Proceedings of the 1999 IEEE/RSJ
International Conference on
Intelligent Robots and Systems

Mechanism and Control of a Leg-Wheel Hybrid Mobile Robot

H. Adachi and N. Koyachi
Mechanical Engineering Laboratory
Namiki 1-2, Tsukuba, Ibaraki
305-8564 Japan

T. Arai
Osaka University
Machikaneyama 1-3, Toyonaka
Osaka, 560-8531 Japan

A. Shimizu and Y. Nogami
Nisshinbo Industries, INC.
Azukizaka 30, Miai, Aichi
444-0802 Japan

Abstract

This paper describes mechanism and control of leg-wheel hybrid mobile robot. Legged locomotion has high adaptability for rough terrain, and wheeled locomotion posses speed and efficiency. A new locomotion mechanism that combines legs and wheels is proposed, and a prototype mobile robot that adopts the mechanism is introduced. The robot has four legs, and a wheel is attached at the end of each leg. The front leg has three joints and a passive wheel. The rear leg has one joint and an active wheel. In order to make the best of the mechanism, three locomotion modes, wheel mode, hybrid mode, and step mode, are developed. In the wheel mode, four wheels are used on flat terrain. On the rough terrain, the hybrid mode is select, and two legs and two active wheels are used for locomotion. To climb or descend a large step, the step mode is used.

1. Introduction

Recently, works in manufacturing industry have been automated. In the case of outdoor works, mechanization such as construction machines has been done only on relatively flat terrain. Japan is a mountainous country, and seventy percent of the land is mountain area. Most of works in the mountain sites depends on human labors. For the future, the works in such area will become important from the point of view of the prevention of natural calamities or the environmental problems. To automate such works, development of the locomotion system that can move in mountainous environment is essential. The mountain environment includes steps, inclined terrain, and easily deformed and collapsed terrain.

Many mobile robots for outdoor environment are equipped with wheels or crawlers. However, they cannot move on discontinuous terrain like steps. Although legged robots have great adaptability for complicated environment, they have some difficulties also. Generally, legged robots require large number of actuators and complicated mechanism. Moreover, their walking speed is slow even on flat terrain. Considering these facts, authors propose a new locomotion mechanism that combines legs and wheels.

Up to the present, several leg-wheel hybrid type mobile robots have been developed. Hitachi, Ltd. developed a five-legged robot, whose leg has two joints and an active wheel at its tip [1]. It has fifteen degrees of freedom. A robot that has four legs and six wheels was developed by Mitsubishi Heavy Industries, Ltd. [2]. The robot body was equipped with two active wheel and four legs that has two joints and an active wheel at their end. It has fourteen actuators. Kobe Steel, Ltd. constructed a six-leg-wheel type robot in the Japanese national project named Advanced Robot Technology [3]. This robot has six two-degrees of freedom legs, and each leg has a two-degrees of freedom (steerage and traction) wheel. Totally, it has twenty-four degrees of freedom. ETH (Switzerland) also developed a mobile platform for rough terrain [4]. It has two three-degrees of freedom legs and also has two one-degree of freedom legs that have a passive wheel at their end. Its number of active degree of freedom is eight. Tohoku University (Japan) constructed a leg-wheel separation type robot [5]. It has two big active wheels at the both sides of the body, and four legs with three joints at the both ends of the body. Fourteen actuators are used for the robot.

In this paper, classification of the environment for mobile robot is considered from the viewpoint of locomotion mechanism at first. In section 3, a new locomotion mechanism is proposed, and a prototype robot that employs the mechanism is introduced. Section 4

0-7803-5184-3/99/$10.00 © 1999 IEEE

describes moving algorithm for the prototype robot. Implementation of the algorithm is explained in section 5.

