \tag{3}$$

Then we obtain the following differential equation owing to assumptions 3.2 and 3.3.

$$\left.\begin{array}{rcl} \dot{z}_n(\tau) &=& \mathcal{A}_n(\tau) z_n(\tau) \\ z_n(t_n) &=& z_{nt_n} \qquad (t_n \le \tau \le T_n) \end{array}\right\} \tag{4}$$

where t_n and T_n are start time and finish time of jacking the n-th pipe respectively. Moreover the system matrix $\mathcal{A}_n(\tau)$ is described by

$$\mathcal{A}_n(\tau) = \begin{bmatrix} B_0(\tau) & C_0(\tau) & 0 & \cdots & 0 \\ A_1(\tau) & B_1(\tau) & C_1(\tau) & & \\ 0 & A_2(\tau) & B_2(\tau) & & \vdots \\ & & & \ddots & \\ & & \vdots & B_{n-1}(\tau) & C_{n-1}(\tau) \\ 0 & & \cdots & A_n(\tau) & B_n(\tau) \end{bmatrix}$$

where

$$A_i(\tau) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -\frac{\ell_i}{2I_i}\left\{F_{i-1}(\tau) + \frac{\ell_{i-1}}{2}K_J\right\} & 0 & \frac{\ell_i}{2I_i}K_J & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{m_i}\left\{F_{i-1}(\tau) + \frac{\ell_{i-1}}{2}K_J\right\} & 0 & \frac{K_J}{m_i} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B_i(\tau) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ B_i^1(\tau) & -\frac{\ell_i^2}{4I_i}D & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ B_i^2 & V & B_i^3 & -\frac{D}{m_i} & 1 \\ \frac{K_S V}{m_i} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C_i(\tau) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -\frac{\ell_i}{2I_i}\left\{F_{i+1}(\tau) + \frac{\ell_{i+1}}{2}K_J\right\} & 0 & -\frac{\ell_i}{2I_i}K_J & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{1}{m_i}\left\{F_{i+1}(\tau) + \frac{\ell_{i+1}}{2}K_J\right\} & 0 & \frac{K_J}{m_i} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and where

$$B_i^1(\tau) = \begin{cases} \dfrac{\ell_0}{2I_0}\left\{F_1(\tau) - \dfrac{\ell_0}{2}K_J - \dfrac{\ell_0}{2}K_S\right\} \\ \dfrac{\ell_i}{2I_i}\left\{F_{i-1}(\tau) + F_{i+1}(\tau) - \ell_i K_J - \dfrac{\ell_i}{2}K_S\right\} \quad (i = 1, 2, \ldots, n) \end{cases}$$

$$B_i^2 = \begin{cases} \dfrac{1}{m_0}\left\{DV - \mu p_d d^o \ell_0 - F_0 + \dfrac{K_J \ell_0}{2}\right\} \\ \dfrac{1}{m_i}\{DV - \mu p_d d^o \ell_i\} \qquad (i = 1, 2, \ldots, n) \end{cases}$$

$$B_i^3 = \begin{cases} -\dfrac{1}{m_0}\{K_J + K_S\} \\ -\dfrac{1}{m_i}\{2K_J + K_S\} \quad (i = 1, 2, \ldots, n) \end{cases}$$

Besides these equations and in Fig.2, $\theta_\bullet(\tau)$, $\eta_\bullet(\tau)$, D, K_S, K_J, $\ell_\bullet$, $I_\bullet$, μ, p_d, d^o, $F_\bullet(\tau)$, $F_\bullet^t(\tau)$ and f are the argument from the planning line, the displacement from the planning line, the damping modulus of the soil, the spring modulus of pipes' connectors, the length of pipes, the pipe's moment of inertia, the friction modulus between the pipe and soil, the pressure from the soil, the outer diameter of the pipe, the forth caused by the dislocation between ith pipe and $\bullet$th pipe and the external force respectively.

Moreover, n, " $\dot{}$ ", " $\ddot{}$ " and "t" imply the number of jacking pipes, $d/d\tau$, $d^2/d\tau^2$ and transportation respectively.

