Paper:

Adaptive Gait for Large Rough Terrain of a Leg-wheel Robot (First Report : Gait Strategy)

Shuro Nakajima and Eiji Nakano

The Department of Advanced Robotics, Chiba Institute of Technology
2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan
E-mail: shuro.nakajima@it-chiba.ac.jp

[Received April 4, 2008; accepted April 4, 2008]

A leg-wheel robot with four mechanically separated legs and two wheels is highly mobile and stable on rough terrain. We discuss the strategy for the robot movement over large rough terrain, classifying topographical features into 13 patterns of combined terrain surface. To traverse all classified terrain, we propose three adaptive gaits: (1) Step-up gait in which frontfoot landing is higher than contact with the wheel ground, and the robot raises itself toward frontfoot landing; (2) Step-down gait in which frontfoot landing is lower than contact with the wheel ground, and the robot lowers itself toward frontfoot landing; and (3) Step-over gait in which frontfoot landing is no higher than contact with the wheel ground, but the robot raises itself as high as possible.[1]

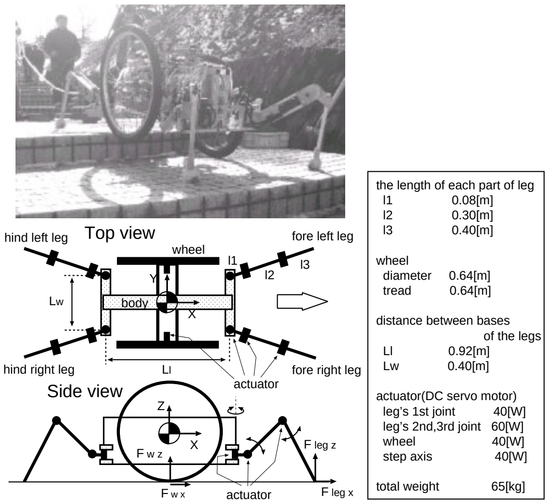
Keywords: mobile robot, leg-wheel robot, adaptive gait, gait strategy, large rough terrain

1. Introduction

Wheels and crawlers are mainly used for traveling – wheels for mechanical simplicity and traveling efficiency, despite lower general adaptability to rough terrain, and crawlers for their adaptability to rough terrain and many applications, including construction machinery but limited to terrain that enables the crawler to remain in contact with the ground continuously.

Legs enable arbitrary discrete contacts with the ground, resulting in a wide range of traveling terrain including steps with stability even on slopes and uneven ground. Legs, however, are complex mechanically and positioning and leg control relies on recognition of the external environment, making practical use difficult.

We have been studying leg-wheel robots with 4 legs, two on the front side and two on the back side, each having 3 degrees of freedom (DOF) and independent 2 wheels on both sides to enable robots to travel on rough terrain but requiring less accuracy of the external environment and simpler control to make the robot practical [1, 2] (**Fig. 1**).



the length of each part of leg	
l1	0.08[m]
l2	0.30[m]
l3	0.40[m]
wheel	
diameter	0.64[m]
tread	0.64[m]
distance between bases of the legs	
Ll	0.92[m]
Lw	0.40[m]
actuator(DC servo motor)	
leg's 1st joint	40[W]
leg's 2nd,3rd joint	60[W]
wheel	40[W]
step axis	40[W]
total weight	65[kg]

Fig. 1. A leg-wheel robot "Chariot 3."

We propose basic movement control [1] for rough terrain with unevenness within ±0.1 m, i.e., regular rough terrain, without using environment-recognition sensors. Basic movement control does not cover all rough terrain since much is more uneven than regular rough terrain. We studied gait strategy and topography classification for leg-wheel robots targeting terrain roughness with unevenness of ±0.2 m, i.e., large terrain roughness by expanding basic movement control travel. One main factor in target unevenness of 0.2 m is that many road obstacles are this height, e.g., sidewalks, and traversing this height enables applications on roads. Unevenness of 0.3 m, however, is less common and is not addressed here. Although traversing steps of 0.2 m may be solved by enlarging robots, we addressed this task by improving movement control strategy to enabling the size of robot to be limited to that of wheel chairs, a typical vehicle with minimum size for use.

