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Automatic Stair-Climbing Algorithm of the Planetary Wheel Type Mobile Robot in Nuclear Facilities

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원자력시설내에서의 유성차륜형 이동로보트의 자동계단 승월기법

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Abstract

A mobile robot, named KAEROT, has been developed for inspection and maintenance operations in nuclear facilities. The main feature of locomotion system is the planetary wheel assembly with small wheels. This mechanism has been designed to be able to go over the stairs and obstacles with stability.

This paper presents the inverse kinematic solution that is to be operated by remote control. The automatic stair climbing algorithm is also proposed. The proposed algorithms generates the moving pathes of small wheels and calculates the angular velocity of 3 actuation wheels.

The results of simulations and experiments are given for KAEROT performed on the irregular stairs in laboratory. It is shown that the proposed algorithm provides the lower inclination angle of the robot body and increases its stability during navigation.

요 약

원자력시설에서 점검 및 보수작업을 위하여 이동로보트 KAEROT을 개발하였다. 이동로보트의 주행장치는 소차륜들이 부착된 유성차륜의 형태로 구성되어 높은 안정성을 유지하며 계단을 포함한 많은 장애물의 승하강이 가능하도록 설계하였다

본 논문에서는 로보트의 원격조작을 용이하게 하기 위하여 이동로보트의 기구학적 해석을 통하여 역기구학 해를 구하였고, 자동 계단승월 알고리즘을 제안하였다. 제안된 알고리즘은 이동경로를 결정한 후 제안된 기준경로를 추종할 수 있도록 각 차륜의 각속도를 구하는 것이다.

제작 오차가 있는 실험실내 계단에 대하여 시뮬레이션 및 실험을 수행 하였다. 제안된 알고리즘은 로보트 몸체의 경사각도를 낮게 유지시킬 수 있었고, 주행중 안정성을 높혀주었다.

1. Introduction

Because of high radioactive dose rates inside a nuclear power plant the teleoperated mobile robot is important for decontamination, inspection, maintenance, and so on [1, 2, 3]. There are 3 approaches in designing the mechanism of the mobile unit such as wheel, leg, and crawler types [4, 5, 6]. Wheel mechanism has been commonly used since the ancient time due to its simple shape, high efficiency, and high speed. However, this system can't go over obstacles and stairs. Other types, including crawler type, have good mobility over unterrain, whereas they have a lot of problems in complexity and stability for intelligent control.

The mobile robots, such as TO-ROVER, AMOOTHY, AIMARS, and KAEROT employ the planetary-wheel mechanism [7, 8, 9]. Still teleoperators have much difficulties in controlling stair climbing because the front and rear planetary wheels are controlled independently. In addition, it is very difficult to develope the automatic stair-climbing method beacuse the procedure of climbing stair [7, 8, 9] requests the succesive rotation of planetary wheel assembly as shown in Figure 1.

In this paper, we propose a new procedure of climbing stairs. The porposed procedure has some advantages. This procedure reduces the number of small wheels into 2. Kinematic analysis through the proposed procedure is much easier than the precious one because the positions of 3 small wheels are changed in every 120° rotation of planetary wheel assembly.

The automatic stair climbing method has been developed to overcome stairs without the intervention of human operator. In the following section, we will describe the kinematic analysis of KAEROT and the

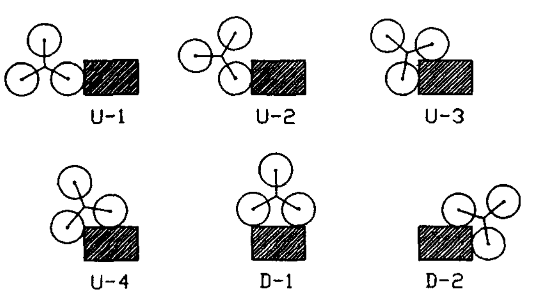


Fig. 1. The Procedure of Climbing Stairs for Previous Mobile Robot [7, 8, 9]

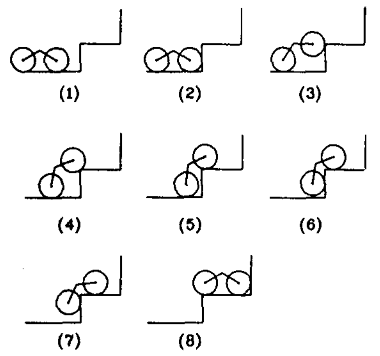


Fig. 2. New Procedure of Climbing Stairs for KAEROT

path planning method for climbing stairs automatically. Then, we will evaluate the effectiveness of the proposed algorithm by means of computer simulation and experiments.