3.1 System Dynamics

As the Micro-tunnelling Robot needs the steering control action, we add the control signal $C^u(\tau)u(\tau)$ to the system described by eq.(4). Then we have the system dynamics with the control signal as follows

$$\left.\begin{aligned} \dot{z}_n(\tau) &= \mathcal{A}_n(\tau)z_n(\tau) + C^u(\tau)u(\tau) \\ z_n(t_n) &= z_{nt_n} \qquad (t_n \le \tau \le T_n) \ . \end{aligned}\right\} \tag{5}$$

where $C^u(\tau)$ is $5(n+1) \times 4$ dimensional matrix and $u(\tau)$ is 4 dimensional vector.

3.2 Time Invariant Model

By the way, (5) is the time variant model why the force of $F_{n+1}(\tau)$ is the function of the time τ. This can be understood in the following equations[2].

$$F_i(\tau) = \sum_{k=0}^{i} \mu p_d d^o \ell_k + F_0 \tag{6}$$

$$\begin{aligned} F_{n+1}(\tau) &= \mu p_d d^o \int_{t_n}^{\tau} V ds + \sum_{k=0}^{n} \mu p_d d^o \ell_k + F_0 \\ &= \mu p_d d^o V(\tau - t_n) + F_n \end{aligned} \tag{7}$$

If we set an approximation as

$$F_{n+1}(\tau) \cong F_{n+1}\left(\frac{T_n + t_n}{2}\right) \tag{8}$$

then the approximation error becomes as follows.

$$\begin{aligned} \Delta_\theta &= \sup_{\tau\in[t_n,T_n]} \frac{\ell_n}{2I_n} \left| \left[F_{n+1}(\tau) - F_{n+1}\left(\frac{T_n + t_n}{2}\right) \right] \theta_n(\tau) \right| \\ &= 108.8 \sup_{\tau\in[t_n,T_n]} |\theta_n(\tau)| \end{aligned} \tag{9}$$

Now, we regard the approximation error as a system noise which adds (5) as a White Noise.

So, we set $C^u(\tau) = \widehat{C}^u$ and $\mathcal{A}_n(\tau) \cong \mathcal{A}_n\left(\frac{T_n+t_n}{2}\right) \triangleq \widehat{\mathcal{A}}_n$ then we have the following system dynamics which a time invariant model.

$$\left. \begin{aligned} dz_n(\tau) &= \widehat{\mathcal{A}}_n z_n(\tau)d\tau + \widehat{C}^u u(\tau)d\tau + \widehat{G}_n dw(\tau) \\ z_n(t_n) &= z_{nt_n} \qquad (t_n \le \tau \le T_n) \end{aligned} \right\} \tag{10}$$

where $\widehat{G}_n$ is $5(n+1) \times 5(n+1)$ dimensional matrix and $w(\tau)$ is 4 dimensional standard Wiener process.

This formulation is a standard tactics in the Stochastic System Theory [3) 4)].

3.3 Identification of the Approximation Error

We must identify the approximation error of Δ_θ. In this paper, we set next demand of the work quality.

- The pipe's deviation from the planning line is almost smaller than 30[mm]. Moreover the probability is 99%.

This demand is that the construction work by Micro-tunnelling Robots almost passes the inspection with criteria set in this paper.

From this consideration, we can identify the approximation error covariance of Δ_θ as follows.

$$\mathrm{cov}[\Delta_\theta] = 108.8 \times \arcsin\left(\frac{60[\mathrm{mm}]}{2400[\mathrm{mm}]}\right) \div 3 \cong 0.9$$

3.4 Observation Mechanisms

We can have the information of the Micro-tunnelling Robot's state directly. However there exit some observation errors and the observation noise at the real observation system.

Then the observation mechanism is formulated as

$$\left. \begin{aligned} dy(\tau) &= Hz_n(\tau)d\tau + Rdv(\tau) \\ y(t_n) &= 0 \qquad (t_n \le \tau \le T_n) \end{aligned} \right\} \tag{11}$$

where $y(\tau)$ is 4 dimensional vector, H is $4 \times 5(n+1)$ dimensional matrix, R is 4×4 dimensional matrix and $v(\tau)$ is 4 dimensional standard Wiener process.

