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Development of Four-wheel-type Mobile Robot for Rough Terrain and Verification of Its Fundamental Capability of Moving on Rough Terrain

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***Abstract* - In many fields employing robots, e.g., wheelchair robots, rescue robots, and construction robots, robots that can move on rough terrains are desired. A robot with a simple mechanism and high mobility for all terrains is discussed in this paper. A four-wheel-type mobile robot is developed, and its design is discussed from a functional viewpoint. Its fundamental capability of moving on rough terrains is verified through simulations and experiments.**

Index Terms – Mobile Robot, Rough Terrain, Wheel-type Robot, Mechanism, Leg-like Axle.

I. INTRODUCTION

In many fields, there is a strong demand for mobile robots that can move on rough terrains, for example, to aid people who have difficulty in walking, for transportation purposes at disaster sites, for the performance of tasks at outdoor sites like forests, and in the construction industry. However, there are few robots that are suitable for use in rough terrains.

Broadly speaking, the functions necessary in a mobile robot for use in rough terrains are path planning ability and movement ability. Many researches have been performed on both these functions. Many researches have also dealt with improving the mobility performance. To provide a few examples of leg-type robots, there is the ASV [1] and the TITAN series [2]. Examples of wheel- and crawler-type robots are Sojourner that was built by NASA, CRAB [3] and TAQT Carrier [4]. Roller-Walker [5], Whegs[6], Wheeleg [7] and the Chariot III [8] are examples of leg-wheel robots. Most of these researches realized high performance with regard to the mobility in assumed environments.

For providing a rough terrain mobile robot with the path planning ability, it is necessary to develop a method that will facilitate high mobility performance by using a simple mechanism. In other words, there are few robots that can be used to address the path planning problem since only robots that show sufficient mobility performance for rough terrains and that employ a simple mechanism and involve a conventional control method can be used.

In this study, a robot that shows sufficient mobility performance on rough terrains is examined. The robot employs a simple mechanism that is different from those of conventional mobile robots [1]-[8]. It has four wheels at every leg tip, and the leg is the simplest one. It can move like a wheeled robot and get over a step like a legged robot. In addition, its fundamental capability of moving on rough terrains is verified through simulations and experiments.

A. Target Environments

In this study, I define the target environment as follows.
1) An indoor environment with an uneven ground surface
2) An artificial outdoor environment with an uneven ground surface and a staircase
3) Natural terrain like a promenade in a forest.

The maximum step height and the maximum height of obstacles such as stones are assumed to be 0.25 (m) and 0.15 (m), respectively. The following are some example applications.
1) As substitute for wheelchairs and senior cars
2) In factories, disaster sites, and construction sites

II. MOBILE ROBOT FOR ROUGH TERRAINS

Table I shows the current state of the practical use of robots with different locomotion mechanisms. It is understood that robots with complex mechanisms are not suitable for practical use from the viewpoint of control, operation, and maintainability. On the other hand, wheel-type robots are suitable for practical applications.

TABLE I
STATUS OF PRACTICAL USE OF MOBILE ROBOTS WITH DIFFERENT LOCOMOTION MECHANISMS

Type	Situation
Leg type	It has not been put to practical use yet.
Wheel type	There are some practical uses (for instance, cleaning robots).
Crawler type	There are a few practical uses (for instance, in the leisure and construction fields).
Composite mechanism type	It has not been put to practical use yet.

The main characteristics that a mobile robot used for general purposes in a rough terrain should possess are enumerated below.
1) Good ability to move on rough terrains (essential for a rough terrain mobile robot)
2) High-speed mobility (essential for a mobile robot)

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3) Easy control (indispensable factor in the operation of a robot)

4) Simplicity of mechanism (indispensable feature for maintenance)

There is no mechanism superior to the wheel mechanism from the viewpoint of high speed, and the leg mechanism is the best from the viewpoint of adjustment to rough terrains. Therefore, to perform the essential functions of mobile robots in rough terrains, both wheel and leg mechanisms are needed. In this paper, under the assumption that the robot performs the functions of both wheel and leg, I attempt to realize both maintainability and easy control by simplifying the mechanism as much as possible.

