Automation and Robotics in Construction X
G.H. Watson, R.L. Tucker and J.K. Walters (Editors)

Research on Components of Underground Excavation Robot

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Abstract

This paper describes the basic research for an underground excavation robot. This robot consists of three system components: the manipulation system, the locomotion system, and the task planning system. In order to keep the operator away from the hazardous worksite, the task should be performed through teleoperation or performed autonomously. Two different teleoperation systems using parallel link manipulators have been built for this purpose. A locomotion system has been proposed, consisting of a mobile platform supported by a pair of crawlers and four legs. A hierarchical control system with one host computer and nine transputers has also been developed. For excavation task planning, a measuring method using tactile sensor data has been proposed. With this method the shape and stiffness of the target soil is determined from force and position data. These soil characteristics are passed to a cutting model of the soil and optimal parameters of excavation are estimated.

1. INTRODUCTION

This research is being conducted as part of a national research and development program on underground space development technology, which was started in 1989 by the Japanese Ministry of International Trade and Technology. Our research addresses the three systems that will comprise the underground excavation robot. In section 2, the manipulation system is described. In section 3, the locomotion system is described. In section 4, the task planning system is discussed. Results are summarized in section 5.

2. MANIPULATION SYSTEM

We have developed a parallel manipulator for excavation. The manipulator was designed to provide uniform force production capability based on a static mechanism analysis. For underground dome excavation the robot will operate either in teleoperation mode or in autonomous mode. While the robot may work autonomously for routine tasks, it should be controlled by a teleoperator in non-routine tasks, for example, when it confronts unexpected and emergent events, or in the process of searching and modeling its environment. The master-slave control technique is well known for refined teleoperation in which a human operator may command the robot simply and dexterously. If we, in addition, feed back reaction forces to the operator, this constitutes a bilateral system and the teleoperation task may be executed more smoothly. Sometimes it is preferable that the robot is capable of working in both teleoperation and autonomous modes, and is capable of switching between modes with no specific control command.

We have proposed and developed two kinds of teleoperation techniques for the excavation task. One is a bilateral master-slave system using a parallel link master. The other is joystick teleoperation enabling the robot to work in either or in both autonomous and teleoperation mode.

In the bilateral system, the master and the slave arms have the same configuration, but differ in size. This fact brings the problem that a translational motion and an orientational motion can not be preserved at the same time if the direct link servo method is introduced. For

