Paper:

Adaptive Gait for Large Rough Terrain of a Leg-Wheel Robot (Fifth Report: Integrated Gait)

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A leg-wheel robot has mechanically separated four legs and two wheels, and it performs high mobility and stability on rough terrains. The adaptive gait for large rough terrains of the leg-wheel robot is composed of three gait strategies. In this paper, the integrated gait of the normal gait and the adaptive gaits for large rough terrain is proposed. The proposed gait has following features: 1. There is a path from a gait to any other gait. 2. The robot does not fall into the endless loop of detection, because it moves whenever it detects something. 3. A gait changes finally to step-over gait which has the maximum ability of movement when the robot can not move. The robot can move on rough terrains where irregular ruggednesses up to 0.2 m in height or depth exist by using the integrated gait. The effectiveness of the integrated gait is verified through simulations and experiments.[1]

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

1. Introduction

Legs, which enable robots to make arbitrary and irregular contacts with the ground, are capable of traversing a wide range of terrain including steps and slopes with stability. Legs are mechanically complex, however, and positioning and leg control rely on recognition of the external environment, leaving a lot of tasks to solve for practical use.

We have been studying separated leg-wheel robots of about the size of a wheelchair with 4 legs, two on the front side and two on the back side, each having 3 degrees of freedom (DOF), and with 2 independent wheels on both sides to enable robots to travel on unknown rough terrain but requiring less accuracy in recognition of the external environment and simpler control to make the robot practical [1, 2]. We propose basic movement control [1] for rough terrain with unevenness within ±0.1 m (regular rough terrain) without the need for environment recognition sensors. Basic movement control does not cover all rough terrain since much terrain is more uneven than regular rough terrain.

We proposed 3 gait strategies for large rough terrain (within ±0.2 m in height) by classifying such terrain for leg wheel robots of the size of a wheelchair to traverse [3]. We discussed step-up gait control [4] targeting rough terrain with ascending steps of 0.1-0.2 m. We discussed step-down gait control [5] targeting rough terrain with descending steps of 0.1-0.2 m. We discussed step-over gait control [6] targeting rough terrain with protrusions of 0.1-0.2 m.

We discuss in this paper an integrated gait that selectively uses gaits for regular rough terrain and large rough terrain as well as its configuration, characteristics and verified ability of the gait.

The gait strategy Ohmichi et al. proposed for similar leg-wheel robots [7] was not targeted at unknown and combined rough terrains. This paper targets an integrated gait consisting of gaits for successive regular and some type of large rough terrains in unknown environment, and verifies traverse capability of the gait.

Conventional 4- and 6-leg-robots realized movement for rough terrain by force control using accurate force information from legs [8–11], but we propose movement control for unknown rough terrain using only internal sensors, i.e., angle sensors for individual joints and positioning (pitch and roll) of the robot, for all gaits in the integrated gait. We do 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. Our research policy holds that robots traversing unknown rough terrain should move based on information from internal sensors alone and that external sensors should be used to further enhance the capability.

2. Integrated Gait

We proposed and discussed gait control methods for regular rough terrain [1, 2] and larger rough terrain [3–6] for leg-wheel robots. It is the integrated gait that combines individual gaits by selecting one gait based on terrain and transfer from one gait to another. The individual gaits that constitute the integrated gait are as follows:

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

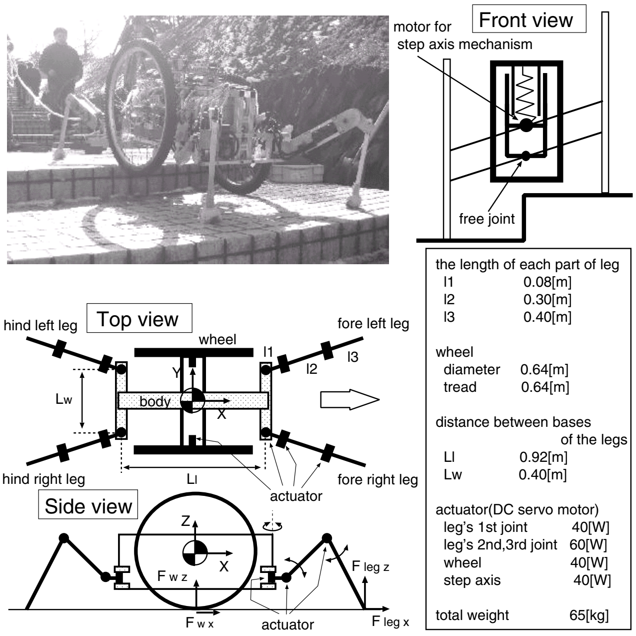


Fig. 1. A leg-wheel robot "Chariot 3".