The gait strategy Ohmichi et al. proposed for leg-wheel robots [3] was limited to basic terrain types. Hirose et al. classified topography [4, 5] from a general view. We, however, have systematically classified topography within a range of a few steps walking and discussed gait strategy for each. Classification considered the geometric relationship between wheel contact height and front leg contact height, which is a specific issue for leg-wheel robots. Our three-gait strategy for large terrain roughness

---

[1] This paper is the full translation from the transactions of JSME Vol.72, No.721.

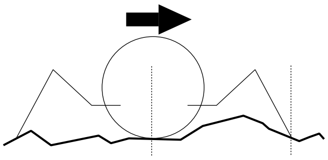


Fig. 2. Leg wheel mode.

covering all types of classified topography is discussed in the sections that follow, together with details and control of gait strategy, to be reported separately.

2. Basic Gait Concept for Large Terrain Roughness

Basic movement control [1] involves traversing unknown terrain roughness using information from a minimum number of internal sensors, i.e., encoders for individual joints and sensors for positioning angle (pitch and roll). We did not use external sensors because they are less accurate in natural environments such as slopes, steps, weedy or muddy land, and snow, with possible errors due to noise and other factors. Unlike external sensors that collect information from the external world, internal sensors detect force generated by robots and their positioning while walking, providing more accurate, stable information in real situations. Our research policy holds that robots traversing unknown terrain roughness should move based on only information from internal sensors and should use external sensors only for high-level operation such as selecting traveling routes. For this reason, we used robots operated by operators and without assuming physically difficult situations such as walls rising in front of the robot.

We realized traversing unknown terrain roughness with basic movement control without recognizing the external environment by making the robot able to absorb uneven terrain roughness using legs with compliance control and wheels with suspension (mechanical compliance). The robot uses “leg-wheel mode,” in which both legs and wheels contact the ground (**Fig. 2**) to drive the robot by using both mechanisms (the wheels and legs), controlling the legs, for example, by trotting [2] and the wheels by rotation. Using an experimental robot (**Fig. 1**), we confirmed travel on terrain with an unevenness of about ±0.1 m.

Problems with leg-wheel mode involve having the robot fail to traverse much larger protrusions and failing to contact the ground in much deeper ruts because actual unevenness is much larger than the level that leg and wheel compliance could absorb.

To realize traversing terrain roughness of about 0.1-0.2 m in leg-wheel mode, the robot must actively raise or lower itself to such a height where leg and wheel compliance can absorb unevenness or errors. The robot must be controlled based on topography without external sensors, so we decided to provide front legs with a function similar to a tactile sensor and to estimate surface conditions to a certain degree from leg contact with the ground and the angle of the robot.

Because terrain roughness is widespread, the robot uses basic movement control and switch to a gait for large terrain roughness as needed.

3. Topography Classification

When the robot’s front legs are used to sense topography for selecting gait strategies, topography is classified into three cases based on the relationship between front leg contact height and wheel contact height. In one case, front leg contact height is 0.1-0.2 m higher than that of wheel contact (type A-1 in **Fig. 3**), in a second case the front leg height is 0.1-0.2 m lower than that of the wheel (type B-1 in **Fig. 3**), and in a third case both are about the same height (within ±0.1 m, type C-1 in **Fig. 3**). While front leg contact is about 1.0 m ahead of wheel contact, the step width is about 0.3 m. This means that even if the wheel moved forward by one step width (0.3 m), the wheels would not reach the place that location of the front leg contacts. Topography is thus classified by combining the relative heights at wheel contact, leg contact, and midway between them.