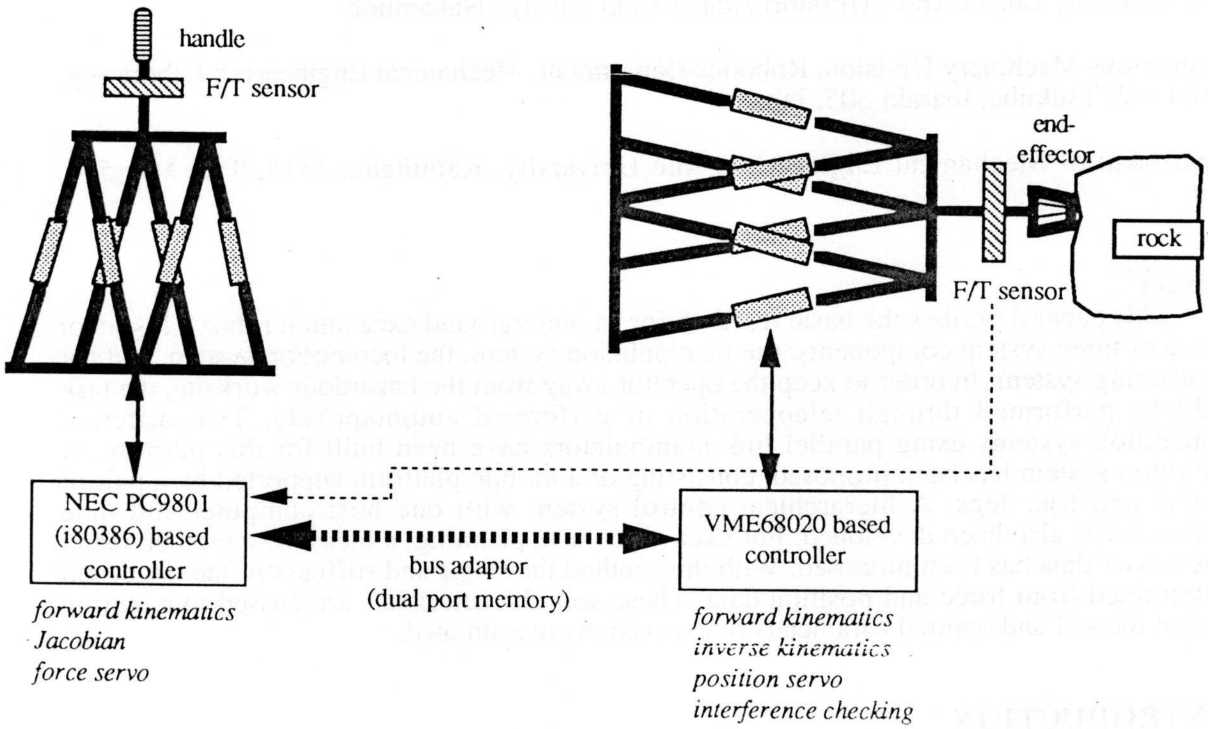

Figure 1. System configuration of bilateral teleoperation system.

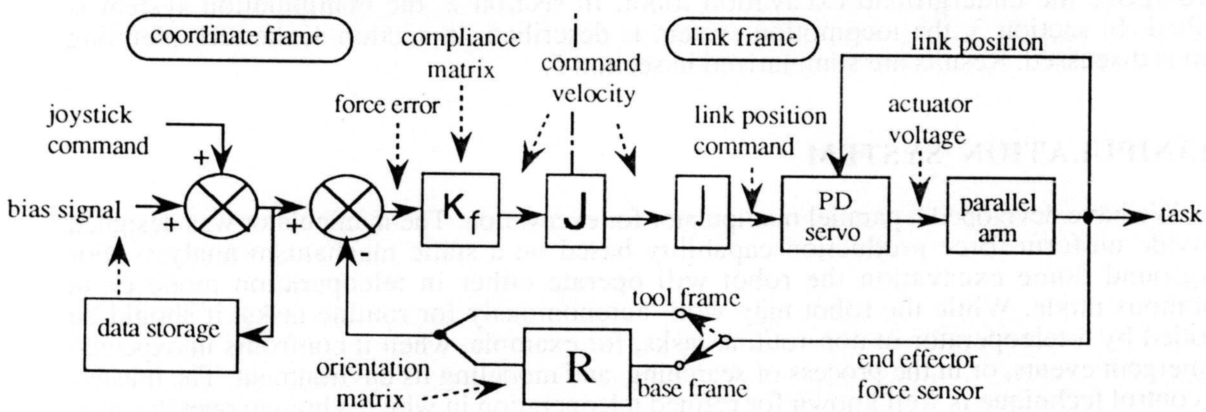

Figure 2. Block diagram of the joystick teleoperation system.

serial manipulators, kinematically dissimilar bilateral master-slave systems have been proposed to realize general bilateral master-slave systems that consists of any kind of master and slave manipulators. In order to solve the present problem, the same concepts can be applied to the parallel manipulator system. Figure 1 shows the configuration of the overall system.

The joystick teleoperation system is proposed based on the following design concept: (i) capable of working both in base and in end effector coordinates, (ii) capable of moving based on rate control without interference from the environment, (iii) capable of working based on hybrid control with interference, (iv) capable of commanding complete 6 DOF motion from the joystick, (v) capable of superimposing joystick commands onto the programmed commands. Figure 2 shows the block diagram of the proposed system. By using this system, the operator can easily intervene to teach the robot task or to modify the programmed robot motion.