- Normal gait [1, 2] (trot gait for legs)
- Step-up gait [4]
- Step-down gait [5]
- Step-over gait [6]

Leg-wheel robots traversing actual rough terrain are required to switch any one gait to any other gait since an order of terrain surfaces is unknown for the robots. For example, when the robot has encountered an ascending step during walking in normal gait, it needs to switch the gait to the step-up gait and to switch back to the normal gait upon completion of the ascent. **Fig. 2** shows the algorithm of the proposed integrated gait that indicates transition between individual gaits.

N_u in **Fig. 2** is a variable representing states during the step-up gait. **Fig. 3** shows a step-up gait. When the robot detects the start position of an ascending step at **Fig. 3(b)**, it repositions all legs to the start positions (preparatory leg repositioning: **Fig. 3(c)**, **(d)**, then raises the body by all-leg-support gait (**Figs. 3(e)-(g)**), finally repositions all legs again to switch back to the normal gait (terminating leg repositioning: **Fig. 3(h)**). The value $N_u = 1$ represents a state in which the robot has detected an ascending step and has started preparatory leg repositioning and it increases by one every time each leg contacts the ground during the preparatory leg repositioning. $N_u = 5$ represent a state in which the robot has completed preparatory leg repositioning and is raising its body by the all-leg-support gait, and $N_u = 6$ in which the robot has started terminating leg repositioning. During the terminating leg repositioning, N_u increases by one every time each of the first two legs contacts the ground and the terminating leg repositioning is completed at $N_u = 8$. When the next leg contacts the ground, the robot starts the normal gait (trot gait) by changing $N_u = 0$.

N_d and N_g are variables representing states of step-down and step-over gaits and values are assigned in the same manner as the step-up gait. For searching the descending step start position [5] in the step-down gait, the variable is assigned in the same manner, i.e., $N_d = 1$ when the robot has detected an descending step, $N_d =$ 1-5 during preparatory leg repositioning, $N_d = 5$ during searching motion for the descending step start position, $N_d =$ 6-8 during terminating leg repositioning.

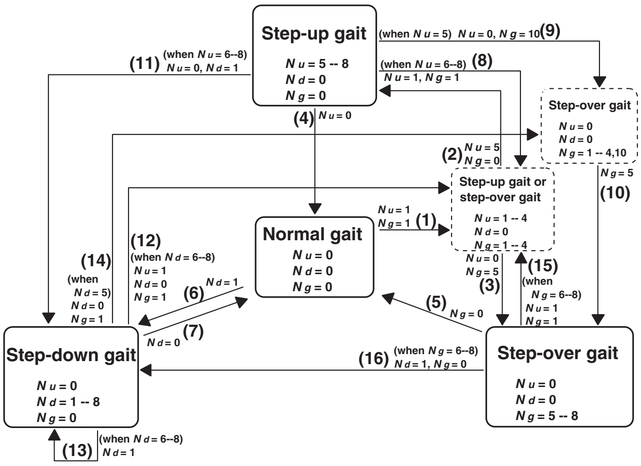


Fig. 2. State transition diagram of the integrated gait for rough terrain.

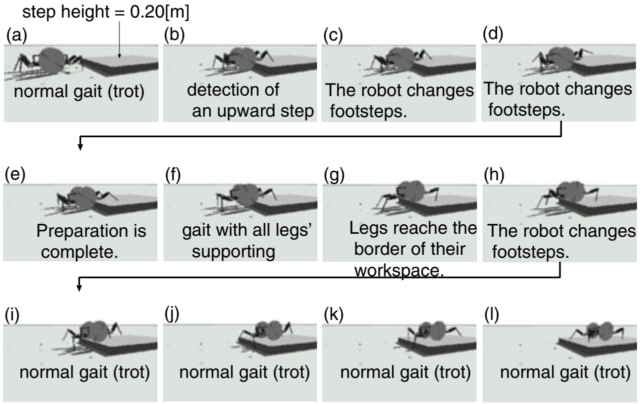


Fig. 3. An image of the step-up gait.