A. Mechanical Design

In this paper, I make the following assumptions.

1) A leg-wheel robot is used as the basic robot to discuss a suitable mechanism for rough terrains because both wheel and leg are necessary for rough terrain mobile robots. This type of robot, which has been studied by Hirose, the present author, and other researchers, has both high speed and high adaptability for unstructured terrains.

2) The proposed robot has four wheels in order to maintain its stability when the center of gravity changes due to any extra load.

3) Each wheel is attached to the tip of a leg because in many cases, sufficient space is not available to set the leg and wheel separately on the body of the robot.

Just like animals and insects living in different conditions have different shapes, there must be specific locomotion mechanisms that are suitable for movement on each rough terrain. Therefore, the proposed mechanism is not the best for all terrains.

TABLE II

STRENGTHS AND LIMITATIONS OF LEG-WHEEL ROBOTS

Strengths	Mobility performance on rough terrains is high because of the use of the leg mechanism.
	High-speed movement is possible because of the use of the wheel mechanism.
	Robot capability can be enhanced by using leg and wheel mechanisms cooperatively.
Limitations	There is a danger of collision between the leg of the robot and a person in the leg's movement range.
	The number of actuators (required for the legs) increases, and thus, the cost also rises.
	Operability and maintainability worsen because of the complexity of the leg mechanism.

Table II shows the strengths and limitations of the leg-wheel robot. It is necessary to reduce the complexity of the leg mechanism and limit the leg's movement range. In the following, the proposed mechanism is discussed by considering the necessary functions.

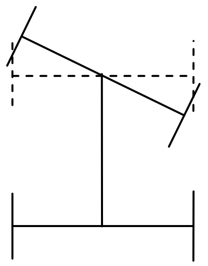


Fig.1: Steering mechanism

B. Stability of Occupant and Load

When the robot traverses a slope, the occupant and the load should be maintained in the horizontal position to make the ride comfortable. Therefore, the pitch of its sheet (i) and the roll of its sheet (ii) should be capable of being adjusted.

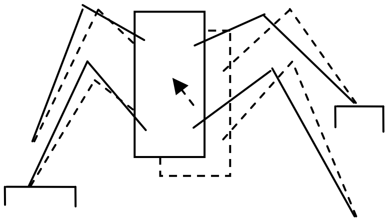


Fig.2: Body position adjustment without displacement of supporting points

C. Steering (iii)

Direction control of the robot is necessary. For this, the Ackermann steering mechanism and the mechanism illustrated in Fig.1 are used for steering.

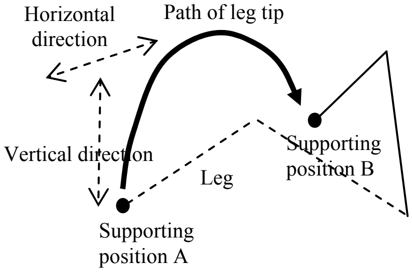


Fig.3: Leg-type robot can select the supporting position arbitrarily.

D. Function of Leg

The general functions that the leg mechanism facilitates are shown in Table III. When all the legs do not possess multiple degrees of freedom, function 3 in Table III cannot be realized (Fig.2). In this paper, it is assumed that only functions 1 and 2 are to be realized because function 3 is not frequently used in rough terrains. For realizing function 2, it is necessary for the leg tip to be capable of moving vertically (iv) and horizontally (v), as shown in Fig.3.

It is preferable to realize two or more functions with one degree of freedom in order to avoid a complex mechanism. Therefore, the axle is made to be controllable in the rolling direction, and both functions (ii) and (iv) are realized, as shown in Fig.4. Moreover, (iii) and (v) are realized by setting the other drivable shaft as shown in Fig.4. This mechanism is hereafter referred to as leg-like axle. Moreover, in order to enable every leg to raise its wheel (Fig.5), the robot is equipped with a leg-like axle at both the front and rear.