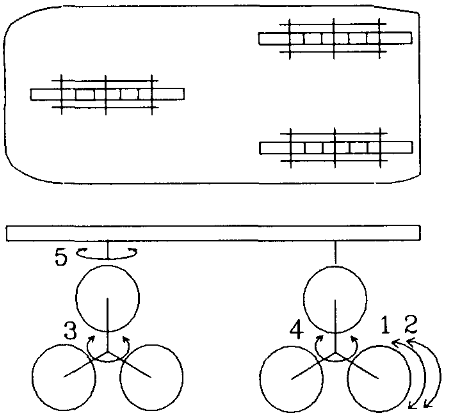
2. Stair Climbing Algorithm

2.1. Kinematic Analysis

The mobile robot developed adopts to 2DW1S (2 Driving-Wheel 1 Steering) as shown in Figure 3. Motor 1 and 2 drive rear small wheels independently, and motor 3 and 4 drive front and rear planetary wheel, respectively and motor 5 steers the robot. This mechanism enables the robot to run on the floor by small wheels, and to go up and down the stairs by planetary wheels [9, 10].

In this part, the planetary wheel assembly using the proposed climbing procedure is assumed to have only two small wheels and the coordinate system of the robot is assigned as shown in Figure 4. The center positions of each small wheel and planetary wheel are defined as (X_i, Y_i) (P_{ix}, P_{iy}), respectively.

The rotation angles of rear left and right small wheels are equivalent to each other because the robot developed does not need the steering motion during climbing stairs. Thus we reduce the robot kinematic model into 2-D case. Figure 5 showes the



1, 2 : Rear Left and Right Small Wheel
3, 4 : Front and Rear Planetary Wheel
5 : Steering Unit

Fig. 3. The Structure of the Mobile Robot

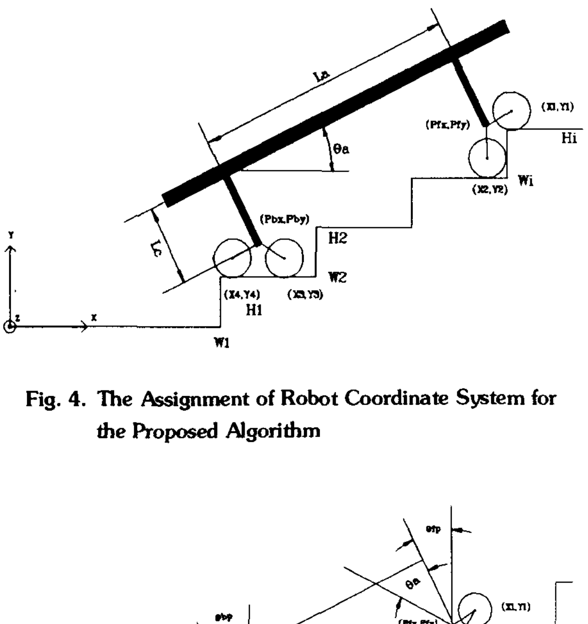


Fig. 4. The Assignment of Robot Coordinate System for the Proposed Algorithm

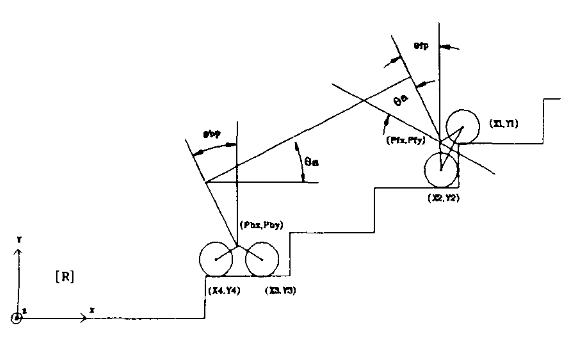


Fig. 5. The 2-Dimensional Modelling of KAEROT

2-dimensional modelling of KAEROT to describe the motion of its stair climbing.