4 Estimation and Control

4.1 Estimation Mechanisms

We can obtain the following estimator whose form is the *Kalman Filter* [5) 6) 7)].

$$\left.\begin{array}{rcl} d\widehat{z}_n(\tau) & = & \widehat{\mathcal{A}}_n\widehat{z}_n(\tau)d\tau + \widehat{C}^u u(\tau)d\tau + PH'(RR')^{-1}\{dy(\tau) - H\widehat{z}_n(\tau)d\tau\} \\ \widehat{z}_n(t_n) & = & \mathcal{E}\{z_n(t_n)\} \qquad (t_n \leq \tau \leq T_n) \end{array}\right\} \tag{12}$$

where $\mathcal{E}\{\bullet\}$ is an expectation operator and P is a positive definite solution of the following Riccati equation.

$$\widehat{\mathcal{A}}_n P + P\widehat{\mathcal{A}}_n' + \widehat{G}_n\widehat{G}_n' - PH'(RR')^{-1}HP = 0 \tag{13}$$

4.2 Optimal Control

There are many control strategies of the PID control, the Bang-Bang control, the Optimal control, the Fuzzy control [8) 9)] and so on. In this paper, we choose the optimal control technology, because this technology is familiar with the *Kalman Filter* and has the history of researches [9) 4)].

First of all, we set a control criterion in order to find the optimal control signal. We accordingly set the control criterion as follows.

$$J_n(u) := \mathcal{E}\left\{\int_{t_n}^{T_n}[z_n'(\tau)Mz_n(\tau) + u'(\tau)Nu(\tau)]d\tau\right\} \tag{14}$$

where M and N are symmetric and positive definite matrices which are usually diagonal matrices and whose dimensions are $5(n+1)\times 5(n+1)$ and 4×4 respectively.

We must calculate a Riccati differential equation if we use the control criterion as (14). We consequently set $T_n \to \infty$ in (14) in order to reduce the calculation duty [7)]. So we obtain the following algorithm to get an optimal control signal $u^o(\tau)$ with respect to $\min_u J_n(u)$.

The algorithm to calculate the optimal control signal is as follows.

$$u^o(\tau) = -N^{-1}\widehat{C}^{u\prime}\Pi\widehat{z}_n(\tau) \tag{15}$$

where Π is a positive definite solution of the following Riccati equation.

$$\widehat{\mathcal{A}}_n'\Pi + \Pi\widehat{\mathcal{A}}_n + M - \Pi\widehat{C}^u N^{-1}\widehat{C}^{u\prime}\Pi = 0 \tag{16}$$

5 Experiments

5.1 Simulation Experiments

We would like to show a set of given and calculated parameters in Table 3 in case of the pipes' inner diameter to be 700[mm] [5) 6)].

$$\widehat{\mathcal{A}}_n := \mathcal{A}_n\left(\frac{T_n + t_n}{2}\right),\ \widehat{C}^u := \begin{bmatrix} I_4 & 0_{4\times(5n+1)}\end{bmatrix}',\ H := \begin{bmatrix} I_4 & 0_{4\times(5n+1)}\end{bmatrix},\ N := I_4,$$

Table 3. Given condition and parameters

ℓ_i[m]	m_i[kg]	d^o[m]	I_i[kg·m^2]	Soil type	N number	μ
2.4	1100	0.85	540	Sand	25	0.3
Depth[m]	D[N·s·m^{-1}]	K_S[N·m^{-1}]	K_J[N·m^{-1}]	p_d[N·m^{-2}]	F_0[N]	V[m·s^{-1}]
10	6.2×10^2	1.4×10^5	7.0×10^5	1.6×10^5	2.6×10^5	2.0×10^{-3}

$$\widehat{G}_n := \mathrm{diag}\{\overbrace{0, 0, \cdots, 0}^{5n+1}, \mathrm{cov}[\Delta_\theta], 0, 0, 0\} = \mathrm{diag}\{\overbrace{0, 0, \cdots, 0}^{5n+1}, 0.9, 0, 0, 0\},$$

$$M := \mathrm{diag}\{\overbrace{M_w, M_w, \cdots, M_w}^{n+1}\},\ M_w := [100, 900, 100, 900, 1],\ I_4 := \mathrm{diag}\{1, 1, 1, 1\}$$

The result of the simulation experiment is shown in Fig.3.