Threshold values below are experimentally determined based on the operation policy that terrain with heights up to about 0.1 m is covered by normal gait and terrain with heights between 0.1 and 0.2 m is covered by gait for large rough terrain. In other words, regular rough terrain, in which the heights are roughly less than 0.3 times of the radius of the wheels, is traversed by absorbing surface roughness with legs' and wheels' compliance using normal gait, and large rough terrain, where heights are roughly between 0.3 and 0.6 times of the radius of the wheels, is traversed using the gait for the large rough terrain. For details of the determined thresholds for individual gaits, refer to respective papers [4–6]. Path (1) in **Fig. 2** occurs when the robot has encountered an ascending step or protrusion during a traverse in the normal gait. Movement for both step-up and step-over gaits is the same during N_u and $N_g = 1$ to 4, but when N_u and N_g becomes 5, the robot decides which gait to select depending on estimated step height H_{ei} [4]. So, N_u and N_g become 1 at the same time upon detection of an obstacle and increase at the same time during preparatory leg repositioning, i.e., N_u and $N_g = 1$ to 4.

Detection of a step or protrusion is made when the smallest deviation of the right and left wheels between rotation angles and target angles of the wheels exceeds threshold $\Delta_{w\min}$, i.e., 18° for regular rough terrain and 8° for large rough terrain. Threshold $\Delta_{\mathrm{get\,over}}$ for selection of the step-up or step-over gait is determined as $H_e = 0.05$ m. The value $H_e = 0.05$ m was determined because, when one of the right and left wheels is on the surface 0.1 m high, the center of gravity (COG) is already 0.05 m high. When the robot encounters a step of 0.1 m in this condition, it would recognize as $H_e = 0.05$ m.

Path (2) occurs when one of the estimated step heights for the right and left front legs is $H_{ei} \geq 0.05$ m and the robot determines that it's an ascending step and select the step-up gait by changing $N_u = 5$. At this time, N_g for step-over gait, which has concurrently increased, will be reset to 0. Path (3) occurs when both legs show $H_{ei} < 0.05$ m, and the robot determines that it's a protrusion and selects the step-over gait by changing $N_g = 5$.

Path (4) occurs when the step-up gait has been completed with the end of terminating leg repositioning, and the robot returns to the normal gait as $N_u = 0$. Path (5) occurs when the step-over gait has completed, and the robot returns to the normal gait with $N_g = 0$.

Path (6) occurs when the robot has encountered a descending step during a traverse in the normal gait and transfers to step-down gait by changing $N_d = 1$. Descending steps are detected when one of the estimated step heights for the right and left front legs is $H_{ei} \leq -0.10$ m. Path (7) occurs when the step-down gait has completed, and the robot returns to the normal gait as $N_d = 0$.

Path (8) occurs when the robot has encountered an ascending step or protrusion during terminating leg repositioning ($N_u = 6$-8) of the step-up gait. At this time, both N_u and N_g become 1, and a gait is selected when N_u and $N_g = 5$. Detection of an ascending step or protrusion is made using $\Delta_{w\min}$ as in the case of path (1).

Path (9) occurs when the robot detects underestimation of the estimated step height during the all-leg-support gait ($N_u = 5$) in the step-up gait and transfer to the step-over gait. At this time, the robot lowers the body ($N_g = 10$) for preparatory leg repositioning for step-over gait and the step-up gait is terminated by changing $N_u = 0$. After lowering the body ($N_g = 1$), the robot performs preparatory leg repositioning and transfers to step-over gait ($N_g = 5$) via path (10). Underestimation of the estimated step height is detected when the sum of the deviations δ_{wi} of the right and left wheels from target angles exceed threshold $\Delta_{w\mathrm{up}} = 30°$.

Path (11) occurs when the robot has detected a descending step during terminating leg repositioning ($N_u = 6$ to 8) of the step-up gait and transfers to step-down gait by changing $N_d = 1$. At this time, the step-up gait is terminated by changing $N_u = 0$. Descending steps are detected when the estimated step height is $H_{ei} \leq -0.10$ m as in the case of path (6).