When a case is defined as type A where front leg contact (P2) is 0.1-0.2 m higher than that of wheel (P1), it is further classified by mid way height: single step (type A-1), double step where the mid-point is between point P1 and P2 (type A-2), upward step with a protrusion (type A-3), upward step with a rut (type A-4, A-5) (**Fig. 3**). The difference between type A-4 and type A-5 lies in whether the wheel drops into the rut causing the robot body to drop, in other words, whether the rut affects as large terrain roughness. Similarly, type B is defined in which front leg contact (P2) is 0.1-0.2 m lower than that of the wheel (P1) and is further classified in the same manner. Again, type C is defined in which front leg contact height point (P2) is about the same (within ±0.1 m) as that of the wheel (P1). Type B-4 and 5, and type C-2 and 3 are different in the same way as in the case between type A-4 and 5.

Classification is expressed as follows: First, the surface is divided into sections of 0.3 m in the direction of movement, then a typical height is selected for each section, and classification is defined by combinations of relative heights. We excluded the following topography:

1. The step is a slope (slope-based terrain roughness).
2. Topography that has a height difference exceeding 0.25 m between the wheel contact and the front or back leg contact in the direction of $z-$axis coordinates (**Fig. 1**).

We exclude the topography 1, above, because a) this is our first study of leg-wheel robots for traveling over rough large terrain roughness and b) manmade steps we encounter outdoors mostly have even surfaces.

We exclude topography 2, above, because the leg contact height may exceed the lower limit of legs with the

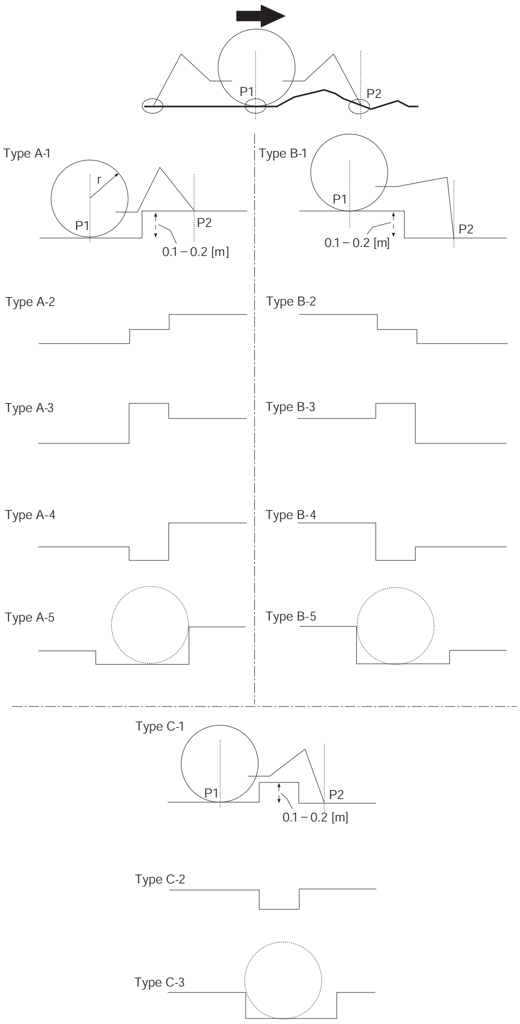


Fig. 3. Classification of large rough terrain.

dimensions in **Fig. 1**, making it difficult to contact the ground.

Although terrain roughness here does not cover all terrain roughness, we think much of it can be practically associated with the topography type classified in this study.

4. Gait Strategy for Large Terrain Roughness

We propose three gait strategies covering all types of classified topography (**Fig. 3**).

Heights to which the robot must be raised or lowered based on topography so that leg and wheel compliance absorbs unevenness is at front leg contact height, as in type A-1 or B-1 typical in **Fig. 3**. We regard these two cases as references for gait strategy and set front leg heights to the targeted leg height. In this case, step patterns are roughly classified into four:

1. Front leg height contact is higher than that of the wheel and the robot is raised to the height of front leg.
2. Front leg height contact is lower than that of the wheel and the robot is lowered to the height of front leg.