3. LOCOMOTION SYSTEM

In order to construct a huge underground dome, it is necessary for the excavating machine to have locomotion capability. The locomotion system has to offer good mobility for efficient task execution. In addition, the locomotion system has the potential to assist the excavation operation because it is the contact point between the machine and the supporting land surface. At present, three types of locomotion have been considered for this machine: wheels, crawlers, and legs. Wheels offer fast and efficient locomotion on hard and flat terrain, but have difficulty on rough terrain. Crawlers have terrain adaptability to same extent, but it is difficult to execute the fine motion for assisting the excavation task. Although legs are capable of adapting to a variety of terrains and generating motions for the task, they are not capable of fast locomotion. Therefore, a hybrid locomotion system consisting of both legs and crawlers was adopted for the excavation machine. Figure 3 shows the experimental vehicle and the locomotion system for the excavation machine. The vehicle has four 3-DOF legs, and a pair of crawlers.

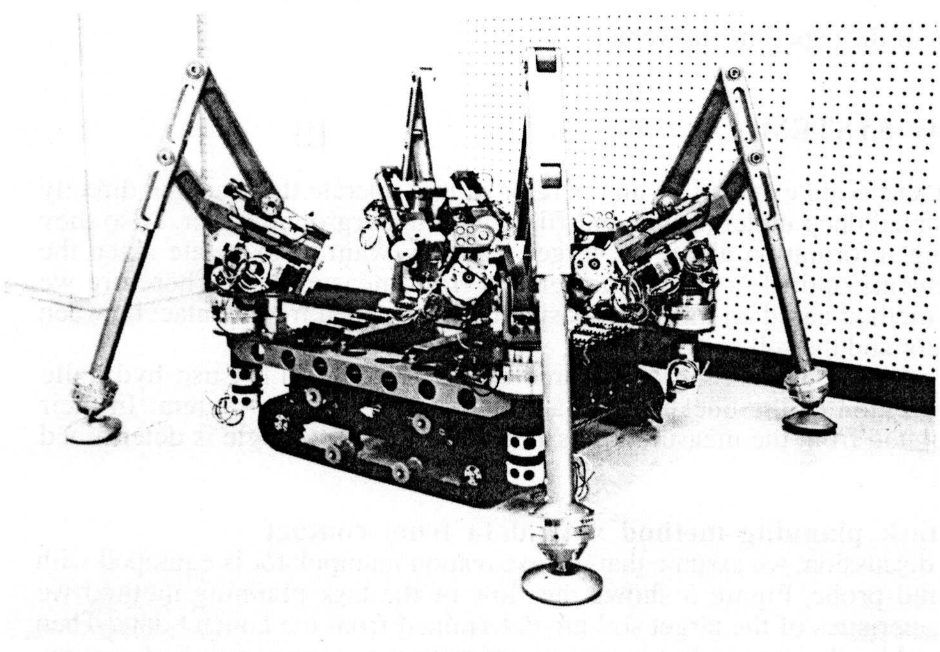

Figure 3. Apparatus of the experimental vehicle.

Figure 4 shows the control system and sensors for the vehicle. It consists of one host computer and nine transputers. Control software is developed on the host computer, and executed on the transputers. It has a hierarchical structure, with one transputer for higher level control and eight transputers to control the interface boards. The lower level transputers are divided into two groups. One group is for controlling the legs and crawlers, and the other group controls the attitude sensor in the body and the force sensors in the feet.