The joint angles of the front and rear planetary wheels, θ_{fp}, θ_{bp}, and the inclination angle of the robot, θ_a, are expressed by the center positions of 4 small wheels as (X_1, Y_1), (X_2, Y_2), (X_3, Y_3), (X_4, Y_4).

$$\theta_{fp} = \arctan\left(\frac{Y_1 - Y_2}{X_1 - X_2}\right) - \theta_a \tag{1}$$

$$\theta_{bp} = \arctan\left(\frac{Y_3 - Y_4}{X_3 - X_4}\right) - \theta_a \tag{2}$$

$$\theta_a = \arctan\left(\frac{P_{fy} - P_{by}}{P_{fx} - P_{bx}}\right) \tag{3}$$

where

$$P_{fx} = \frac{1}{2}\left(X_1 + X_2 - \frac{Y_1 - Y_2}{\sqrt{3}}\right)$$

$$P_{fy} = \frac{1}{2}\left(Y_1 + Y_2 + \frac{X_1 - X_2}{\sqrt{3}}\right)$$

$$P_{bx} = \frac{1}{2}\left(X_3 + X_4 - \frac{Y_3 - Y_4}{\sqrt{3}}\right)$$

$$P_{by} = \frac{1}{2}\left(Y_3 + Y_4 + \frac{X_3 - X_4}{\sqrt{3}}\right).$$

And the rotational angle of rear small wheels θ_w is given by

$$\theta_w = \frac{MAX(\Delta X_3, \Delta X_4)}{r_0} + \Delta C \tag{4}$$

where

$$MAX(\Delta X_3, \Delta X_4) = \begin{cases} \Delta X_3 & (\Delta X_3 \geq \Delta X_4) \\ \Delta X_4 & (\Delta X_3 < \Delta X_4) \end{cases},$$

$$\Delta C = 0.4\Delta\theta_{bp} + \Delta\theta_a,$$

and r_0 is the radius of small wheel.

When the robot moves on the floor, ΔX_3 is equal to ΔX_4. For the robot moving on the stairs, the values of ΔX_3 and ΔX_4 are different because one small wheel of them has no contact on the stairs. The contact displacement of the small wheel with this stairs must be selected. MAX operation is used for selecting the appropriate displacement of small wheel.

The coupling term ΔC in equation (4) is caused by θ_{bp} and θ_a. The structure of planetary wheel assembly is dual pivot type. The rotation of rear small wheel is dependent on the rotation of the rear planetary wheel and the inclination angle of the robot. Given the center positions of 4 small wheels the actuation angles, θ_{fp}, θ_{bp}, and θ_{w}, are calculated [11].

2.2. Overview of Control Algorithm

The control method of KAEROT is based on teleoperation, but it is very difficult to operate the mobile robot on the stairs from remote location. We have developed the semi-automatic control scheme that human operates the mobile robot on the floor monitoring it from remote site.

The proposed automatic stair-climbing algorithm is composed of the recognition of stair size, the determination of contact-posture, and the path planning of 4 small wheels as shown in Figure 6. Stair size recognition unit has been developed to measure the height and width of the stairs in real time [12, 13]. The path planning of 4 small wheels is discussed in the next section.

