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TELEOPERATED MOBILE ROBOT FOR INSPECTION IN NUCLEAR FACILITIES

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ABSTRACT

This paper gives an account of teleoperated mobile robot system which is intended to operate in hostile environments where human access is limited or prohibited. A prototype mobile robot equipped with manipulator was designed and initial tests were made in laboratory environment. Test results, yet preliminary, have been encouraging for further research efforts. Future plans emerging from these initial results are also summarized.

1. INTRODUCTION

Nuclear power now accounts for over a half of the domestic electric supply with a sizable scale of nuclear power plant operation. Hence the demands of advanced technologies to support nuclear industry have also been steadily growing in the associated areas.

Taking advantage of recent tremendous progress in computers, sensors, precision engineering, and artificial intelligence, the technologies for autonomous robot application under hostile or unstructured environments have been accomplished partly. The development of a remote-controlled equipment has been motivated, as resource demands increase and environment constraints tighten. This type of equipment has many incentives which reduced radiation exposure, lower man-hours, shorter power outage, less waste material, and improved worker safety concerns. The most important advantage is the ability to perform hazardous and dangerous tasks regardless of high radiation exposure. The teleoperated robot, yet requiring human intelligence to guide unstructured activities offers potential usefulness in many future application. Some of the advanced nations in nuclear field have long been front runners in the development of remote control technologies. Analyzing the cost-effective for robotic applications to surveillance and inspection works in the existing nuclear power plant, it is concluded that robotic inspection devices can be retrofitted into power plants and will reduce both exposure to workers and plant operating costs [1].

In the late 1940s bilateral mechanical master-slave manipulators were designed and fabricated to develope remotely controlled mechanical manipulators at the Oak Ridge and Argonne National Laboratories for the handling of radioactive materials. This system was designed to reproduce faithfully hand and arm motions made by human operator. In 1982 fully distributed, digitally controlled servomanipulator was designed and manufactured at the same laboratories[2].

If radioactive dose rates at the site of an incident are very high, then manipulator vehicles are important devices to be used in decontamination, inspection, maintenance, and so on. There are several approaches for designing the mechanism of mobile robot such as wheel , leg, and crawler type. Wheel type was commonly used due to its simple design feature, high efficiency, and high speed. But unfortunately this system can't go over obstacles and stairs. Other types have good mobility over uneven terrain, but they have a lot of problems in complexity and stability for intelligent control. To come up with these problems, recently specially designed planetary wheel mechanism was considered seriously for locomotion system to get a relatively high speed, stability and controllability[3].

This paper presents the development of teleoperated mobile robot which is somewhat dissimilar to industrial robot. A prototype mobile robot installed with manipulator is described and initial test results which have been obtained in laboratory conditions are summarized. To obtain a dexterous handling, conceptional designs of redundant manipulator are studied, and the control systems using the technique of off-line programming are presented.

2. TELEOPERATED MOBILE ROBOT KAEROT

2.1 Design Summary

The technology of the tele-operation is indispensable for robot by reason of autonomous operation being far from realization. The mobile system is a planetary wheel type to be able to climb up and down stairs with three wheel assemblies each of which consists of three small wheels between two triangle plates. On the top of the mobile body, 4 DOF manipulator is mounted. Sensory system that is used for autonomous operation includes inclination sensor , touch sensor and proximity sensors, as well as CCD cameras. For better dexterity, the manipulator is designed of redundant type that resembles a human arm motion. The robot is tele-operable by operator-in-the-loop manner in unstructed environments or programmed for routine inspection.

The control system is consisted of distributed multiprocessor architecture to be able to expand easily for further usage. Suggested control system is expected to contribute to secure independency and reliability. Table 1 illustrates a design summary of KAEROT.

Table1. Design Summary of KAEROT.