Path (12) occurs when the robot has detected an ascending step or protrusion during terminating leg repositioning ($N_d = 6$ to 8) of the step-down gait and transfers from the step-down gait by changing N_u and $N_g = 1$ and $N_d = 0$. Detection of an ascending step and protrusion is the same as in the case of path (1).

Path (13) occurs when the robot has detected a descending step again during terminating leg repositioning ($N_d =$ 6-8) of the step-down gait, and it changes $N_d = 1$. Since consecutive descending steps tend to exhibit larger estimated step height H_{ei}, they are detected by $H_{ei} \leq -0.05$ m for one of the right and left front legs.

Path (14) occurs when the robot has encountered a protrusion during searching motion for descending step start position ($N_d = 5$) unable to go forward, and transfers to the step-over gait by changing $N_g = 1$. At this time, the step-down gait is terminated by changing $N_d = 0$. Protrusions are detected when the sum of the deviations δ_{wi} of the right and left wheels from target angles exceed threshold $\Delta_{w\mathrm{down}} = 25°$.

Path (15) occurs when the robot has detected an ascending step or protrusion during terminating leg repositioning ($N_g = 6$-8) of the step-over gait, and it changes N_u and N_g to 1. Detection of an ascending step and protrusion is the same as in the case of path (1).

Path (16) occurs when the robot has detected a descending step during terminating leg repositioning ($N_g = 6$-8) of the step-over gait and transfers to the step-down gait by changing $N_d = 1$. The step over gait is terminated by changing $N_g = 0$. Detection of a descending step is the same as in the case of path (6).

3. Features of Integrated Gait

This section describes features of the algorithm of the proposed integrated gait for leg-wheel robots. At first, features are listed and then detailed.

1. Transition paths are provided between the individual gaits.
2. When unable to traverse with a gait, the robot transfers to the step-over gait for the obstacle to achieve higher traverse capability.
3. Gait transition caused by detection of environment always involves forward movement, bringing environmental changes to the robot, thus preventing the robot from falling into an endless loop in which the robot goes back and forth in two states.

Then the feature 1 is detailed. As mentioned before, various surfaces will appear randomly in actual rough terrain, all gaits need to switch to one another. Each gait transfer to the other gaits, for example, from the step-up gait to the normal gait via path (4), to step-up or step-over gait via path (8), to the step-over gait via path (9), and to the step-down gait via path (11) (**Fig. 2**). Of them, the path (4) to the normal gait is automatically performed

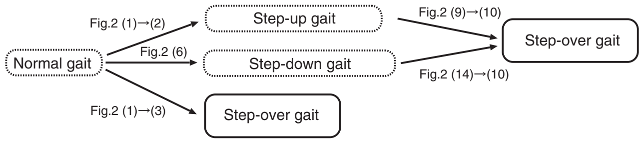


Fig. 4. Placement of step-over gait.

when the step-up gait is completed. Gaits for rough terrain via paths (8) and (11) are determined to be switched to upon completing leg repositioning ($N_u = 6-8$) to respond to terrain immediately after movement by the all-leg-support gait. For transition via path (9) to the step-over gait, the necessity of transition is determined during the all-leg-support gait ($N_u = 5$) to respond to a situation in which the robot is unable to ascend due to underestimation of the estimated step height. In this manner, timing for transition is set at appropriate time to achieve transition to the best gait.

Similarly, the step-down and step-over gaits have transition paths to all other gaits and the transition timing is determined at appropriate time. The step-over gait, in which the robot advances by one stride with its body raised to the highest and lowers the body until its wheels contact the ground, do not transfer to another gait during the all-leg-support gait ($N_g = 5$) because if a terrain surface cannot be traversed by the step-over gait, it would be difficult to traverse the surface by the other gaits.

Then the feature 2 is detailed. When traversing large rough terrain, a gait is selected that is appropriate at the first stage. When the robot is unable to traverse with a selected gait during the all-leg-support period in the step-up gait or searching motion for a descending step start position in the step-down gait, it transfers to the step-over gait for the obstacle to achieve higher traverse capability. **Fig. 4** shows transition patterns from the normal gait. The reason for using this two-step transition to the step-over gait is this. The step-over gait provides higher capability for traversing rough terrain, but involves time-consuming movement such as raising the body to the highest. So, if the terrain surface can be traversed by another gait, it should be done by the gait. In addition, it seems less frequent to encounter such terrain surfaces that require two-step transition to the step-over gait from the step-up or step-down gait.