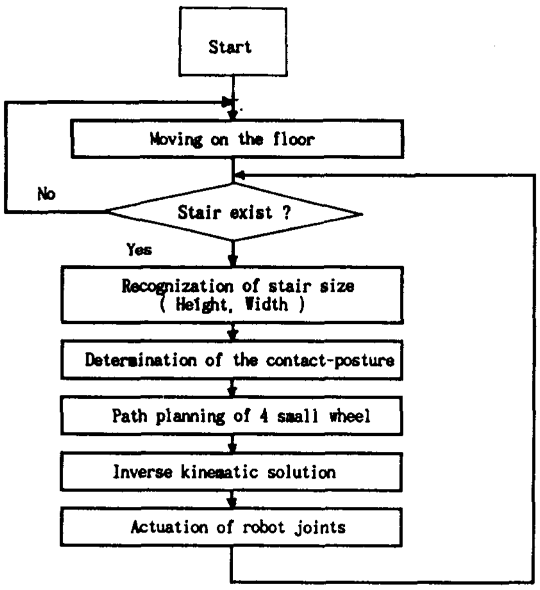


Fig. 6. Flow Diagram of Automatic Stair-Climbing Algorithm

2.3. Path Planning of 4 Small Wheels

Figure 7 shows the proposed method of path planning which take into account the stable-posture and simplicity. The dashed line denotes the moving pathes. In this section the center positions of 4 small wheels must be calculated every sampling period so that they are always enforced to follow the dashed line.

8 unknown variables, X_1, X_2, X_3, X_4, Y_1, Y_2, Y_3, and Y_4, must be solved analytically. The contact-posture between the surface of stairs and small wheel is limited to 4 cases as shown in Figure 8 because all small wheels are on the same path in the proposed algorithm. This contact-posture is able to apply either the front or rear planetary wheel assembly. That is, X_a is X_1 or X_3, X_b is X_2 or X_4, Y_a os Y_1 or Y_3, and Y_b is Y_2 or Y_4. The contact postures of Figure 8 are the same attribute, and two variables are constant at each contact-posture as follows;

- X_a and Y_b are constant in contact-posture 1
- X_b and Y_a are constant in contact-posture 2
- Y_a and Y_b are constant in contact-posture 3, 4

The number of unknown variables is reduced to four.

Figure 9 shows the constraints of small wheel and robot body. 3 constraint equations are given by

$$(X_1-X_2)^2+(Y_1-Y_2)^2=3R^2 \tag{5}$$
$$(X_3-X_4)^2+(Y_3-Y_4)^2=3R^2 \tag{5}$$
$$(P_{fx}-P_{bx})^2+(P_{fy}-P_{by})^2=La^2 \tag{7}$$

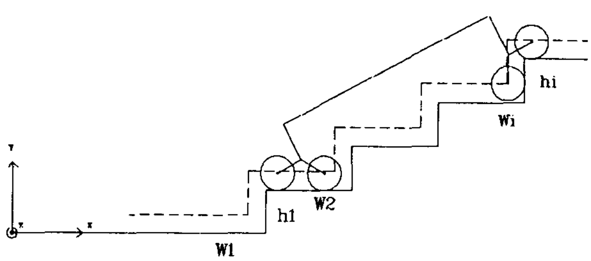


Fig. 7. The Pathes of 4 Small Wheels

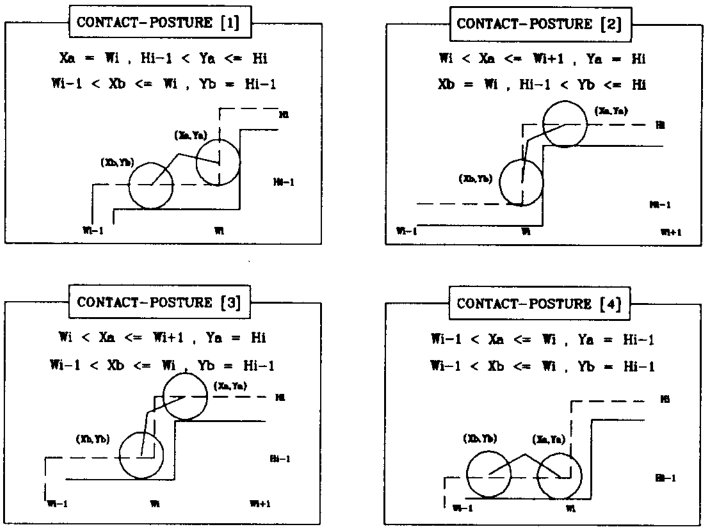


Fig. 8. Contact Posture between Small Wheels and Stair

where R is the arm length of planetery wheel, and La is the distance between the front planetary wheel and the rear one.