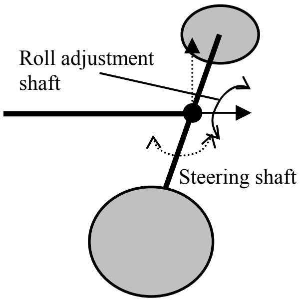


Fig.4: Mechanism of leg-like axle

TABLE III

FUNCTIONS FACILITATED BY A LEG

No.	Function
1	Body can be supported
2	Location of a supporting point can be arbitrarily selected
3	Body position can be adjusted without changing the supporting points

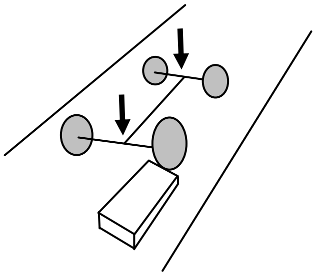


Fig.5: Leg-like axle is provided at both the front and rear in order to enable every leg to raise its wheel.

Each wheel is driven and controlled independently owing to the following reasons.

1) There is a possibility of the body falling when moving over a rough terrain on a slope, as shown in Fig.6, if all the wheels are not active wheels.

2) The speed of the right wheel is different from that of the left wheel, even when moving straight on a rough terrain, because on a rugged road, the path of each wheel is different from the paths of the other wheels.

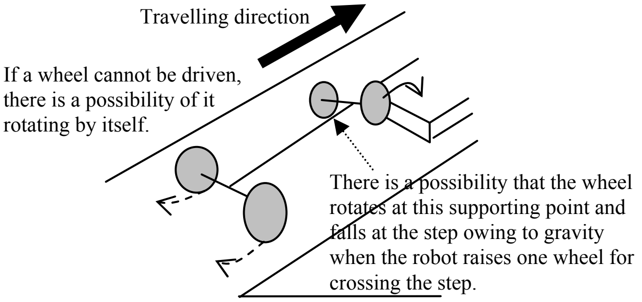


Fig.6: There is a possibility of the body falling if all the wheels cannot be driven.

Finally, the body is provided with an adjustment shaft, as shown in Fig.7, to control the sheet's horizontal pitch.

The proposed robot, which was named "RT-Mover," was designed as shown in Fig.7. The dimensions of the robot were approximately half of the actual dimensions for simplifying the experiments performed to evaluate it.

TABLE IV
MAIN SPECIFICATIONS

Principal dimensions	Length: 800 (mm); Width: 450 (mm); Height: 134 (mm)
Wheel size	Radius: 100 (mm); Width: 30 (mm)
Weight	21.5 (kg) (Weight of sheet part: 1.5 (kg))
Motor (DC Servo)	23 (W) (Steering: 2; Sheet's pitch: 1)
	40 (W) (Wheel: 4; Sheet's roll: 2 (front and rear))
Gear ratio	40 (Sheet's pitch: 1 (warm gear))
	100 (Wheel: 4; Sheet's roll: 2 (harmonic gear))
	400 (Steering: 2; (Harmonic gear: 100; Belt drive: 4))
Sensor	Posture angle sensor (sheet's pitch and sheet's roll)
	Encoder and current sensor (each motor)
Power supply	Battery 24 (V)

