Development of a Mobile Manipulator for Underground Excavation Task

Hironori Adachi*, Tatsuo Arai*, Noriho Koyachi*,
Keiko Homma*, and Ken'ichiro Nishimura**

* Mechanical Engineering Laboratory, AIST, MITI, Namiki 1-2, Tsukuba, Ibaraki, 305 Japan
** Nisshinbo Co. Ltd., Azukizaka 30, Miai-machi, Okazaki, Aichi, 444 Japan

ABSTRACT

A national research and development program on Underground Development Technology has started in 1989. In this program, a basic study of a excavating robot has been done at the Mechanical Engineering Laboratory. This paper describes an experimental mobile manipulator for the excavating task. Four legs and a pair of crawlers are equipped with the mobile platform, and a manipulator is set on it. Legged locomotion has potential to move on rough terrain, and crawlers contribute fast locomotion. When the robot is supported by the legs, not only the position but also the posture of the robot body can be controlled without changing foot points. This feature shows that legs can be used for assisting manipulator task also. For efficient task performance, an coordination control method between the arm and the legs are introduced, and it is tested by an experiment.

1. INTRODUCTION

Japan is a mountainous country and her plain are densely populated especially in large cities such as Tokyo, Osaka, etc. The Japanese Ministry of International Trade and Industry (MITI) has started a national research and developing program on Underground Space Development Technology to establish a new frontier at depth of greater than 50 meters below ground level. In this program, an automated excavating robot will be developed to construct an underground dome of approximately 100 meters diameter and 30 meters height. The Mechanical Engineering Laboratory has been engaged in the basic research for the robot.[1)]

In our concept, the excavating robot should consist a manipulator on a mobile platform. Recently, research that deals with the combination of a manipulator and a mobile manipulator has become popular. The combination of a manipulator and wheeled type vehicle is reported for an autonomous assembly task[2)], and for nuclear plant facilities[3)]. Crawler type mobile platform is also reported[4)]. Although legged locomotion is not practical at the present, some researches for the combination of legs and a manipulator have been done[5),6),7)].

In the excavation task, there are two kinds of locomotion. One is global locomotion, the other is local locomotion. The global locomotion is movement between excavation sites. It is relatively long distance locomotion and requires speed. The local locomotion is movement while executing excavating task. For efficient excavating task, it is required that the robot moves on unstructured terrain in any direction smoothly from the current position without changing its orientation. In addition, the local locomotion has to be executed on rough terrain. Considering above requirements, we decided to employ two kinds of locomotion mechanism; crawlers and legs. Crawlers are used for the global locomotion, and legs are used for the local locomotion.

Legs can be used for not only locomotion but also assisting excavation task. Legged system is capable to change the three degrees-of-freedom(d.o.f) position and three d.o.f posture of the robot body without changing foot points. This means that a mounted manipulator is able to obtain extra motion. We can consider legged system as a parallel manipulator to move the mounted manipulator. By coordinating leg and manipulator motion, the endeffector can obtain sophisticated motion.

This paper describes a mobile manipulator using leg and crawlers developed at the Mechanical Engineering Laboratory and a coördination control method of a manipulator and legs. In section 2, mechanism and control system of the mobile manipulator is introduced. In section 3, a coordination control method is proposed, and experimental results are showed in section 4.

2. EXPERIMENTAL MOBILE MANIPULATOR

2.1 MECHANISM

In this section, developed mobile manipulator is described. It is called "MELMALEC" (Mechanical Engineering Laboratory Mobile Arm using Legs and Crawlers), and its overview and basic specification are shown in Fig.1 and Table 1. This robot has four legs, a pair of