Only one variable between X_1 and Y_1 is given as a input data. When the robot is operated in manual mode, the data is entered from the joystick. On the automatic mode we select appropriate value considering robot stability.

The number of constraint equation is equal to one of unknown variables. Thus, the constraint equations can be solved for unknown variables. But it is possible only to solve numerically rather than deterministically. The detailed expressions are referred to [14].

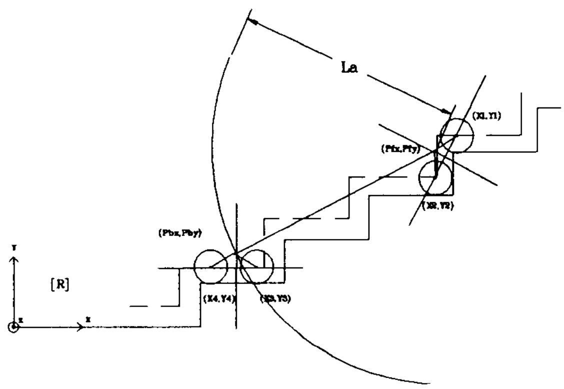


Fig. 9. The Constraint of the Robot Body

3. Simulated and Experimental Results

3.1. Simulated Results

We should consider the constraint of stair size to be applied the proposed algorithm as shown in Figure 10. The height and width of the stairs are constrainted as expressed in equation (8) because the proposed algorithm take use of the procedure of climbing stairs as shown in Figure 2.

$$\frac{H_i}{\sqrt{3}} \leq R \leq \frac{W_i - r_0}{\sqrt{3}} \tag{8}$$

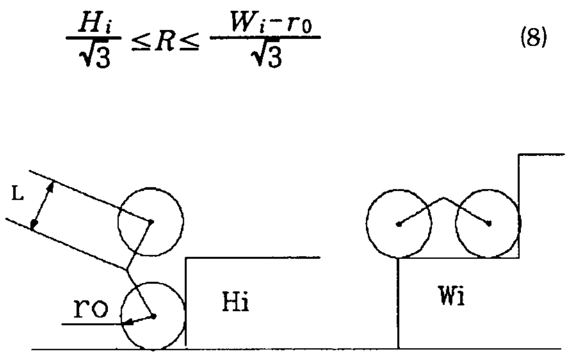


Fig. 10. The Constaint of Stair Size

In KAEROT, R and r_0 are 12cm and 7.5cm, respectively. From the equation (8) the constraint of stair size can be represented as follow;

$$H_i \leq 20.8cm,\ W_i \geq 28.3cm,\ \theta_a \leq 35.6^\circ$$

Considering the above constraint, stairs used for the simulation and the experiment are shown in Figure 11. Height, width, and slope of the stairs are about 18 cm, 38cm, and 25°, respectively.

We execute the graphic simulation on IBM PC using the proposed algorithm. At this point, we assumed that the size of the stairs is known parameter. For the animation of the proposed algorithm, we used the graphic software package developed in 1990 [15, 16].

In simulation the moving pathes of 4 small wheels and two planetary wheels are generated through the proposed algorithm [14]. The actuation velocities, $\dot{\theta}_{fp}$, $\dot{\theta}_{bp}$, and V_w are shown in Fig. 12. The sampling time is 100 msec. The graphic simulated result is represented in Figure 13.