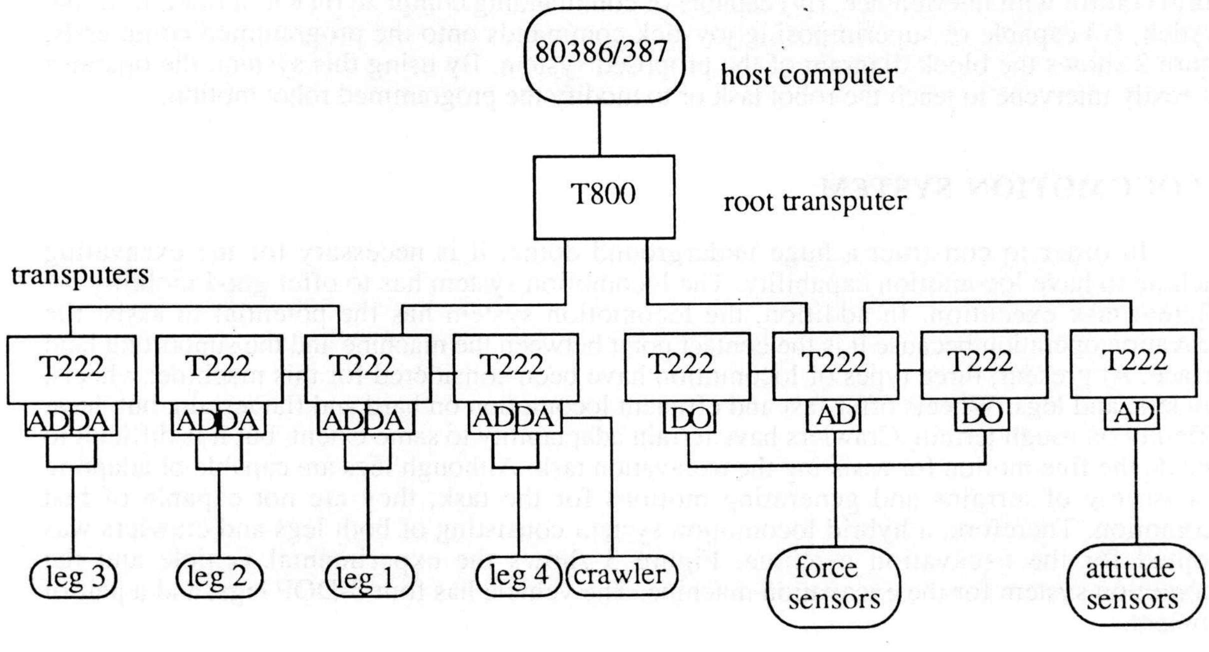

Figure 4. Control system of the experimental vehicle.

4. TASK PLANNING SYSTEM

In the case of underground excavation, an operator cannot operate the machine directly since the worksite is located deep underground and filled with underground water. Also they have difficulty in getting information about the target soil they want to excavate since the contaminated water prevents optical or ultrasonic sensors from measuring it. Therefore we propose a task planning method based on force and position data obtained from contact between the excavation manipulator and the soil.

As an example of motion planning with force data, Gocho et al.[1] use hydraulic pressure to control the motion of the bucket in an automatic wheel loader system. In their system the load is calculated from the measured pressure, and the bucket angle is determined according to the load.

4.1. Concept of the task planning method with data from contact

In the following discussion, we assume that the excavation manipulator is equipped with a force/torque sensor and probe. Figure 5 shows the flow of the task planning method we propose. First, the characteristics of the target soil are determined from the contact data. Then those parameters are used by the excavation model to estimate the reactive force of cutting. From the estimated force, we determine the optimal parameters for excavation.

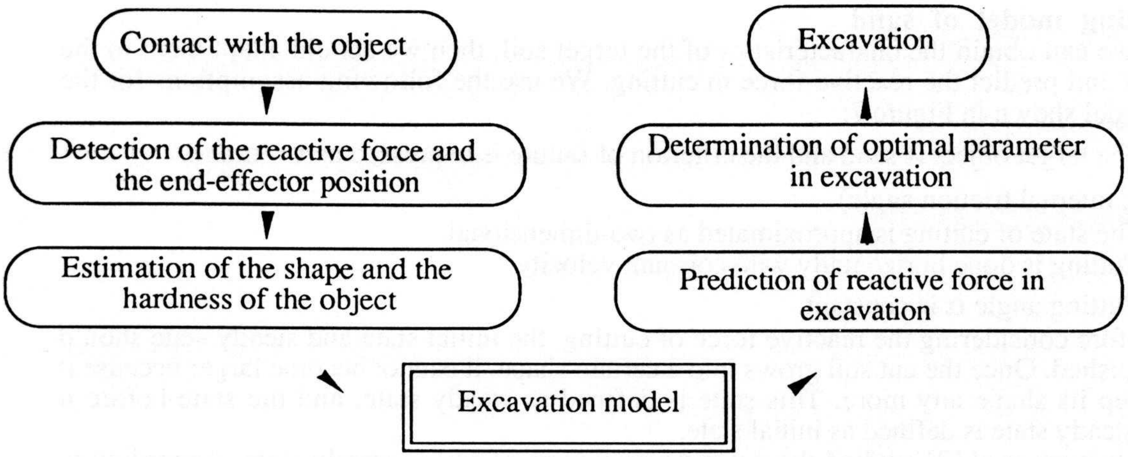

Figure 5. Task planning with contact data.