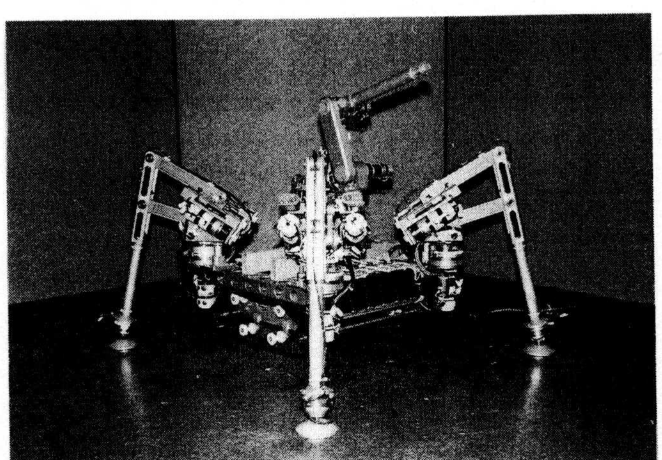

Fig.1 Photograph of MELMALEC

Table 1 Basic specification of MELMALEC

Configuration	4 legs (3 d.o.f., 4 bar closed loop linkage) 1 pair of crawlers (1DOF) 1 manipulator (3 d.o.f., 3 bar seroal linkage)
Length	700 mm
Width	700 mm
Height	500 mm
Weight	70 kg
Distance between legs front-rear right-left	 500 mm 570 mm
Actuator	16 DC servo motor
Sensors	force/torque sensor (6-axis, each leg) attitude sensor (pendulum type and rate gyro)

crawlers, and a manipulator. Configurations of the leg and the manipulator are shown in Fig.2. The leg employs closed-loop structure in order to increase the rigidity. Each leg has three d.o.f., and they are driven by three DC servo motors. A pair of crawlers are also driven by a DC servo motor. The mounted manipulator has three d.o.f. serial-link structure. For the excavation task, a parallel link manipulator has advantage such as large load capacity. The authors have actually developed such type manipulator[1]. However, a conventional serial link manipulator with 3 d.o.f was mounted since main target of the robot is coordination control of legs and arm. Totally, the robot has 16 DC servo motors. As for sensor system, each leg has 6-axis force/torque sensor at the ankle. For attitude detecting, pendulum type sensors and rate gyros are attached to the body. The control computer and the electric power source are physically separated from the robot, and they are connected by cables.