Item	Specification
Function	Inspection & Maintenance
Locomotion	
Body : Width	73 cm
Length	106 cm
Planetary Wheel Weight	
: Front	12.5 kg
: Rear	14.5 kg
Obstacle	
: Min. Width	5 cm
: Max. Height	8 cm
Manipulator	
: Length	110 cm
: DOF	4

2.2 Mobile System

2.2.1 Kinematic Modelling of Climbing Stairs

2DW1S(2 Driving Wheels 1 Steering) is adopted with 5 degrees of freedom as shown in Fig. 1. Motor 1 and 2 drive rear wheels independently, and motor 3 and 4 drive planetary wheels, and motor 5 steers the robot. This mechanism enables the robot to run on the flat floor by small wheels , and go up and down stairs by planetary wheels.

To control the mobile robot appropriately, a methodology for modelling and analyzing of robot has to be develped in conjunction with the proven technology. First of all, the modelling of the planetary wheel is shown in Fig. 2.

$$G_y = G_y\,\phi \quad (1)$$

$$G_z = r + L\cos(\pi/3 - \theta_p) \quad (2)$$

$$Y_{fb} = G_y + L\cos(\pi/6 - \theta_p) \quad (3)$$

$$Z_{fb} = G_z + L\sin(\pi/6 - \theta_p) \quad (4)$$

$$Y_{uf} = G_y + L\sin\theta_p \quad (5)$$

$$Z_{uf} = G_z + L\cos\theta_p \quad (6)$$

$$Y_{ub} = G_y - L\sin(\pi/3 - \theta_p) \quad (7)$$

$$Z_{ub} = r\,\phi \quad (8)$$

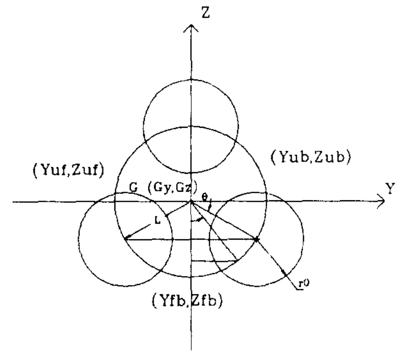


Fig.2. The Modelling of Wheel

The modelling of mobile system is depicted in Fig.3, and the points $P_b(P_{bx}, P_{by}, P_{bz})$ and $P_f(P_{fx}, P_{fy}, P_{fz})$ are represented as follows;

$$P_{by} = R_y + r\{\theta_w + 0.6(\theta_p + \theta_a)\} \quad (9)$$

$$P_{bz} = R_z - L/2 + L\cos(\pi/3 - \theta_p) \quad (10)$$

$$P_{fy} = P_{by} + L_a\cos\theta_a \quad (11)$$

$$P_{fz} = P_{bz} + L_a\sin\theta_a \quad (12)$$

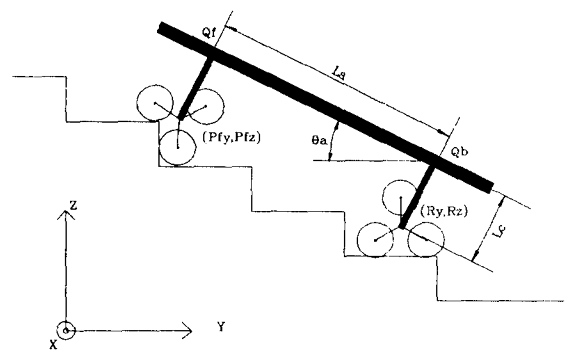


Fig.3. The Modelling of Locomotion System.

2.2.2 Locomotion Algorithm.

KAEROT turns by means of the difference of velocities between right and left wheels on the flat floor. Geometric Arrangement of rear wheel is depicted for the rotation angle of θ_r in Fig.4.

$$V_r = (L_r + \theta_r w/2)/\tau \quad (13)$$

$$V_l = (L_r - \theta_r w/2)/\tau \quad (14)$$

$$\theta' = \tan\{L_a/(r+w/2)\} \quad (15)$$

where L_r, θ_r, τ are the average speed, rotating angle, and sampling time.