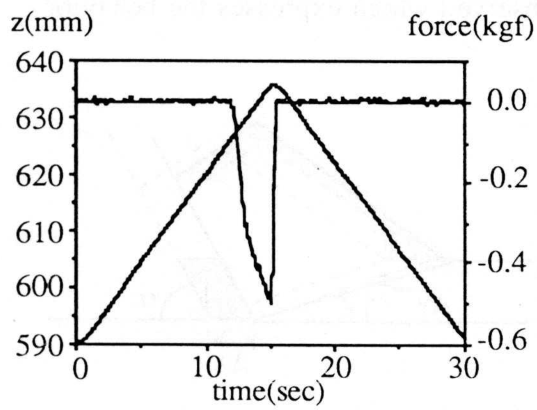

Figure 6. Contact data of soil.

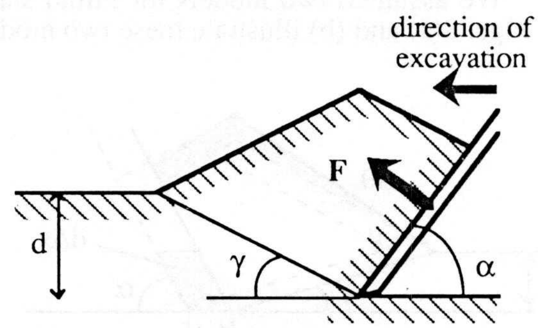

Figure 7. Two-dimensional cutting model.

4.2. Identification of shape and hardness of the soil

Measurement of shape and hardness by force sensor has the advantage of robustness and efficiency over measurement by non-contact sensors, such as optical sensor or ultrasonic sensor. That is, the shape and hardness of the object can be measured simultaneously.

To obtain the surface of the object, the robot is kept in motion and the measurement of force and position is repeated until a reactive force is obtained or the robot moves a certain distance. In the former case, the surface of the object is assumed to be at the position where the reactive force is measured. In the latter case, it is assumed that there is no object at least in the area where the robot passed.

To determine the stiffness, the probe is pushed into the object after the surface is determined. If the object is hard, the reactive force grows instantly while the position of contact between the robot and the object moves only slightly. If the object is soft, the position of contact keeps on moving a certain distance after contact occurred, and reactive force grows gradually.

Figure 6 shows the position of the end of the probe and the reactive force around the moment of contact.

4.3. Cutting model of sand

If we can obtain the characteristics of the target soil, then we should adapt them to the soil model and predict the reactive force in cutting. We use the following assumptions for the cutting model shown in Figure 7:

- The target object is sand and the criterion of failure is expressed as $\tau = \sigma \tan\phi$. (ϕ: internal friction angle)
- The state of cutting is approximated as two-dimensional.
- Cutting is done horizontally with constant velocity.
- Cutting angle α is constant.

Before considering the reactive force of cutting, the initial state and steady state should be distinguished. Once the cut soil grows into a certain shape, it cannot become larger because it cannot keep its shape any more. This state is defined as steady state, and the state before it comes to steady state is defined as initial state.

Hatamura et al.[2] studied the cutting mechanism of soil in steady state. According to them, the reactive force of cutting **F** is almost proportional to the depth of cutting. They also say **F** does not have any relation to the cutting velocity. We take it as a steady state model.

At the beginning of cutting, on the other hand, cut soil continues to grow until it comes to steady state. Hatamura's model cannot apply to this state.

We assumed two models for initial state and observed which expresses the behavior best. Figs. 8(a) and (b) illustrate these two models.

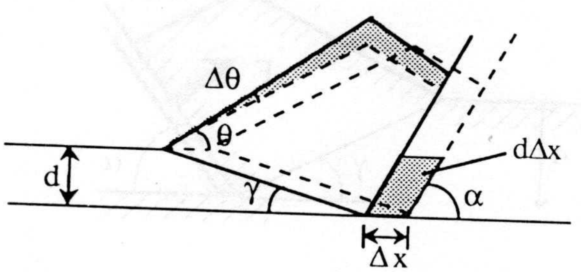

Figure 8(a). Initial model(I).