2. Locomotion mechanism and environment

Now we consider classification of the environment from the contact between locomotion mechanism and the ground. When terrain is flat, the locomotion mechanism can always keeps contact with the ground. We call this kind of terrain continuous contact locomotion environment. In this environment, conventional wheels and crawlers are available. Although wheels and crawlers have different locomotive capability, both mechanisms always keep contact with the ground during locomotion. The trace of movement in this environment is continuous lines. One of the causes wheeled or tracked vehicle cannot move is existence of obstacles like steps. We call the terrain that includes such obstacles discontinuous contact locomotion environment. In order to move in this kind of environment, robots that have actively suspended wheels or shape-changeable crawlers have been developed. In this environment, a mechanism that switches the contact point between the locomotion mechanism and the ground is essential. The trace of the movement is line segments. More serious environment is discrete contact locomotion environment. In this environment, continuous contact between locomotion mechanism and the ground is not allowed. Locomotion mechanism has to support and propel the robot only by using discrete point contacts with the ground. Robots in this environment must be equipped with legs. The trace is sequence of points.

Our research target is locomotion in mountainous area, and it is considered as discontinuous contact locomotion environment. To move over obstacles such as steps, legged locomotion is effective. However, legged mechanism has demerits also. The mechanical configuration is complicated, and it requires large number of degrees of freedom. Generally, three degrees of freedom are necessary for each leg. In the case of a quadruped, total number of actuator is twelve. Moreover, moving speed or energy efficiency is lower than wheeled or tracked locomotion when it moves on relatively flat terrain.

3. Proposed locomotion mechanism

We set basic requirements for our experimental mobile robot as follows.

1) On flat terrain, fast and efficient locomotion is realized with simple control.
2) The robot can move in the discontinuous contact locomotion environment.
3) For the movement on steep slope, traction is generated at the all contact points between the robot and terrain.
4) In order to increase the reliability and decrease the cost, the robot has less number of actuators than normal legged robot.

To satisfy above requirements, we propose a new configuration as shown in Fig.1. Many mobile robots developed earlier have an active wheel at the tip of their leg. Though such a mechanism shows high adaptability to the environment, it requires large number of actuators. In our proposed scheme, different kinds of mechanism are employed at the front end and rear end in order to decrease the number of actuators. The robot has two front legs and two rear legs. Front leg has a serial link structure, and has three rotational joints. A relatively small lockable passive wheel is attached at the tip of each front leg. The first joint, that links the body and the thigh, has vertical axis and the second and third joints have horizontal axis. End of the front leg (passive wheel) can be positioned arbitrarily in its work space. Rear leg has a rotational joint, and also has a relatively large active wheel at the tip of the leg. The joint axis is horizontal, and its movable range is over one round. Accordingly, the active wheel moves on a circular trajectory in the lateral plane. Totally, this configuration has ten degrees of freedom, and it is smaller number than that of a normal quadruped robot, twelve. On a flat terrain, four wheels are used for locomotion. Wheels contribute

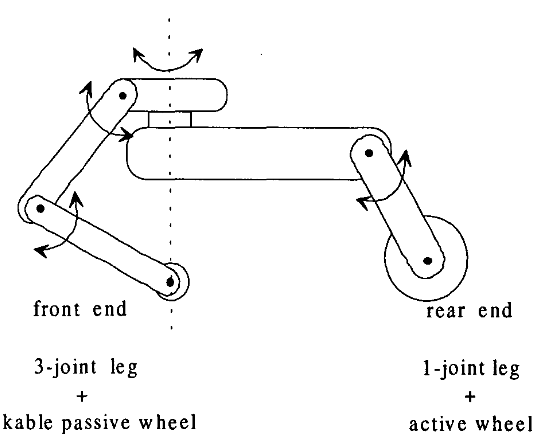

Fig. 1 Proposed configuration

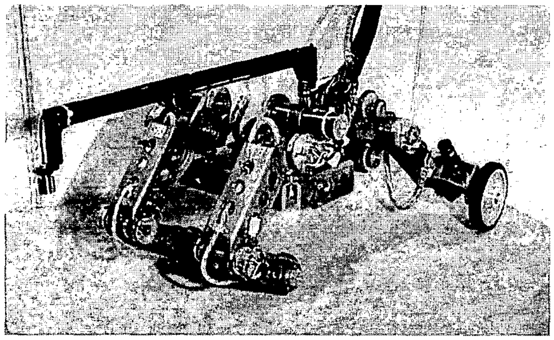

Fig. 2 Photograph of "Walk'n Roll"