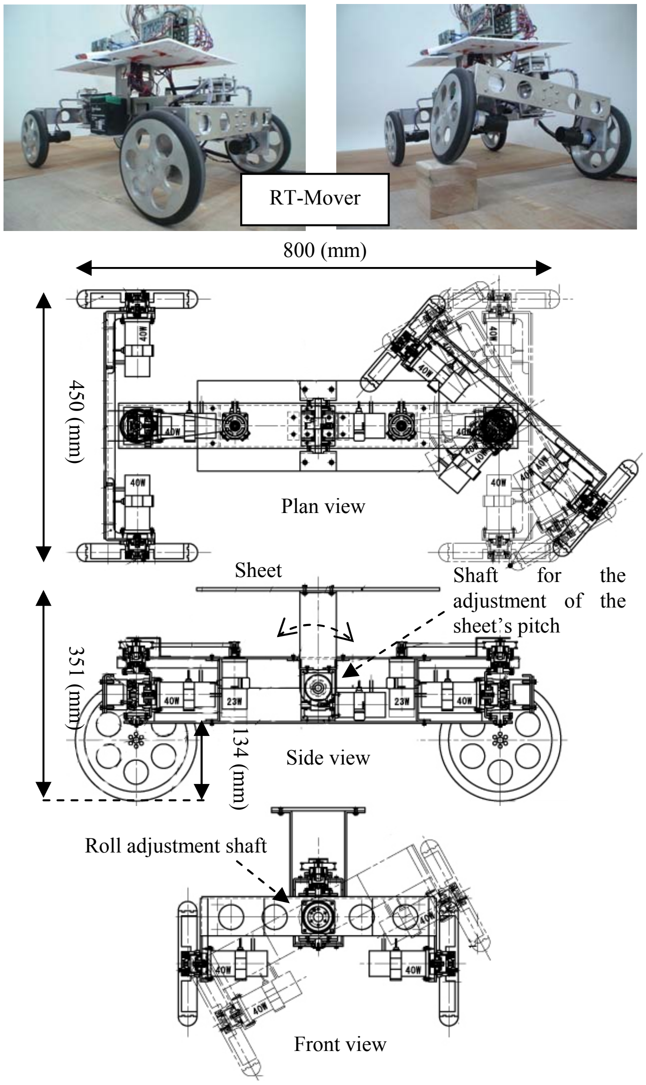


Fig.7: Assembly drawing of RT-Mover

III. VERIFICATION OF FUNDAMENTAL CAPABILITY OF MOVING ON ROUGH TERRAIN THROUGH SIMULATION

Three fundamental cases were simulated in order to confirm that the robot can maintain the sheet in a horizontal position when moving on a rough terrain. The three cases are (a) moving on a slope, (b) traversing a slope, and (c) crossing random obstacles.

The control law concerning the sheet's pitch is

$$T_{\theta_p} = -K_p(\theta_p - \theta_{dp}) - D_{p'}(\dot{\theta}_{p'} - \dot{\theta}_{dp'}) = -K_p\theta_p - D_{p'}\dot{\theta}_{p'}, \quad (1)$$

where T_{θ_p} is the torque of the adjustment shaft controlling the sheet's pitch, θ_p is the sheet's pitch, θ_{dp} is the desired pitch, $\dot{\theta}_{p'}$ is the angular velocity of the adjustment shaft controlling the sheet's pitch, $\dot{\theta}_{dp'}$ is the desired angular velocity of that, K_p is the angle gain, and $D_{p'}$ is the angular velocity gain. Both the desired pitch and desired angular velocity become 0 when the desired pitch is horizontal. The reason why not $\dot{\theta}_p$ but $\dot{\theta}_{p'}$ is used is that in case of the actual robot in this study, the data of angular velocity of the sheet's pitch is a little delayed owing to the specification of the posture angle sensor (max 10 (ms), Fig.12) . Therefore, $\dot{\theta}_{p'}$, which is the data of the adjustment shaft's encoder, is better for controlling the robot in this study. On the other hand, if there were no data delay and no back lash etc., that is, the ideal situation, $\dot{\theta}_{p}$ should be used for better performance.

The control law concerning the sheet's roll is

$$T_{\theta_r} = K_r(\theta_r - \theta_{dr}) - D_{r'}(\dot{\theta}_{r'} - \dot{\theta}_{dr'}) = K_r\theta_r - D_{r'}\dot{\theta}_{r'}, \quad (2)$$

where T_{θ_r} is the torque of the roll adjustment shaft, θ_r is the sheet's roll, θ_{dr} is the desired roll, $\dot{\theta}_{r'}$ is the angular velocity of the roll adjustment shaft, $\dot{\theta}_{dr'}$ is the desired angular velocity of that, K_r is the angle gain, and $D_{r'}$ is the angular velocity gain. This control law is applied to both the front and rear shafts. Because this roll adjustment shaft is for controlling not the sheet's roll but leg, the sign of K_r in (2) is different from that of (1).