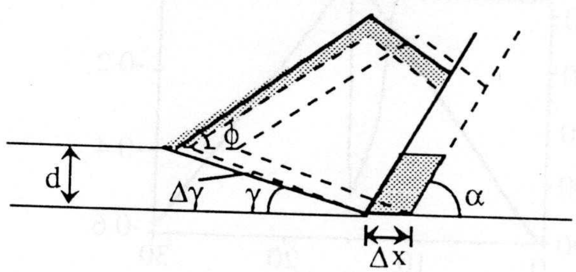

Figure 8(b). Initial model(II).

Model(I) assumes that the shearing angle γ is constant and the cut soil angle θ grows until it equals the internal friction angle ϕ. When the cutter moves a small distance Δx, it cuts the sand of volume $d\Delta x$, which is assumed to be equivalent to the increment of the volume of cut soil. Then equation (1) is introduced.

$$\Delta x = d\{1/2\tan^2\gamma + 1/\tan\gamma(\tan\alpha + \tan\phi)\}\Delta\theta \tag{1}$$

Figs. 9(a) and (b) show estimated θ and **F** from the formula above. Simulation is done with the following conditions.

- Angle of the cutter from horizon: $\alpha = 60$ degrees
- Depth of cutting: $d = 10$ cm
- Internal friction angle of sand: $\phi = 38$ degrees
- Length of cutter: $L = 20$ cm
- Density of sand: $\rho = 0.00146$ kg/cm^3

Model(I) predicts that the cutting process reaches the steady state at about 40cm from the beginning of cutting, and cutting force grows to about 2.5kg.

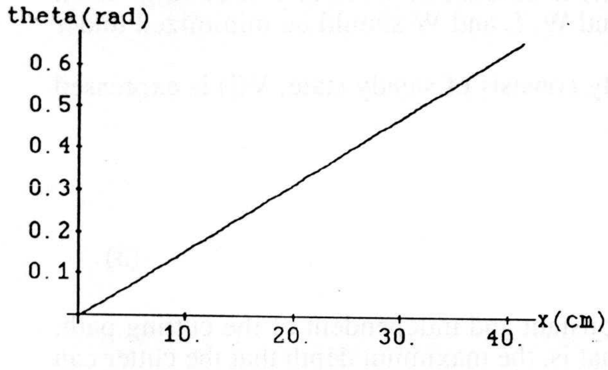

Figure 9(a). Estimated angle of cut soil θ.

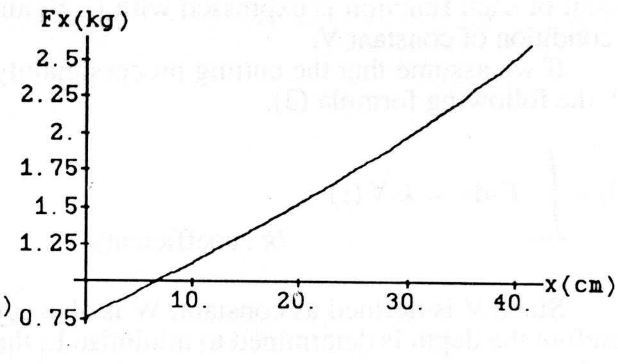

Figure 9(b). Estimated reactive force of cutting Fx.

Model(II) assumes that the cut soil angle is constant and equal to the internal friction angle ϕ, and that the shearing angle γ becomes smaller as the cutter moves. As for model(I), the cut volume is assumed to be equal to the increment of cut soil. This introduces the equation (2).

$$\Delta x = -[\{d\tan\phi + d^2\tan\phi(2\tan\alpha+\tan\phi)/(\tan\alpha+\tan\phi)^2\}1/\tan\gamma + d\tan\phi(2\tan\alpha+\tan\phi)/(\tan\alpha+\tan\phi)^2]\Delta\gamma \qquad (2)$$

Figs. 10(a) and (b) show estimated γ and F from formula (2). Simulation is done under the same conditions as model(I). This model shows that steady state is reached at a cutting distance of about 15cm, and that the reactive force is about 1.2kg.