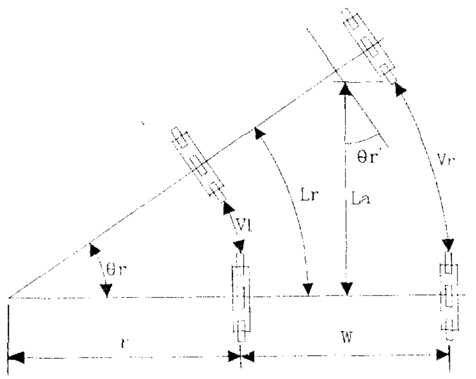


Fig.4. The Moving Configuration of Wheels on Steering

The control procedures for going up stairs are as follows;

- o In running mode, the condition for the front planetary wheel collides with front panel of the first step is detected by using the stair measurement unit.
- o Front planetary wheel assemblies rotate forward until upper wheel reaches at the upper plate of stairs.
- o To maintain two small wheels being contacting upper plate of stairs, the front planetary wheel rotates 120 °.
- o Repeat the above procedures.
- o Going down the stairs is done in the opposite way.

2.2.3 Experiment

Initial tests going over one step stair with the 18cm height and 30cm width are carried out. At the end of the 2nd procedure, the rotating angle θ_p of planetary wheel is about $\pi/3$. Maximum inclination angle for going over one step is 17 °. The result of initial test shows the feasibilities on full steps.

Photo 1 shows the appearance under the 2nd procedure. Fig.5 shows the trajectory of the center point of planetary wheel and the inclination angle during climbing stairs.

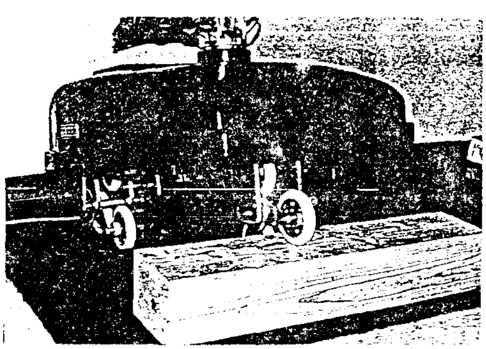


Photo 1. The Appearance of Going up the 2nd Step.

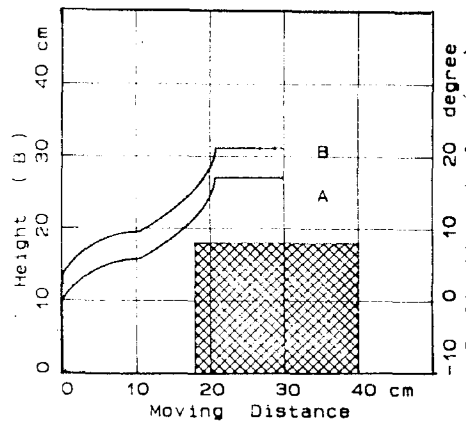


Fig.5. The Trajectory of the Center Point of Planetary Wheel and Inclination Angle.

2.2.4 Sensory System and Control Console

Ultrasonic sensors are used in stair-detecting unit to recognize the stair size. Also contact sensor is attached around the robot and contact points with obstacles are detected by the differnce of pressure.

One CCD Camera, mounted on the elbow, provides a wide view of the working area. Another miniature borescope is installed on the hand, looking out at the tooling. CCD camera has remote tilting machanism and automatic zoom controller. Images from these cameras are transmitted to a couple of monochrome monitors, which are mounted on the operator console in control room.

To ensure that the operation will be able to efficiently and safely manage the system, a man - machine interaction consideration is required. Toward this end, the conceptual control panel design is conducted. A 4 DOF manipulator controller and mobile controller are available on console. The design also allows for their replacement with a 7 DOF manipulator controller. A standard keyboard, push buttons, switches, driving handle, and pendant are provided.

2.3 Manipulator System

(1) Design concepts

For the manipulator in the complex environment such as nuclear power plant to complete the given task successfully, It is required that the manipulator should have a quite different kinematic structure and functions compared with the industrial manipulator. KAEROT manipulator was designed and built on the bases of following design concepts[4,5].

- o Simple geometric structure
- o Wide workspace of the end effector
- o Kinematic structure to keep away from obstacle
- o Sensing function for the tele-manipulation
- o Light weight.

The geometric structure in the view point of kinematic aspect varies with the sequence of the joint type, dimensions of link, and parameters which relate the adjacent coordinate systems attached at the each joint.