The conditions employed in the simulation are as follows.

1) K_p = 150 (N·m), $D_{p'}$ = 0.8 (N·m·s), K_r = 220 (N·m), $D_{r'}$ = 0.8 (N·m·s)

2) The speeds of all the wheels are maintained at a constant value ((a), (b): 0.3 (m/s); (c): 0.15 (m/s))

3) The steering angle of both the front and rear axles is maintained at 0.

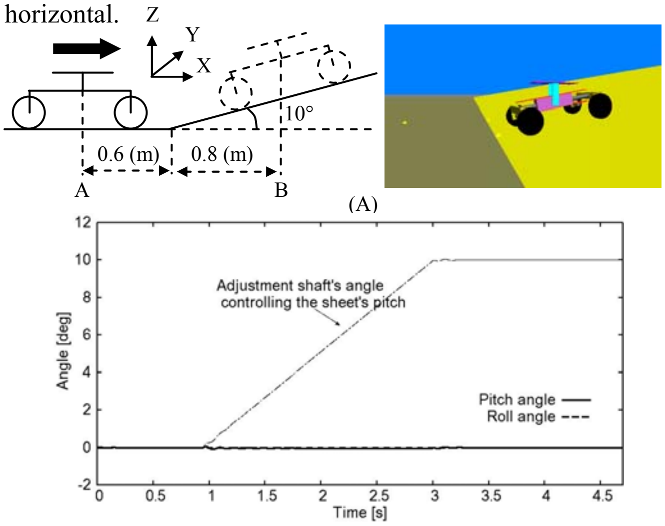
4) The wheels and steering are controlled by PD control.

Fig.8 shows (A) the shape of the road in and a scene from the simulation and (B) the data of the sheet's pitch and roll and the adjustment shaft of the sheet's pitch for the movement from point A to B in (A). After moving on the plane, the robot ascended the 10° slope.

Both the sheet's pitch and roll are maintained at almost 0; however, this is hard to view in the figure because of overlapping data. Fig.8 shows that because the adjustment shaft controlling the sheet's pitch is appropriately controlled, the sheet's pitch continues to be horizontal.

At point A, the robot has already attained a constant speed, and hence, the influence of the acceleration at the beginning is not evident. (Figs.9 and 10 are similar to Fig.8.) The coordinate system used in the simulation is shown in Fig.8 (A).

Fig.9 presents the simulation data for the case of traversing a slope. After moving on the plane, the robot traverses the 10° downward slope. For the left wheel, the road height is the same between the plane and the slope. On the other hand, there is a downward step for the right wheel (actually, the rear left wheel moves on a very small downward step because of a little change of traversing direction after the right front wheel moves down the step). Fig.9 (B) shows the data of the sheet's pitch and roll and both the front and rear roll adjustment shafts for the movement from point A to point B. Both the sheet's pitch and roll are maintained at almost 0; however, this is hard to observe in the figure because of overlapping data. When each axle enters the sloping region, the corresponding roll adjustment shaft is controlled according to the inclination of the slope. As a result, the sheet's roll is maintained to be horizontal.

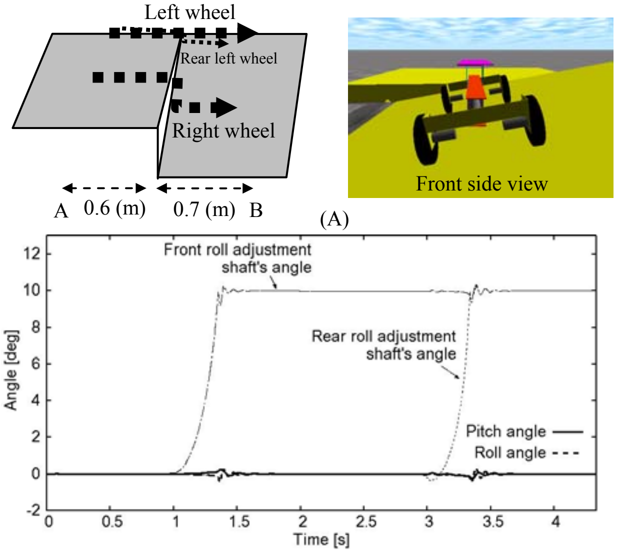


(A)