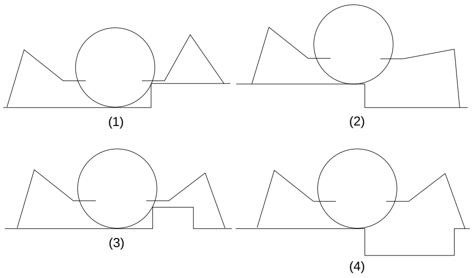


Fig. 4. Four patterns of relation between front leg's position and the target height of the body.

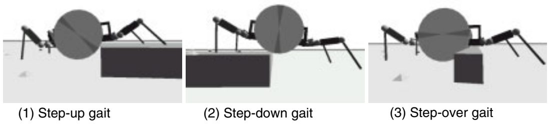

(1) Step-up gait (2) Step-down gait (3) Step-over gait

Fig. 5. Three strategy patterns for moving over large rough terrains.

3. Front leg height contact is about the same as that of the wheel but the robot is raised.
4. Front leg height contact is about the same as that of the wheel but the robot is lowered.

Among (1) to (4) above (**Fig. 4**), if the rut is longer than the stride and the step duty ratio exceeds 0.5, the strategy for case (4) is replaced by the strategy for case (2) followed by the strategy for case (1), because the front leg contacts the bottom of the rut before the robot arrives at it. Summing up, all we need to study is gait strategies (1) to (3) in **Fig. 5**.

Gait strategy (3) could not be replaced by other strategies because a case may occur in which the width of a protrusion is short in case (3) and the front leg may step over the protrusion to land on a plane ahead of the protrusion during leg swinging, so the front leg cannot recognize the height of the protrusion to which the robot must be raised. In other words, the robot does not necessarily obtain the target height for robot-raising itself. If the rut is narrow in case (4), the robot does not reach the bottom of the rut, so it can move by the movement control [1] even without recognizing the rut. Even with a narrower rut, if the front leg touches to the rut, it may go into strategy (2) depending on the depth. When the body does not go into the bottom of the rut, even in case, the target lowering depth estimated by the height of the front leg differs from the depth actually lowered. This problem is specifically addressed in gait strategy (2), step-down gait described separately.

As stated, at least three gait strategies are needed for traversing large terrain roughness. We define gait strategy as follows:

Step-up gait: Gait in which front leg height contact is higher than that of the wheel (**Fig. 5(1)**) and the robot is raised to the height of front leg.

Step-down gait: Gait in which front leg height contact

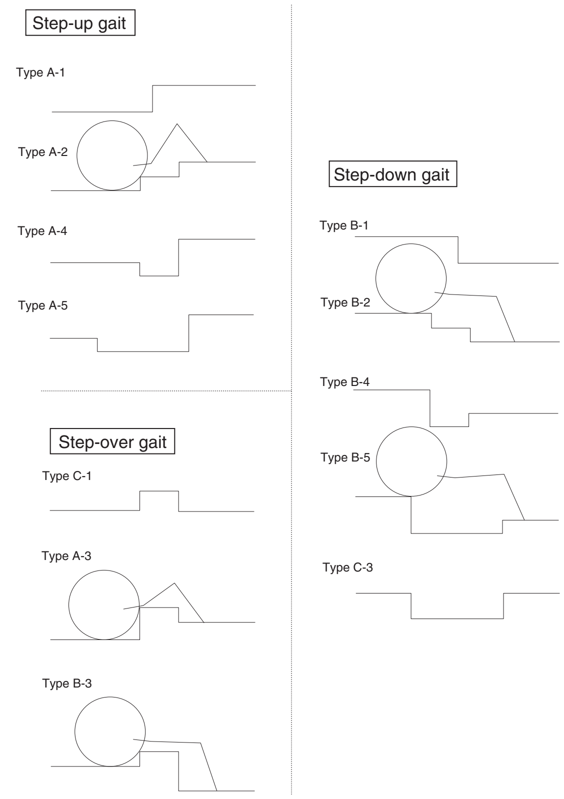


Fig. 6. Targeted rough terrains of each gait.

is lower than that of the wheel (**Fig. 5(2)**) and the robot is lowered to the height of front leg.

Step-over gait: Gait in which front leg height contact is about the same as that of the wheel (**Fig. 5(3)**) but the robot is raised to step over it.