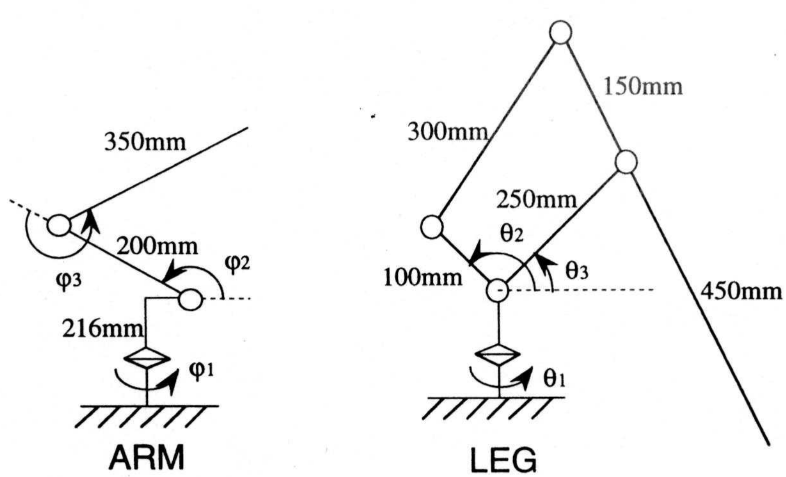

Fig.2 Link configuration

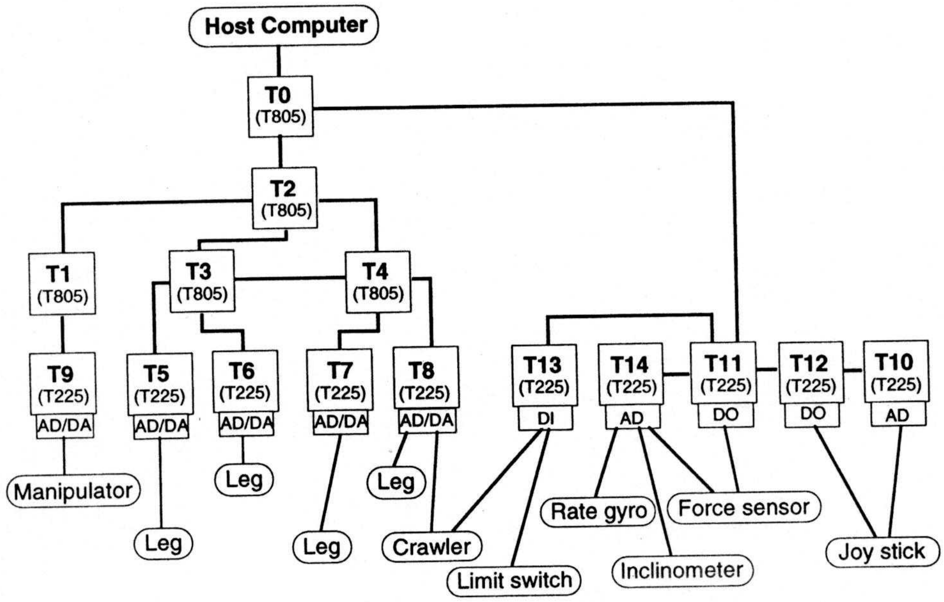

Fig.3 Averall control system

2.2 CONTROL SYSTEM

In general, legged robots like MELMALEC have a large number of actuators. In the case of MELMALEC, 16 motors must be controlled coordinately. For heavy load task like this, a multi-processor control system is desirable. The command supplied to the robot is usually only the locomotion route or the trajectory of the end effecter. However, the final controlled objects are the individual actuators. Therefore, the control system must break down this global command to control signals for the actuators. To perform this task, it is convenient for the control system to have multi-layered structure. When MELMALEC is considered as a mechanical system, it is found that it has five similar-structured mechanical units (legs and arm). Each mechanical unit has three actuators. It is desirable that motion control of each mechanical unit is executed in parallel. Considering above discussion, the control system for MELMALEC should satisfy following requirements.

1) Hierarchal structure
2) Parallel structure of the lower parts that depend on the mechanical system

Fig.3 shows the control system for MELMALEC. This system is a transputer based multi-processor system and satisfies above requirements. It consists of a host computer, 15 transputers, and interface unuts. The control software is developed on the host computer (IBM/AT compatible personal computer), and executed on the transputer network. Five transputers (T0,..,T4, 32bit processor) perform higher level control, and ten (T5,..,T14, 16bit processor) control the mechanism or sensors. Five transputers (T5,..,T9) have the A/D and D/A converters, and each transputer control one leg or a manipulator. Five transputers (T10,..,T14) are used for the communication to the various sensors and a joystick. In this system, the joystick, which consists of 6 axes force/torque sensor, is used as a input device. A human operator can provide 6 components command to the robot by using the joy stick.

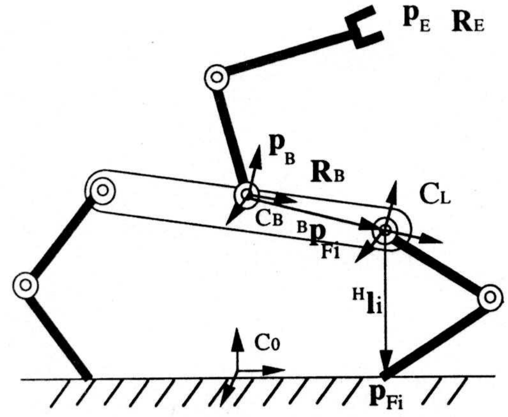

Fig.4 Coordinatuin control of legs and arm

3. COORDINATION CONTROL OF LEGS AND ARM

As mentioned previous section, the arm of MELMALEC has only three d.o.f. Therefore, the arm cannot control the position and the orientation of the end effector simultaneously by itself. Here, we consider six d.o.f position and posture control of the end effecter of MELMALEC's arm as an example of the coordination control of legs and arm. When the six d.o.f translational and angular velocity command is given, a calculation method of each joint driving velocity to realize the command is considered.

Here, we set three kinds of coordinate system, First is the world coordinate system (C_0) fixed to the terrain, the second is the body coordinate system (C_B) fixed to the robot's body, the third is leg coordinate system (C_L), and its origin is set at each leg base. The orientation of the leg coordinate system is same as that of the body coordinate system. Position vector of the end effector in the world coordinate system $\mathbf{p}_E$ and a 3 by 3 orientation matrix of the end effecter in the world coordinate system $\mathbf{R}_E$ are expressed as follows.

$$\mathbf{p}_E = \mathbf{p}_B + \mathbf{R}_B {}^B\mathbf{p}_E \tag{1}$$

$$\mathbf{R}_E = \mathbf{R}_B {}^B\mathbf{R}_E \tag{2}$$

Here, $\mathbf{p}_B$ is a position vector of the robot's body in the world coordinate system, ${}^B\mathbf{p}_E$ is a position vector of the end effector in the body coordinate system. $\mathbf{R}_B$ and ${}^B\mathbf{R}_E$ are orientation matrices of the body in the world coordinate system, and the end effector in the body coordinate system respectively. By differentiating these equation, we obtain velocity relationships as followings.