According to Hatamura's model, the reactive force of cutting at a depth of 10cm is about 1.3kg. Observation of the cutting distance and behavior of the cut soil also indicates that model(II) is more similar to the real process of cutting soil.

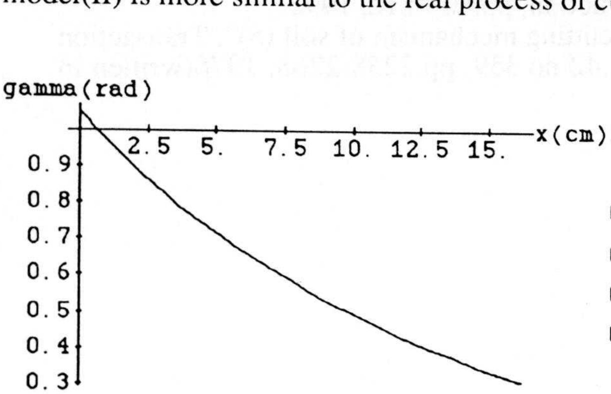

Figure 10(a). Estimated shearing angle γ.

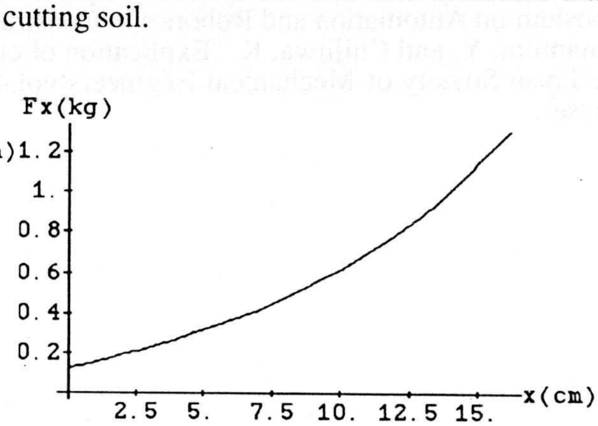

Figure 10(b). Estimated reactive force of cutting Fx.

4.4. Task planning with cutting model

What we ultimately want to do is to determine optimal parameters of cutting. In the case of horizontal cutting of sand, the main parameters are depth and speed of cutting.

Three cost functions L(i), V(i), W(i) are introduced. L(i) is the length of i-th cutting. V(i) is volume of cut soil of i-th cutting. And W(i) is amount of work of i-th cutting. Total amount of each function is expressed with L, V, and W. L and W should be minimized under the condition of constant V.

If we assume that the cutting process mainly consists of steady state, V(i) is expressed with the following formula (3).

$$W(i) = \int_{L(i)} \mathbf{F} \cdot dx = k \cdot V(i) \qquad (k : \text{coefficient}) \tag{3}$$

Since V is defined as constant, W is also constant and independent of the cutting path. Therefore the depth is determined to minimize L, that is, the maximum depth that the cutter can afford.

Optimization can also be done relative to actuator power. Optimal torque and velocity are determined to maximize the power.

Thus the depth and speed of cutting can be determined and excavation can be carried out.

5. SUMMARY

This paper describes research on three components of an underground excavation robot: the manipulation system, the locomotion system, and the task planning system. For the manipulation system, a teleoperation/autonomous control system with parallel link manipulator has been developed. For the locomotion, an experimental vehicle with a hierarchically controlled hybrid legged/crawler system has been developed. For task planning, a method using contact data and a cutting model of soil has been proposed and simulation has been carried out.

REFERENCES

1 Gocho, T., Yamabe, N., Hamaguchi, T., Hitomi, S., Ono, T., Oshima, H., Mori, M., and Fukuda, M. "Automatic Wheel-loader in Asphalt Plant", Proceedings of the 9th International Symposium on Automation and Robotics in Construction, pp.803-812, 1992.

2 Hatamura, Y. and Chijiiwa, K. "Explication of cutting mechanism of soil (5)", Transaction of the Japan Society of Mechanical Engineers vol.42 no.359, pp.2258-2268, 1976(written in Japanese).