5. Gait Functions and Targeted Geography

Figure 6 reclassifies results for **Fig. 3** by targeted patterns for each gait based on the three proposed gait definitions. Type C-3 uses two gaits, namely, the gait to step down to the rut followed by the gait to step up from the rut,but is classified as a step-down gait for convenience. For type A-3, the robot starts with a step-up gait that fails to raise the robot to the height of the obstacle because it is higher than that of front leg contact. It will switches to a step-over gait. Similarly, for type B-3, the robot uses a step-over gait after it encounters a protrusion, then use a step-down gait to descend the step. As in the cases above, some gaits may consist of multiple gaits, but they are classified as single for convenience. Type C-2 is not included in **Fig. 6**, because the wheel does not go into the rut and the robot continues traveling using basic movement control [1]. Control methods and switching conditions for gaits are described separately.

As in basic movement control, compliance parameters are provided to legs and wheels so a certain degree of unevenness can be absorbed. By absorbing unevenesses with compliance, robot can use the rough value of the height of steps estimated by using only internal sensors, i.e., the robot estimates the height of steps using only internal sensors, i.e., angle sensors for individual joints and positioning of the robot without requiring a high degree of accuracy.

5.1. Step-Up Gait

Basic function: This determines the target robot-raising height based on front leg contact height and that of the wheel and raises the robot accordingly supported by legs and wheels for stabilizing the robot, distributing weight, and saving energy supporting weight by mechanical wheels. This includes detecting step start to determine the timing for raising the robot.

Function 1: When front leg height contact (targeted height) is higher than that of the wheel (actual height) as in type A-2, a measure is required to keep from raising the robot too much in the step-up gait.

Function 2: When front leg height contact (targeted height) is lower than that of the wheel (actual height) as in type A-3, the next gait (step-over gait) must be switched to further raise the robot.

Ruts 0.1 m or less deep (as in type A-5) do not require a special function because basic movement control covers that level of rut. For type A-4, the gait is the same as type A-1 because the wheel scarcely go into the rut.

5.2. Step-Down Gait

Basic function: This determines the target robot-lowering height based on front leg contact height and that of the wheel, and lowers the robot accordingly supported by legs and wheels for stabilizing the robot, distributing weight, and saving energy. This includes detection of step start.

Function 1: When front leg height contact (targeted height) is lower than that of the wheel (actual height) as in type B-2, a measure is required not to lower the robot too much in the step-down gait.

Function 2: When the depth of the front leg contact (targeted depth) is short for the distance the robot is lowered as in type B-5 and C-3, a measure is required to further lower the robot until the wheel touches the bottom.

For type B-4, the gait is the same as type B-1 because the wheel scarcely go into the rut. Although type C-3 is classified as a step-down gait, it also requires a step-up gait to climb the step.

5.3. Step-Over Gait

Basic function: The robot cannot always obtain the target raised height because the front leg does not necessarily contact the top of a protrusion. To cope, the robot is raised to the maximum height, moved forward, then lowered until the wheel touches the surface. This includes detection of the protrusion start.

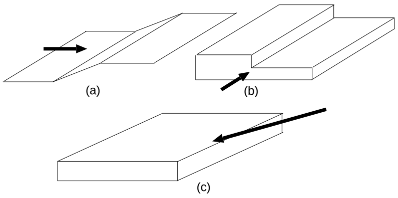


Fig. 7. Rough terrain.

Function 1: The robot is not raised enough in type A-3, because the target height is lower than that of the obstacle. If the robot cannot move ahead by a step-up gait, it must switch to a step-over gait.

Function 2: The wheel hits a protrusion in type B-3 in the step-down gait, unable to move ahead. If the robot cannot move ahead by a step-down gait, it must switch to a step-over gait. In the actual case, this function is required at a stage to detect down-step start in a step-down gait. Details of the step-down gait including detection of the protrusion starting position are described separately.

Both A-3 and B-3 gaits require the step-down gait after having climbed the protrusion.