For the simple geometric structure, KAEROT manipulator was designed that the twist angle of the links is equal to zero or $\pi/2$ and the distance between the links is equal to zero. For performing the tasks effectively in the environment with complex obstacles, 7DOF anthromorphic manipulator is designed and links dimension ratio is determined to be similar with the human arm for the sake of easy and realistic operation of the slave manipulator in the master-slave control mode.

(2) 7 DOF manipulator

The manipulator is designed to be wrist partitioned type. The redundant positional structure consists of 4 DC servo motors and the orientational structure consists of 3 DOF wrist with a gripper.

For modularity and simplicity, localized actuator system was selected for using in a contamination area. Localized actuation reduces torque transmission elements and permits minimum inertia. The torque of each joint of the positional structure is transmitted through the harmonic gear for the torque amplification and accurate positioning by eliminating backlash.

The rated torque of each joint of the positional structure is 80W, 250W, 80W, 80W in serial. One harmonic gear DC servo motor and two planetary geared motors are assigned for the orientational structure. The rated torque of each joint of this part are 20W, 20W, 15W in serial. Every joint except the joint 4 has a incremental encoder with 500-1000 PPR.

For the positioning a 12 bit absolute encoder attached at the link 4 for the purpose of reducing the dimension of the joint shape. Also, every joint has a tacho-meter or a F/V converter which provides the velocity of the motor shaft.

These motors are harmonic geared units and their direction of rotation is easily reversed. Electro-magnetic brake is fitted to the shoulder to prevent from over-running when power is removed. Gripper can rotate continuousely by using a slip ring for a fore arm roll motor. The developed manipulator joint configuration is shown in Fig.6 and the assembly drawing describing the each link length is depicted in Fig.7.

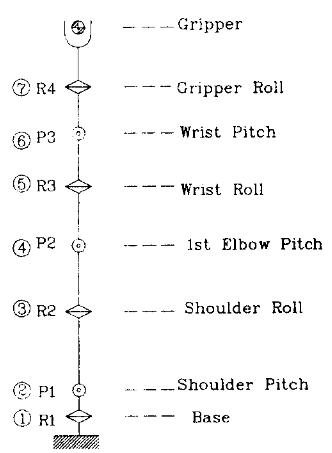


Fig.6. Joint Configuration.

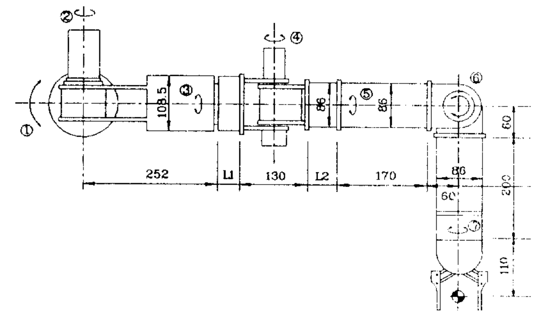


Fig.7. Joint Assembly Drawing.

PWM amplifiers for these motors include a current limiting circuit protects the motors in the stall condition. DC servo motors which comprising the positional structure can be controlled in either mode of the torque controlled mode or velocity controlled mode, so this current mode amplifier can be switched to voltage mode amplifier with easy. The servo mechanism consists of a 32 bit digital computer, D/A converters, tacho-generators, encoders, and servo motors. The block diagram of the servo mechanism is depicted in Fig. 8.

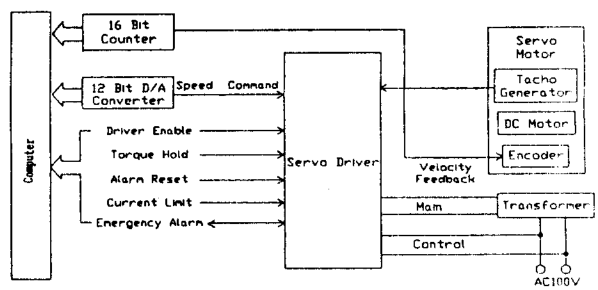


Fig.8. Block Diagram of Servo Mechanism.