Table 1 Basic specifications

structure	front: 2 legs (3 joints and lockable passive wheel) rear : 2 legs (1 joint and active wheel)
size (home position)	length: 630[mm] width: 440[mm] height 280[mm]
weight	14[kg] (approximately)
actuator	11 DC servomotors (leg joint, wheel, sensor arm) 2 solenoids (break)
key dimension	distance between legs 180[mm] (front/front) 300[mm] (front/rear) distance between rear wheels 432[mm] wheel diameter 60[mm] (front) 120[mm] (rear) leg length 170[mm] (front thigh) 140[mm] (front shank) 150[mm] (rear)
sensor	ultrasonic range sensor (mounted on active sensor arm) pendulum type attitude sensor (mounted in the body)

fast and efficient locomotion. When front passive wheel is positioned at just bellow the first joint axis, steering action is performed by controlling the first joint only. In addition, legs can function as active suspensions. In the case of rough terrain, the front passive wheels are locked, and front two legs are used to walk. Rear active wheels are still used for locomotion. The robot can generate traction at the all the contact points between the robot and the ground. When the robot encounters a large step

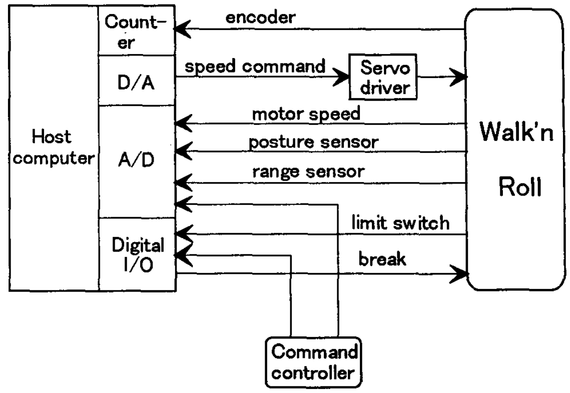

Fig. 3 Control system

where rear wheel can not climb, the rear leg is moved from the rear side to the front side through the air by leg joint motion.

Fig.2 shows a photograph of constructed mobile robot, and it is called "Walk'n Roll". Basic specifications are also shown in Table 1. The robot is separated from the power source, motor amplifiers, and a control computer, and they are connected by the cables. DC servo motors are used to drive the joints and rear wheels. Solenoids are used to lock the front wheels. Rotary encoder is attached at each joint and active wheel. In order to detect a step, the robot is equipped with an ultrasonic range sensor. The sensor head is attached at the tip of an arm that rotates around the vertical axis on the body. The altitude of the terrain around the robot is measured by the sensor. Control is performed by a personal computer. The whole control system is shown in Fig.3. In order to provide the command to the robot, the control system is equipped with a command controller. Operator can give four analog and six digital signals to the computer as the control commands.

4. Locomotion algorithm

Walk'n Roll has several locomotion modes by selecting wheeled function or legged function.

4.1 Wheel mode

In this mode, four wheels are used for locomotion, and fast and efficient locomotion is realized on relatively flat terrain. Rear wheels are driven, and front wheels are free and perform steering action. When front wheel is positioned just bellow the first joint, steering action is done by controlling the first joint only. The other two joints and rear legs can be used as active suspension.