3.2. Experimental Results

To evaluate the effectiveness of the proposed algorithm the inclination angle sensor is attached to the robot body and the real slope of robot is measured during climbing stairs. The configuration of control system for the experiments is shown in Figure 14. The inclination angle sensor, ACO-200, was manufactured by the ALEC Corporation. Its operating

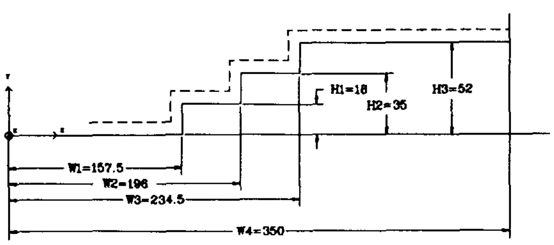
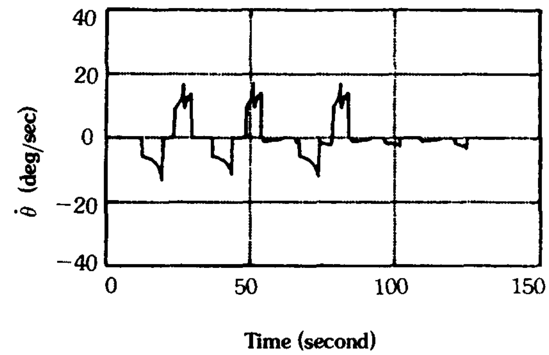
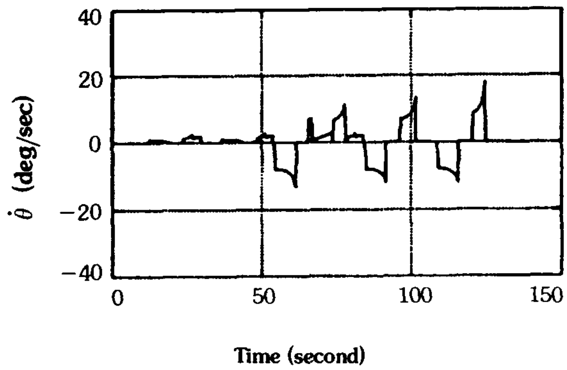


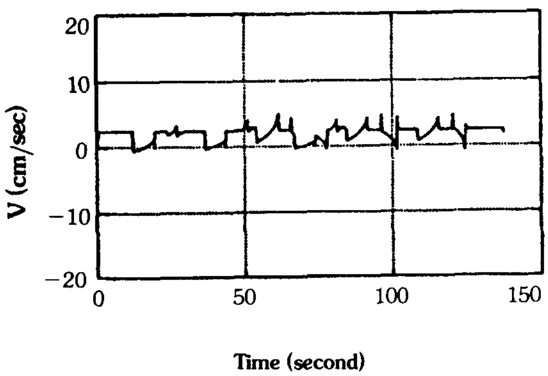
Fig. 11. The Stairs Used for Experiments



(a) $\dot{\theta}_{fp}$



(b) $\dot{\theta}_{bp}$



(c) V_w

Fig. 12. The Velocity of the Actuated Joints

range is $\pm 70^{\circ}$ as dual axes.

The inclination angle of robot obtained from the simulation and experiment are described in Figure 15. The dashed line denotes experimental value and the solid line simulated one.

The experimental values, as shown in Figure 15, show a good agreement with the simulated one during the stage of climbing up the stairs. The transient errors are due to the bending of elastic tire, the backlash of reduction gear, and the noise of sensor. They are negligible so thst they can not degrade the performance of the robot. Hence, it is proved that the proposed algorithm is very effective. The outlook of robot to climb up the stairs is shown in photo 1.