Then the feature 3 is detailed. When an obstacle is detected (N_u, N_d and $N_g = 1$), the robot always involves movement of N_u, N_d and $N_g = 5$. With this movement, the environment of the robot will change, thus preventing the robot from falling into an endless loop.

4. Simulation

This section verifies by simulation that the proposed integrated gait performs transition to appropriate gaits for given terrain, which includes successive regular and large rough terrain [3], and that the robot achieves traverse capability over comprehensive rough terrain with heights and depths up to 0.2 m.

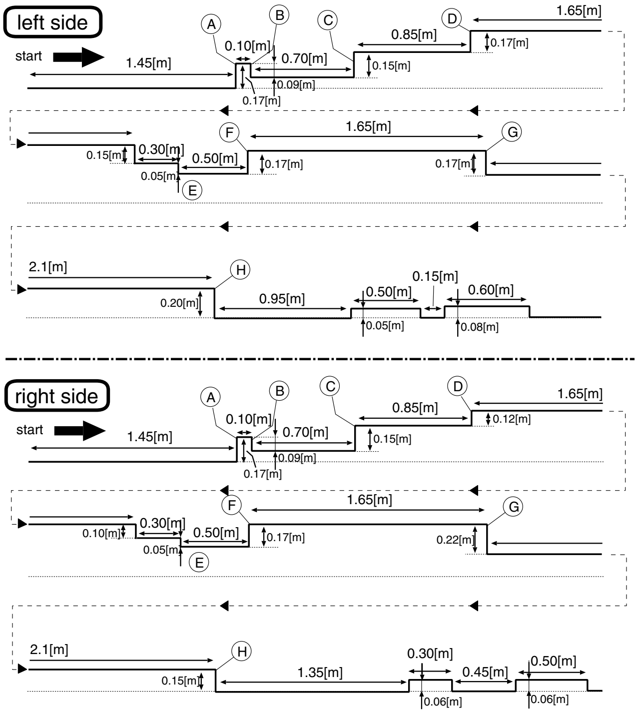


Fig. 5. Surface of the random rough terrain in the simulation.

Simulation and experimental conditions were set the same as in the previous experiments [4] as follows: swing leg speed was 0.5 m/s, swing leg lifting height 0.2 m, maximum leg lowering for a swing leg to land 0.4 m, stride width 0.35 m, basic deviation of actual leg locations from targets $\Delta_s = 0.043$ m, stiffness for all legs and for suspension in the direction of the Z axis 7500 N/m, the basic load sharing ratio between legs and wheels 1:1, P and D gains for wheel rotation control 80 Nm/rad and 20 Nm/rad/s, and P and D gains for step axis control 1000 Nm/rad and 100 Nm/rad/s. The gait was a trot [2] and the environment was assumed to be unknown. We used dynamics simulator Open Dynamics Engine (ODE) for simulation assuming the rigid contact between legs and the ground, and wheel and the ground. Friction coefficient between legs and the ground was set to 0.4 and that between wheels and the ground to 0.7.

Figure 5 shows rough terrain used in the simulation. As seen in the figure, the terrain surfaces are different on right and left sides of the robot. The terrain is made up randomly so that different gaits are required except for the exclusion surfaces (Section 3, [3]).

Figures 6 and **7** show results of the simulation. The figures demonstrate that the robot traversed the terrain selecting appropriate gaits based on the surfaces in **Fig. 5**. **Fig. 8** shows target velocity and transition of N_u, N_d and N_g. **Fig. 9** shows body angles, and **Figs. 10** and **11** show actual and target leg positions in the Z-direction of the robot coordinates for the front and rear legs, respectively. **Table 1** shows the estimated step heights H_e [4] for the gaits. **Fig. 9** shows that the body pitch angle followed the imaginary inclination and that body roll angle was kept near 0°, demonstrating traverse capability maintaining the desired body angles [4–6].