Next, we consider relation between steering angle and wheel driving. Now we consider a situation as shown in Fig.4. We set a coordinate system fixed to the robot body, and its x-axis is moving direction and the y-axis is a line connecting two rear wheels. A wheeled vehicle whose front wheels perform steering action has a turning center on the line connecting rear wheels. In this figure, θ_1 and θ_2 denote the steering angle. When the coordinate of the turning center is r, θ_1 and θ_2 are calculated as following equations.

$$\theta_1 = \tan^{-1}\{a/(r-b)\} \quad (1)$$

$$\theta_2 = \tan^{-1}\{a/(r+b)\} \quad (2)$$

Here, a is wheel base, and b is half of front wheel tread. A ratio of travelling distances of two rear wheels w_3/w_4 is given by next equation.

$$w_3 / w_4 = (r-c)/(r+c) \quad (3)$$

Here, c is half of rear wheel tread. Above analysis is done when the turning center is outside of the robot. However, It is possible for the robot to turn with the turning center inside of two rear wheels as shown in Fig.5. Obtained results are the same as equations (1)-(3). It should be noticed that steering and wheel driving directions are different in both sides. When absolute value of r is smaller than c, wheel driving directions are different each other. In the case of the steering, the directions are different when the absolute value of r is smaller than b.

4.2 Hybrid mode

In this mode, front passive wheels are locked, and front two legs are used to walk. This mode is cooperative locomotion of front legs and rear driving wheels. Two merits appear by using front legs to walk. One is traction. When the robot moves by the wheel mode, traction is generated only rear wheels. In the hybrid mode, a front leg drags the robot body during its support phase. Traction is generated at all the contact points between the robot and the ground, and it contributes to the mobility on the slope or soft terrain. The other merit is adaptability for steps. Front passive wheel is relatively small, and its adaptability is limited. By using leg function, the robot can move over higher steps.

Here, we consider a gait for front legs. First we assume the robot moves straight, and we consider the leg motion in the horizontal plane. The leg moving trajectory is seen as a dotted line in Fig.6. We define forward end point of the trajectory as 0, and the backward end as 1. The robot is also assumed to maintain static stability during locomotion. Therefore, the robot must always have more than three contact points with the ground. This means that duty factor β (fraction of a locomotion cycle that each leg spends in contact with the ground) must be between 0.5 and 1.0. Considering the symmetry of walking, phase difference between front two legs ϕ is set to 0.5. In order to continue steady walking, it is assumed that each leg repeats forward and backward motion. Now we set a reference position of leg motion. For the left leg, we select forward end point of the trajectory as a reference position. In the case of the right leg, reference position is automatically calculated from duty factor β and phase difference ϕ, and its value is $1/(2\beta)$. After front two legs are positioned at their