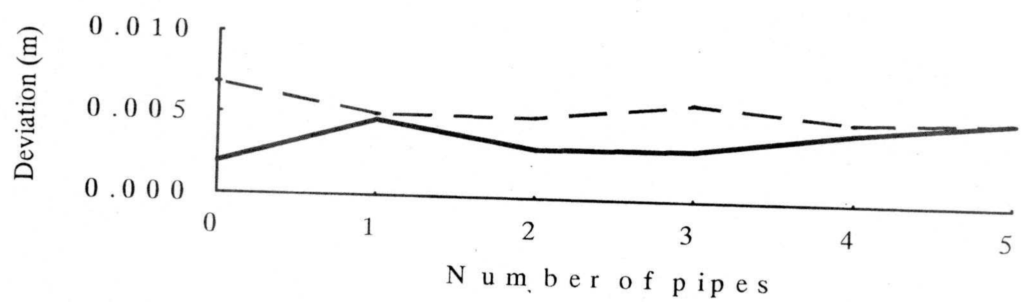

Fig.3. The simulation experiment of the relation between the work quality and the trajectory of the Micro-tunnelling Robot. The solid line is the work quality and the broken line is the trajectory of the Micro-tunnelling Robot.

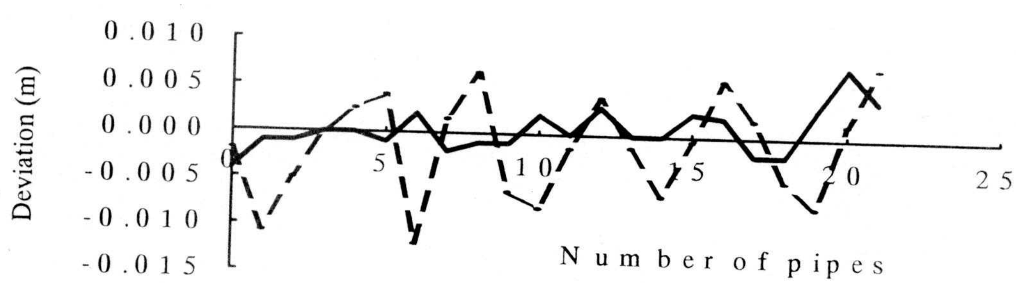

Fig.4. Real data of a construction work. The solid line is the work quality and the broken line is the trajectory the Micro-tunnelling Robot.

5.2 Real Data

In this section, we show real data in order to give the result of the simulation experiment a propriety. The real data are obtained as follows.

Place: Iwate prefecture in Japan.

Conditions: The same as the simulation experiment.

Measuring: The Laser measuring system.

Controller: The common Fuzzy controller for Micro-tunnelling Robots[9].

Control limit: The deviation is smaller than 30[mm].

From real data which are shown in Fig.4, we can obtain that the result of the simulation experiment has the propriety.

6 Conclusions

From Fig.3, we can see that the deviation of the work quality is smaller than that of the trajectory of the Micro-tunnelling Robot. The conclusion of this is that the work quality is better than the trajectory of the Micro-tunnelling Robot. This result from simulation experiment is supported by the real data shown in Fig.4.

From the result of simulation experiments and real data, we can get the following procedure to design a control limit of the Micro-tunnelling Robot.

Step 1: We research inspection criteria. If there does not exist any inspection criterion, then we set 30[mm] of vertical and 50[mm] of horizontal to inspection criteria.

Step 2: We make a simulation experiment for the objective construction condition. When we make the simulation experiment, we set the value of the inspection criterion to a temporary control limit.

Step 3: We confirm that the work quality is better than the trajectory of the Micro-tunnelling Robot.

Step 4: If the work quality is better than the trajectory of the Micro-tunnelling Robot at the simulation experiment, then we set the temporary control limit to a regular control limit for the Micro-tunnelling Robot.

Step 5: If the work quality is not better than the trajectory of the Micro-tunnelling Robot at the simulation experiment, then we try simulation experiments with other temporary control limits again. And we go to the Step 3.

We can use this procedure to design the control limit for any Construction Robot. This is because that most Construction Robots have the relation between the trajectory of them and the work quality.

By the way, real data give the propriety to the simulation experiment. This implies that the mathematical model appeared in this paper is proper. So, we can use this model as a standard model like the standard model of shield tunneling machine[10) 11)].

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