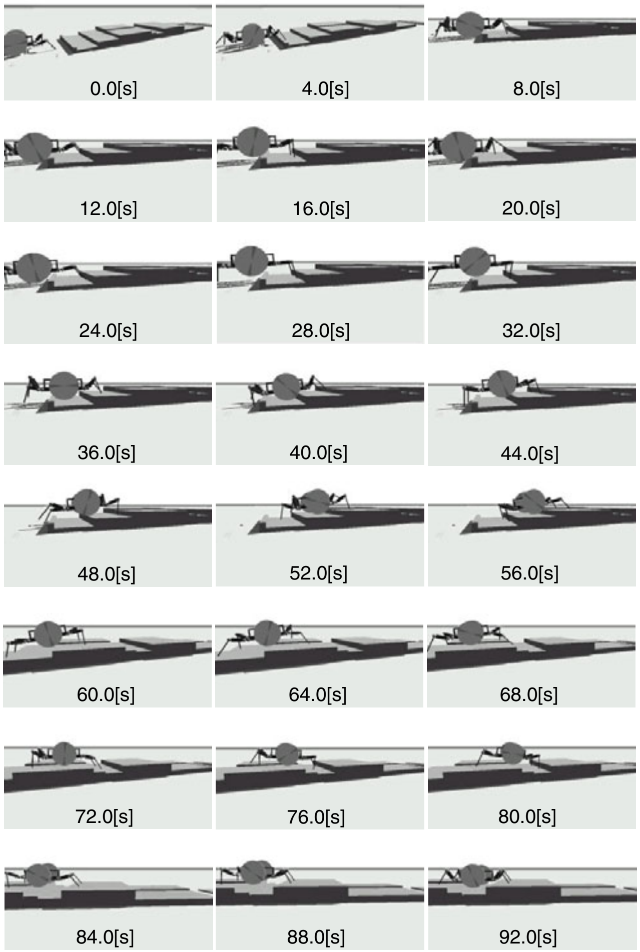


Fig. 6. Scenes in the simulation (1).

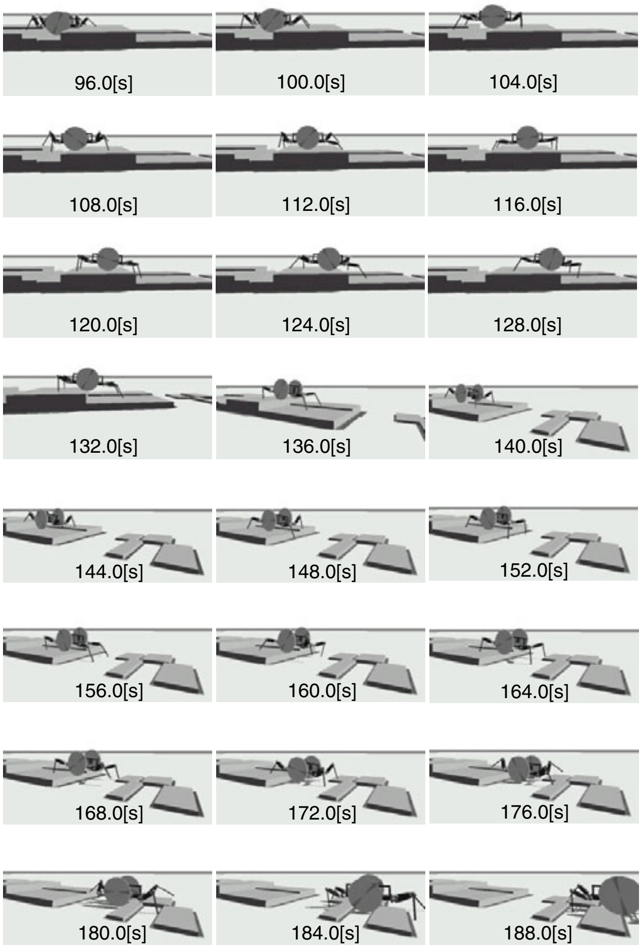


Fig. 7. Scenes in the simulation (2).