5.4. Common Functions

In actual cases including outside operations on rough terrain, cases may occur in which the step is a slope (**Fig. 7(a)**), step height is laterally different (**Fig. 7(b)**), or the robot moves toward a step diagonally (**Fig. 7(c)**), so gaits may require movement control for these.

In summary, we require functions to adjust gaits to differences between estimated and actual patterns of topography and three basic gait strategies for terrain roughness to realize movement control for topography.

6. Conclusions

We have discussed a gait strategy for leg-wheel robots to traverse large terrain roughness. Classifying targeted topography systematically (**Fig. 3**), we think actual rough terrain can be broken down into one of the classification types. We proposed three gait strategies for classified topography, discussing functions required to traverse each type of classified topography. The three proposed gait strategies enable leg-wheel robots to traverse many parts of large terrain roughness.

Our objective is to systematically classify large terrain roughness for leg-wheel robots and present three gaits strategies. We will detail these three gaits separately together with a comprehensive gait integrating the three gaits into basic movement control [1].

References:

[1] S. Nakajima et al., “The Motion Control Method for a Leg-wheel Robot on Unexplored Rough Terrains,” Journal of the Robotics Society of Japan, Vol.22, No.8, pp. 1082-1092, 2004.
[2] S. Nakajima, et al., “Trot and Pace Gaits based on the Predictive Event Driven Method for a Leg-wheel Robot,” Journal of the Robotics Society of Japan, Vol.22, No.8, pp. 1070-1081, 2004.
[3] T. Ohmichi and T. Ibe, “Development of Vehicle with Legs and Wheels,” Journal of the Robotics Society of Japan, Vol.2, No.3, pp. 244-251, 1984.
[4] S. Hirose, et al., “The Basic Study of the Intelligent Gait Control for Quadrupedal Walking Vehicle,” Keisoku Jido Seigyo Gakkai Ronbunshu (Transactions of the Society of Instrument and Control Engineers), Vol.18-2, pp. 193-200, 1982.
[5] S. Hirose, et al., “The Gait Control System of the Quadruped Walking Vehicle,” Journal of the Robotics Society of Japan, Vol.3, No.4, pp. 304-323, 1985.

Name:
Shuro Nakajima

Affiliation:
Ph.D. (Information Science), Associate Professor, The Department of Advanced Robotics, Chiba Institute of Technology

Qualification:
Professional Engineer (Mechanical Engineering)

Address:
2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan

Brief Biographical History:
1997- East Japan Railway Company
2005- Future Robotics Technology Center, Chiba Institute of Technology
2006- The Department of Advanced Robotics, Chiba Institute of Technology

Main Works:
- S. Nakajima, E. Nakano, and T. Takahashi, “Motion Control Technique for Practical Use of a Leg-Wheel Robot on Unknown Outdoor Rough Terrains,” Proc. of the Int. Conf. on Intelligent Robots and Systems, Vol.1, pp. 1353-1358, September, 2004.

Membership in Academic Societies:
- Institute of Electrical and Electronics Engineers (IEEE)
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- Japan Society of Kansei Engineering (JSKE)
- The The Institution of of Professional Engineers, Japan (IPEJ)

Name:
Eiji Nakano

Affiliation:
Docter of Engineering, Professor, The Department of Advanced Robotics, Chiba Institute of Technology

Address:
2-17-1, Narashino-shi, Chiba 275-0016, Japan

Brief Biographical History:
1970 Graduated, Postgraduate Course of University of Tokyo
1970 Senior Researcher, Mechanical Engineering Laboratory
1987 Professor, Tohoku University
2005 Professor, Chiba Institute of Technology

Main Works:
- E. Nakano, et al, “Leg-Wheel Robot: A Futuristic Mobile Platform for Forestry Industry,” 1993 IEEE/Tsukuba Industrial Workshop on Advanced Robotics, 1993.

Membership in Academic Societies:
- Robotics Society of Japan (RSJ)
- Japan Society of Mechanical Engineers (JSME)
- Society of Instrument and Control Engineers (SICE)
- Society of Biomechanism (SOBIM)