$$\dot{\mathbf{p}}_E = \dot{\mathbf{p}}_B + \boldsymbol{\omega}_B \times \mathbf{R}_B {}^B\mathbf{p}_E + \mathbf{R}_B {}^B\dot{\mathbf{p}}_E \tag{3}$$

$$\boldsymbol{\omega}_E = \boldsymbol{\omega}_B + \mathbf{R}_B {}^B\boldsymbol{\omega}_E \tag{4}$$

where ω_B and ω_E are angular velocities of the body and the end effector respectively. These equations show that four velocity vectors, $\dot{\mathbf{p}}_B$, ω_B, ${}^B\dot{\mathbf{p}}_E$, and ${}^B\omega_E$, must be decided to realized the command. Since we cannot decide two velocity vectors of the arm in the body coordinate system, ${}^B\dot{\mathbf{p}}_E$ and ${}^B\omega_E$, independently, these are calculated by following procedure. We assume that the end effector translational velocity in the body coordinate system ${}^B\dot{\mathbf{p}}_E$ is proportional to the commanded translational velocity $\dot{\mathbf{p}}_E$.

$$ {}^B\dot{\mathbf{p}}_E = k\,\dot{\mathbf{p}}_E \quad (0 \le k \le 1) \tag{5} $$

From this equation, joint velocity of the arm is calculated as folow.

$$ \dot{\boldsymbol{\phi}} = k(\mathbf{R}_B\mathbf{J}_{AT})^{-1}\dot{\mathbf{p}}_E \tag{6} $$

where $\mathbf{J}_{AT}$ is an arm's Jacobian matrix for translational velocity. Velocities of the body are also calculated.

$$ \boldsymbol{\omega}_B = \boldsymbol{\omega}_E - \mathbf{R}_B\mathbf{J}_{AR}\dot{\boldsymbol{\phi}} \tag{7} $$

$$ \dot{\mathbf{p}}_B = (1-k)\dot{\mathbf{p}}_E - \boldsymbol{\omega}_B \times \mathbf{R}_B{}^B\mathbf{p}_E \tag{8} $$

In these equations, $\dot{\mathbf{p}}_E$ and ω_E are the commanded velocities of the end effector, and $\mathbf{J}_{AR}$ is a arm's Jacobian matrix for angular velocity.

Now, the velocity command of the end effector is divided into the velocity of the arm joints and that of the robot body. Next, joint angular velocity of the legs is obtained from the body velocity. Kinematics relation between the robot body and the leg is expressed next equation.

$$ \mathbf{R}_B{}^H\mathbf{l}_i = \mathbf{p}_{Fi} - (\mathbf{p}_B + \mathbf{R}_B{}^B\mathbf{p}_{Hi}) \tag{9} $$

where R_B is a 3 by 3 matrix expressing the orientation of the body coordinate system, ${}^Hl_i$ is a position vector of the foot in the leg coordinate system. A subscript i is a number of each leg. p_{Fi} is a position vector of the foot point of leg i in the world coordinate system. ${}^Bp_{Hi}$ is a position vector of the origin of the leg coordinate system in the body coordinate system. Next, Eq. (9) is differentiated. Here, the following relation is used.

$$ \dot{\mathbf{R}}_B({}^H\mathbf{l}_i + {}^B\mathbf{p}_{Hi}) = \boldsymbol{\omega}_B \times \{\mathrm{R}_B({}^H\mathbf{l}_i + {}^B\mathbf{p}_{Fi})\} \tag{10} $$

$$ \boldsymbol{\omega}_B = \left[\omega_x, \omega_y, \omega_z\right]^T \tag{11} $$

Here, ω_x, ω_y, and ω_z are the body angular velocities around the each axis of the world coordinate system. From Eqs. (9), (10), and (11), the following equation is obtained

$$ {}^H\dot{\mathbf{l}}_i = \mathbf{R}_B^T\left[\left\{\mathbf{R}_B\left({}^H\mathbf{l}_i + {}^B\mathbf{p}_{Hi}\right)\right\} \times \boldsymbol{\omega}_B - \dot{\mathbf{p}}_B\right] \tag{12} $$