(B)

Fig.8: Simulation for the case of ascending a slope (10°)

Fig.10 shows the simulation data for the case of crossing random obstacles. Fig.10 shows (A) the shape of the road in and a scene from the simulation, (B) the data of the sheet's pitch and the adjustment shaft controlling the sheet's pitch for the movement from point A to point B, and (C) the data of the sheet's roll and both front and rear roll adjustment shafts for the movement from point A to point B. (B) and (C) show that each adjustment shaft is controlled appropriately and the sheet's posture angle is maintained to be horizontal, even when crossing random obstacles.

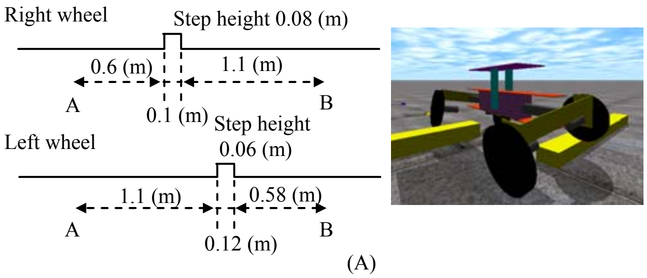


(A)

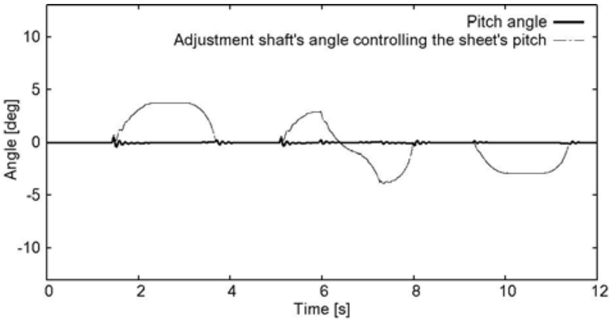
(B)

Fig.9: Simulation for the case of traversing a slope (10°)

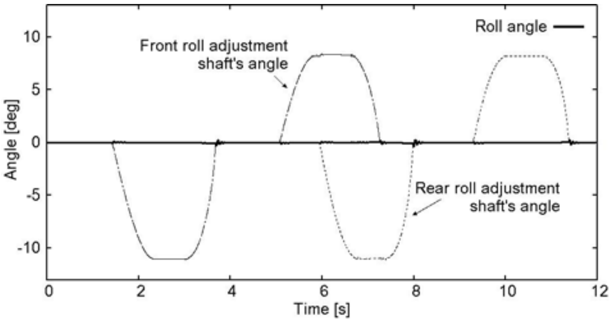
When the wheel hits an obstacle, the steering shaft is blurred because of the reaction force of the obstacle. If the robot is required to move exactly straight, it is necessary to adjust the corresponding wheel speed according to both the rotation angle of the steering shaft and that of the roll adjustment shaft. This case is a subject for a future study.



(A)



(B) Data of the sheet's pitch and adjustment shaft controlling the sheet's pitch



(C) Data of the sheet's roll and roll adjustment shafts at the front and rear

Fig.10: Simulation for the case of crossing random obstacles

IV. EXPERIMENTAL RESULT

The mobility performance of the robot is confirmed through experiments. The main specifications of the proposed robot are shown in Fig.7 and Table IV. The system configuration is shown in Fig.11. The robot is equipped with two SH4 boards—one for controlling the robot and the other for processing the posture angle sensor data. The I/O board is connected to each SH4 board and each of the data is inputted or outputted through the I/O board. Each SH4 board communicates with the other SH4 boards through socket communication. The structure of the software is shown in Fig.12. The robot is controlled in real time on ART-Linux. The control system is divided into two layers—gait strategy layer and motion control layer. In the former, the manner in which the leg-like axle, wheel, steering shaft, and adjustment shaft are used is planned, and in the latter, each actuator is controlled on the basis of the gait strategy.