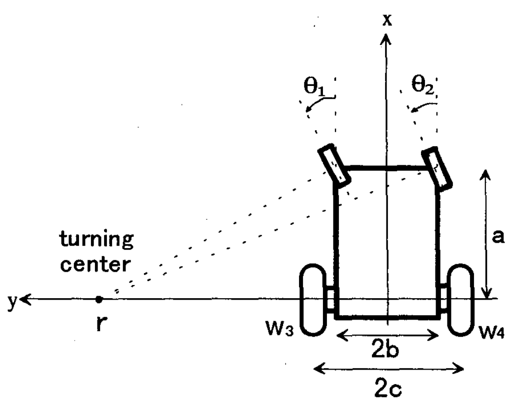

Fig. 4 Wheel mode 1

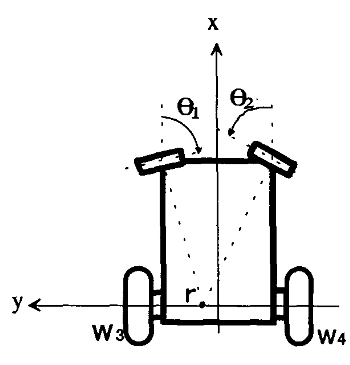

Fig. 5 Wheel mode 2

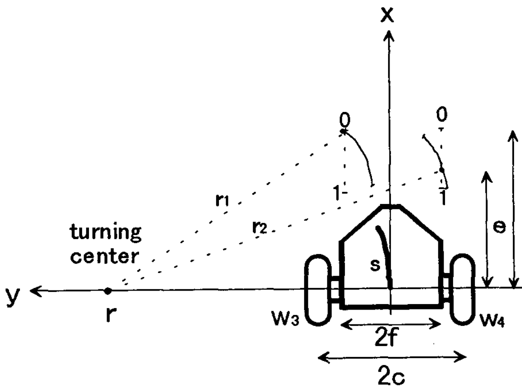

Fig. 6 Hybrid mode

reference positions, each leg is drived along the trajectory. Of course, leg motion must be synchronized to the driving of the rear wheels.

Next, turning gait is considered. In order to simplify the problem, we assume that turning center is constant during a leg motion cycle that starts from the reference position. By this assumption, a transfer from straight movement to turning, or from turning to turning with different curvature is always done at the reference position. Now we define s as robot moving distance in a leg motion cycle. This means that robot body turns against the turning center by s/r in the coordinate system fixed to the ground. On the other hand, a leg turns against the turning center by $\beta s/r$ in reverse direction in the body coordinate system. Turning radiuses of front two legs, r_1 and r_2, are calculated by following equations.

$$r_1 = \sqrt{(r-f)^2 + d^2} \quad (4)$$

$$r_2 = \sqrt{(r+f)^2 + e^2} \quad (5)$$

where, f is half of y-coordinate difference of two reference positions, and d and e are x-coordinates of the left reference position and the right reference position, respectively. Wheel driving distances during the leg motion cycle, w_3 and w_4 are expressed as follows.

$$w_3 = s(r-c)/r \quad (6)$$

$$w_4 = s(r+c)/r \quad (7)$$

where, c is half of rear wheel tread.

4.2 Step mode

In the hybrid mode, front mechanism is used as a leg, and rear is wheel locomotion. Although a relatively large wheel is used, principally a wheel cannot climb a step whose height is larger than half of the wheel's diameter. When the robot encounters a large step, a step mode is utilized. Locomotion algorithm in the step mode is shown in Fig.7. After the robot stand in front of a step (a), front wheel is moved on the step by leg motion (b). The body propelled and rear wheel approaches the step (c). The rear wheel is moved from the rear side to the front side through the air by rear leg motion (d). The rear wheel returns to the rear side (e). Lift up of the wheel must be done without loosing balance. This mode is used only when the robot moves by other locomotion mode and encounters an impassable obstacle.

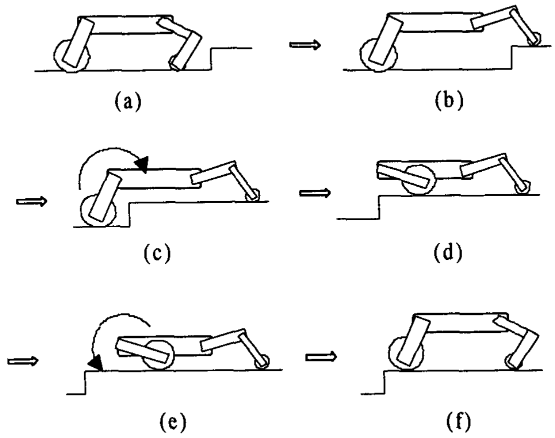

Fig. 7 Step mode

5. Implementation

The locomotion algorithm was implemented to the robot. Ordinarily, wheel mode and hybrid mode are used for locomotion. These two modes are switched by an operator using a button on the command controller. The operator control the robot motion by using two joysticks. One is for moving speed, and the other is for moving direction. During the wheel mode, the altitude of the ground is always measured by the ultrasonic range sensor. When a large step is found, locomotion mode is switched to the step mode automatically. In the step mode, the robot decide the leg and wheel motion autonomously according to the measured step height. After the robot climbs or descend the step, locomotion mode returns to the wheel mode. Photographs in Fig.8 show the robot motion in the step mode. When a rear leg is lifted up, front foot position is changed to the body side to maintain the stability.