2.4 Control System

2.4.1 Multiprocessor

Autonomous robot operating in unpredicted environment requires strong computing power and reliability. KAEROT will signify any device having the functions of sensing, manipulator control, mobile control, and data processing. Hence the control system has to be designed to extend easily for further usage with a modular architecture to get independency and reliability. The distributed system architecture has been designed in two distinct sub-systems;

o Supervisory control part
o Remote control part.

The man-machine interface is encounted under supervisory control part which consist on the base of Intel 80386. Supervisory control system is interconnected with remote control part by means of the protocol of synchrorous Data Link Communication (SDLC) and give a message with the speed of 2.4Mbps by adopting communication protocol.

These systems are seperated with each other to enhance relibility and computing power.

2.4.2 Off-line Programming

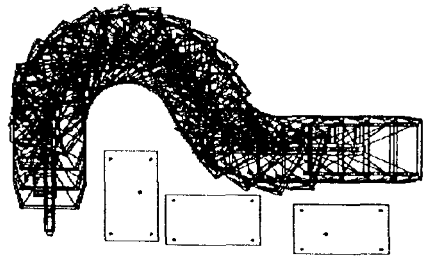
To derive the maximum benefit of robot in nuclear facilities calls for careful evaluation of available robot and varification of collosion free tasks prior to generation of robot program. This advantages make off-line system particulary attractive. Off-line programming which means the programming of physical equipment such as manipulators and other workcell devices without access to the equipment when the programming is performed, is essensial according to the increasing complexity of robot tasks.

As more of the programm development is done away from the robot and potentially hazardous environments. These increase operator safety by detecting dangerous, unpredicted moves of equipment in the workcell before actually operating the robot. The chance for possible damage to workcell equiment is also reduced.

The developed off-line programming includes a CAD system which can be used to create or edit three-dimensional world model, that is, data on the geometric description of components and their relationships within the workspace. Different colors for workcell components facilitate understanding of the layout and interaction of the elements in the system.

Accurate robot kinemetic and dynamic models are important to make sure feasible off-line programming of robot system. Also, to simulate the spatial and temporal aspects of how a given robot moves through space, careful considerations are required in simulating the path generation techniques.

The developed off-line programming provides such as functions, checking for robot joint constraint violations within workspace, and graphical method for programming the robot. In the view point of man-machine interface, all command can be deal conviniently in the menu. The off-line programming package has been developed on Intel 80386 with the C language. The examples of off-line programming results are shown in Fig.9.



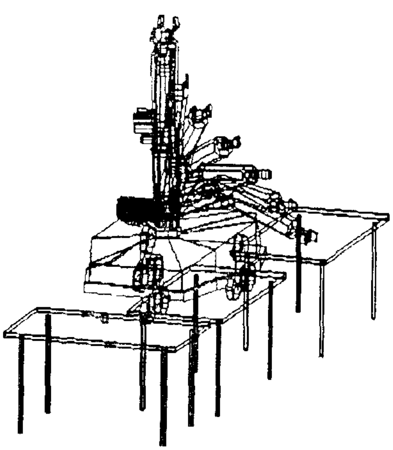


Fig. 9. The Examples of Off-line Programming

3. FUTURE PLANS

Efforts will continue to enhance mobile robot performance using the prototype design as a test bed. Semi-automatic mode control is planned to test the operability in unstructured environments. Control system architecture and software integrated sensor fusion in association with planning and diagnostic functions are envised. These plans will eventually contribute to intelligent system development. Additional control algorithm has to be implemented to the rear planetary wheels to get an appropriate stability margin by minimizing the inclination angle. The next major area of development within off-line programming will be simulation of sensors and the comprehensive language capability offering substantial flexibility. Also, technical development will be continued on the studies for radiation and heat resistant electronics.

4. CONCLUSION

Efforts to develop mobile robot with manipulator have resulted in a prototype design. The design features include multiprocessor control architecture that is suitable for future expansion and locomotion system for better stability. The experiment of prototype mobile robot which was not enough to check overall performances has been encouraging the possibility for developing autonomous robot.

Future plans are directed to the advanced nuclear robotic technology and successful develpment would eliminate human inspection in high dose rate area and improve the safety.

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