The experimental conditions are the same as the conditions in the simulation, excluding $D_{p'}$ = 4.0 (N·m·s) and $D_{r'}$ = 5.1 (N·m·s). Owing to friction, every angular velocity gain value is different from that in the simulation. The experimental data corresponds to the movement from point A to point B in the figure. The speed of the robot steadies at point A.

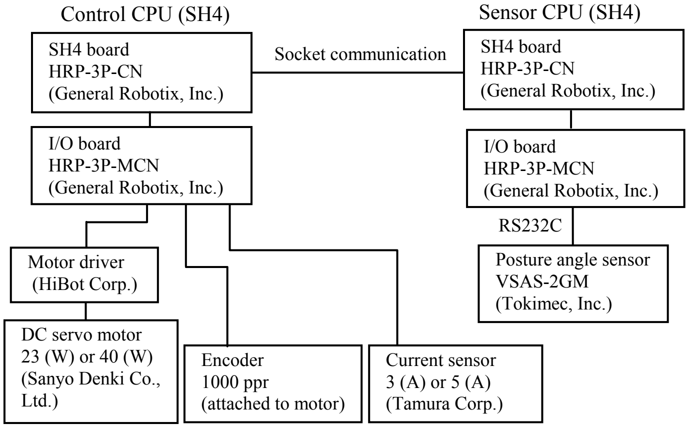


Fig.11: System configuration

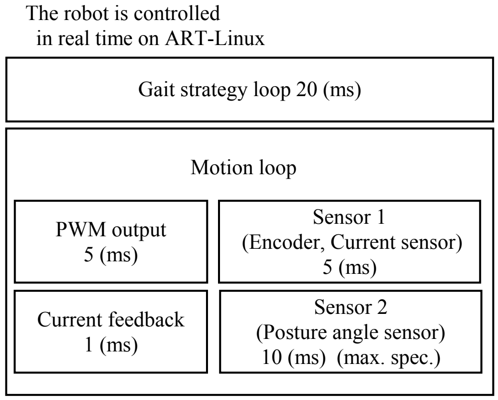
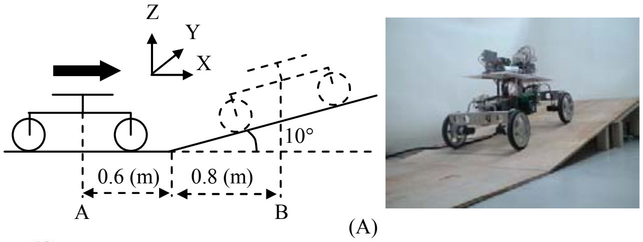
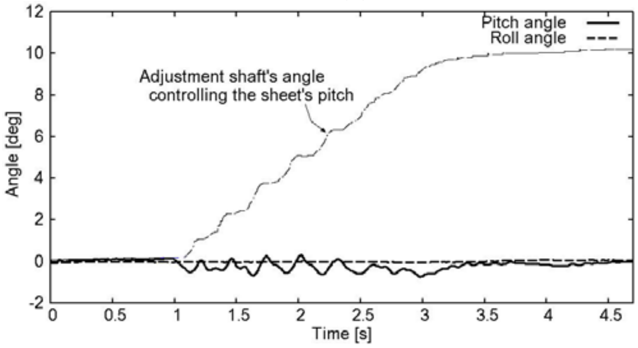


Fig.12: Structure of software

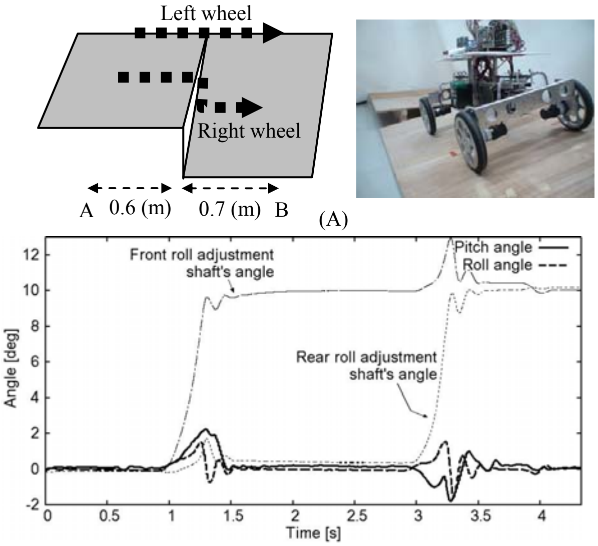


(A)