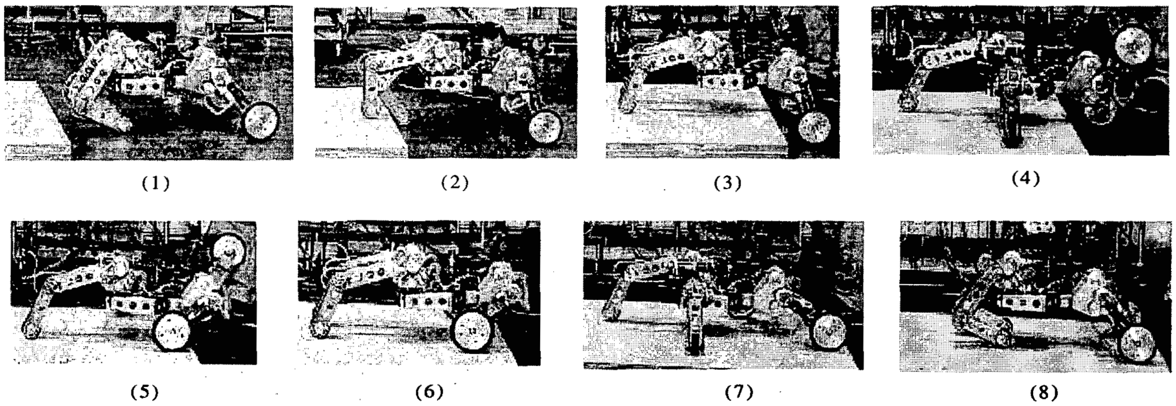

Fig.8 Step climbing experiment

6. Conclusion

A new locomotion mechanism that combines legs and wheels is proposed, and a prototype mobile robot named Walk'n Roll is introduced. The robot has four legs, and a wheel is attached at the end of each leg. The front leg has three joints and a passive wheel. The rear leg has one joint and an active wheel. Total number of actuators is ten, it is smaller than that of normal quadruped robot, twelve. In order to make the best use of the locomotion mechanism, the robot has three locomotion modes. One is the wheel mode, it provides fast and efficient locomotion on flat terrain. The second is the hybrid mode. Legged locomotion by front mechanism and wheeled locomotion by rear mechanism are combined. Traction is generated at the all contact points between the robot and the ground, it is effective for rough terrain. The third is the step mode. In addition to the legged locomotion by the front mechanism, rear leg is used to climb or descend a large step. These locomotion modes are implemented to Walk'n Roll, and their effectiveness is confirmed by the experiments. As future works, improvement of mechanical design and autonomic ability will be considered.

References

[1] Y. Ichikawa, *et. al.*, "A Hybrid Locomotion Vehicle for Nuclear Power Plants", IEEE Trans. On Systems, Man & Cybernetics SMC-13(6), pp.1089-1093(1983)

[2] T. Oomichi and T. Ibe, "Development of Vehicle with Legs and Wheels," J. of Robotics society of Japan, vol.2 no.3, pp.244-251, 1984 (in Japanese)

[3] N. Kimura, *et.al.*, "Locomotion Mechanism and Its Control Architecture for Disaster Preventing Robot", Proc. of '91 Int. Symp. on Advanced Robot Technology, pp.375-380, 1991

[4] G. Schweitzer and M. Werder, "ROBOTRAC –a Mobile Manipulator Platform for Rough Terrain", Proc. of '91 Int. Symp. on Advanced Robot Technology, pp.441-416, 1991

[5] Y-J. Dai, *et. al.*, "Motion Control of Leg-Wheel Robot for an Unexplored Outdoor Environment", Proc. of Int. conf. on Intelligent Robots and Systems, pp.402-409,1996