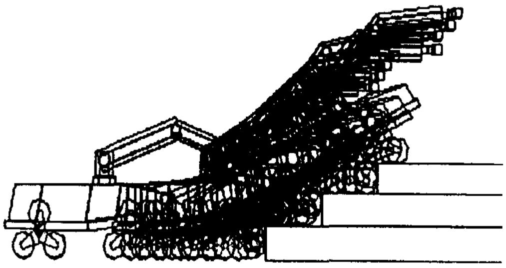


Fig. 13. The Result of Graphic Simulation of Climbing Stairs

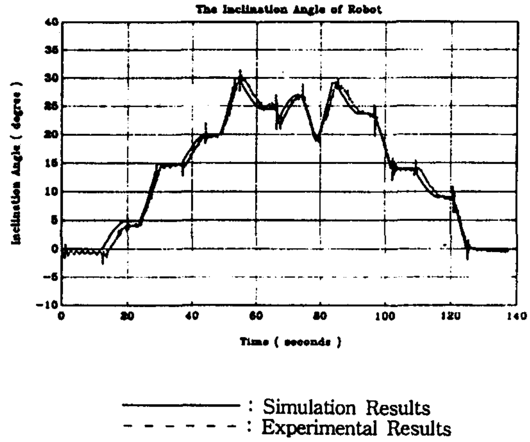


Fig. 15. The Comparison of the Inclination Angle of Robot

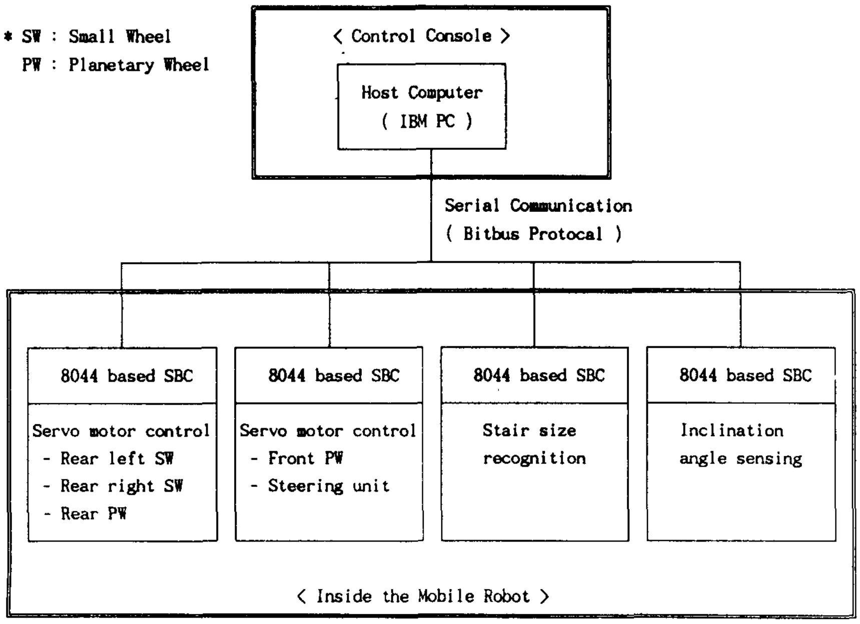


Fig. 14. The Configuration of Control System

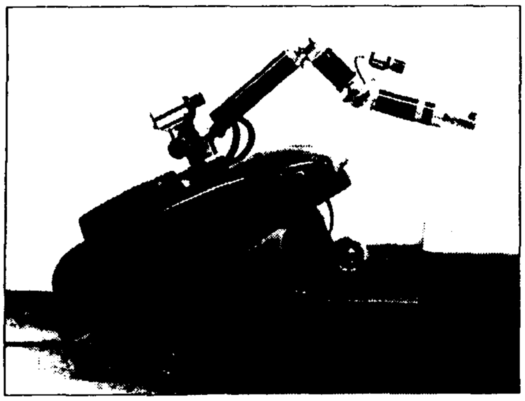


Photo 1. The Appearance of Mobile Robot

4. Conclusions

The importance of development in this work is in providing a teleoperated mobile robot that can be operated from remote site to perform inspection taskes in nuclear facilities without endangering human operators. Moreover when the robot climbs up and down stairs the automatic stair-climbing algorithm proposed lowers the inclination angle of the robot body and increases the stability.

Both simulated and experimental results obtained from the stairs with a slope of 25° and a height of 18cm show that the robot body maintain the inclination angle of 30.8° during stair navigation. It is concluded that the proposed algorithm is effective for the robot to move freely inside reactor and auxiliary buildings.

Futher study is being given to the development of the methods of identifying the size of the stairs in real time and generating the optimized path to overcome various shapes of obstacles.

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