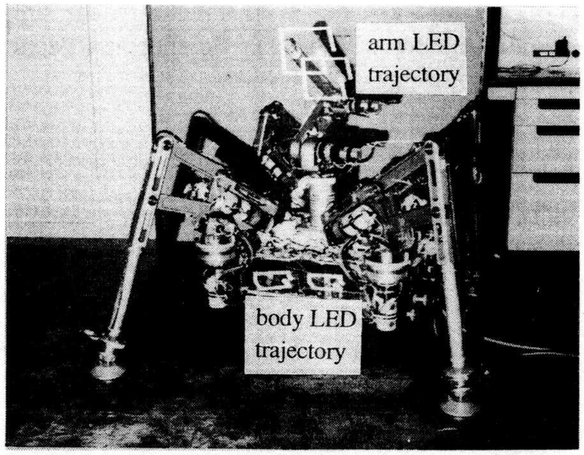

Fig.5 Arm motion and body motion

Eq.(12) provides the relationship between the body velocity, $\dot{\mathbf{p}}_B$ and $\boldsymbol{\omega}_B$, in the world coordinate system and the foot velocity ${}^H\dot{\mathbf{l}}_i$ in the leg coordinate system. By using leg Jacobian matrix J_{Li}, each joint velocity of legs is calculated as next equation.

$$\dot{\boldsymbol{\theta}}_i = \mathbf{J}_{Li}^{-1}\,{}^H\dot{\mathbf{l}}_i \qquad (13)$$

4. EXPERIMENT

The proposed coordination control method was tested using MELMALEC. Fig. 5 shows the motion of the arm and the body when the proposed coordination control is executed. The end link of the arm has two LEDs, and the body also has two LEDs. Each moving trajectory of LED indicates the motion of the end link and the motion of the body. The arm cannot control both position and posture simultaneously by itself since it has only three d.o.f as mentioned section 2. However, it is found from the LED trajectories that the end link posture is kept to be constant during its position change by moving the body. The coordination control enable the robot to control both position and posture of the end link.

5. CONCLUSION

For excavation task, a experimental mobile manipulator was construct. It has four legs and a pair of crawlers as locomotion mechanism, and three d.o.f arm for manipulation. The leg mechanism is used for not only locomotion but also adding extra motion to the mounted arm. A coordination control method of legs and arm is proposed and tested experimentally. The experimental result shows the robot is able to control the position and posture of the end of the arm. In the future works, position and posture control during walking and optimal motion distribution between the arm and the body will be achieved.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to Mr. Yoshinada of Komatsu Ltd.

for constructing the robot. This work has been done with the support of the Office of National R&D Program in the Agency of Industrial Science and Technology.

REFERENCES

1) Adachi, H., *et al.* (1992). Study on underground space excavating machine. *Proceedings of the 9th international symposium on automation and robotics in construction*, pp.751-758.

2) Hörmann, A. and Rembold, U. (1991). The KAMRO system - an advanced robot for autonomous assembly. *Proceedings of '91 international symposium on advanced robot technology*, pp.531-538

3) Nakayama, R., *et al.* (1993). Autonomous mobile robot for nuclear power facilities. *Proceedings of international conference on advanced robotics*, pp.527-532.

4) Fukuda, T., *et al.* (1992). Gravity center control for manipulator/vehicle systems for man-robot cooperation. *Proceedings of the 9th international symposium on automation and robotics in construction*, pp.233-242.

5) Carlton, R.E. and Bartholet, S.J. (1987). The evolution of the application of mobile robotics to nuclear facility operations and maintenance. *Proceedings of international conference on robotics and automation*, pp.720-726.

6) Iwasaki, M., *et al.* (1990). Field test on aquatic walking robot for underwater inspection. *Proceedings of the 4th pacific congress on marine science*, pp.192-195.

7) Uesugi, N., *et al.*, (1991). Total system of advanced robot for nuclear power plant facilities. *Proceedings of '91 international symposium on advanced robot technology*, pp.531-538.

8) Hudgens, J. and Arai, T. (1993). A new prototype parallel manipulator: kinematics and sensor calibration. *Proceedings of IEEE/RSJ international conference on intelligent robots and systems*, pp.194-200.

9) Adachi, H., *et al.* (1994). Control of a quadruped walking robot using parallel programming. In: *Transputer/occam Japan 6* (Noguchi, S., *et al.* (Ed.)), pp.231-237.