(B)

Fig.13: Experimental data for the case of ascending a slope (10°)



(A)

(B)

Fig.14: Experimental data for the case of traversing a slope (10°)

The experimental data are shown in Figs.13–15. The result in each figure shows that the sheet of the robot, on which a person or thing is considered to be positioned in the case of a robot of the actual size, can be stably controlled when moving on three typical rough terrains. The difference between the experimental data and the simulation data is due to errors in modeling the friction along each axis and the inertia of each part. In particular, the cause of the oscillation in the sheet's pitch is the backlash of the adjustment shaft controlling the sheet's pitch.

V. CONCLUSION

In this study, a robot that shows sufficient mobility performance on rough terrains is developed. It has four drivable wheels and two leg-like axles. Each wheel is mounted on one side of the leg-like axles at the front and rear of the body. In addition, its fundamental capability of moving on rough terrain is verified through simulations and experiments.

The simulations and experiments were performed for three road shapes. In every case, the robot was able to move on the rough terrain by maintaining the horizontal position of the sheet. The result obtained was what was expected.

Since this research has just started, there are many aspects that need to be investigated to take this research forward. A few of these aspects are as follows.

1) Techniques for controlling the difference between right and left wheel angles according to the positions of both steering shaft and roll adjustment shafts

2) Strategy for moving on various types of rough terrains

3) Control method for dynamic movement of rough terrains

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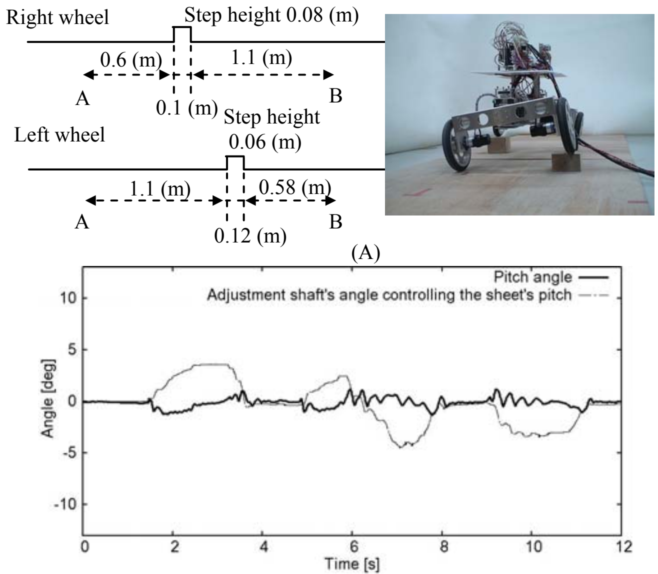
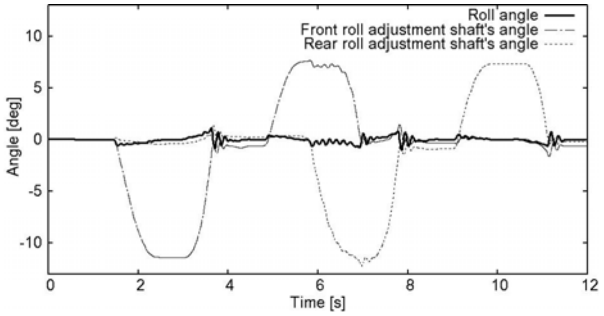


(A)

(B) Data of the sheet's pitch and adjustment shaft controlling the sheet's pitch



(C) Data of the sheet's roll and roll adjustment shafts at the front and rear

Fig.15: Experimental data for the case of crossing random obstacles

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