Table 1. The value of H_e in the simulation.

time	gait	H_e [m]
11.3 s	step-up gait	0.122
40.9 s	step-up gait	0.120
55.2 s	step-up gait	0.091
89.7 s	step-down gait	0.000
98.0 s	step-up gait	0.194
130.9 s	step-down gait	−0.176
168.7 s	step-down gait	−0.124

Here we closely examine **Fig. 8** in the light of appropriate gait selection based on terrain surfaces referring to state transition in **Fig. 2**. Note that, when N_u, N_d and N_g are all 0, it means that the normal gait is selected.

When the robot encountered a protrusion unable to advance at location "A" (**Fig. 5**), at time (1) (**Fig. 8**), it changed $N_u = N_g = 1$. As the estimated step heights H_{ei} (The value at 11.3 s in **Table 1** is the averaged value) of the right and left legs exceeded the threshold for ascending steps $\Delta_{\mathrm{step\,over}}$ $(= 0.05)$ after preparatory leg repositioning, it transferred to the step-up gait. This corresponds to paths (1) and (2) (**Fig. 2**). Until the robot obtained H_e after preparatory leg repositioning, both N_u and N_g changed. The step-up gait was selected around 11 s and N_g for step-over gait was reset to 0.

When the sum of the deviations of the right and left wheels from target angles exceeded threshold $\Delta_{w\mathrm{up}} = 30°$ at time (2) (**Fig. 8**) in the all-leg-support gait, it determined unable to ascend due to the underestimated step height and transferred from the step-up gait to the step-over gait by changing $N_g = 10$ and $N_u = 0$.

Upon encountering a descent at location "B" (**Fig. 5**) at time (3) (**Fig. 8**), the leg load sharing ratio [4], which represents the ratio of the weight supported by legs to the entire weight of the robot, increased more than the basic setting value 0.5 to a certain degree. This caused leg relaxation [4] so the robot stopped.

When the robot encountered an ascending step unable to advance at location "C" (**Fig. 5**) at time (4) (**Fig. 8**), it changed $N_u = N_g = 1$. After preparatory leg repositioning, the estimated step height H_{ei} (refer to the value in **Table 1** at 40.9 s) was more than threshold $\Delta_{\mathrm{step\,over}}$ $(= 0.05)$ so the robot transferred to the step-up gait ($N_u = 5$, $N_g = 0$).

When the robot encountered again an ascending step at location "D" (**Fig. 5**) at time (5) (**Fig. 8**), it transferred to the step-up gait as at the time (4) (**Fig. 8**). The $H_e = 0.091$ (**Table 1** at 55.2 s) was obtained less than the actual step height, because the height is measured from the imaginary surface, which is ascending, and thus the height from the

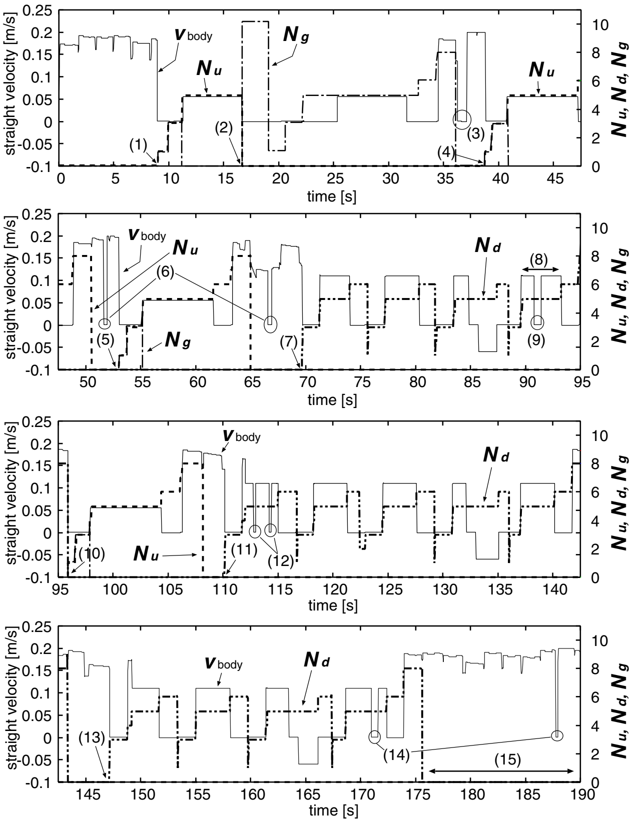


Fig. 8. V_{body}, N_u, N_d, N_g in the simulation.

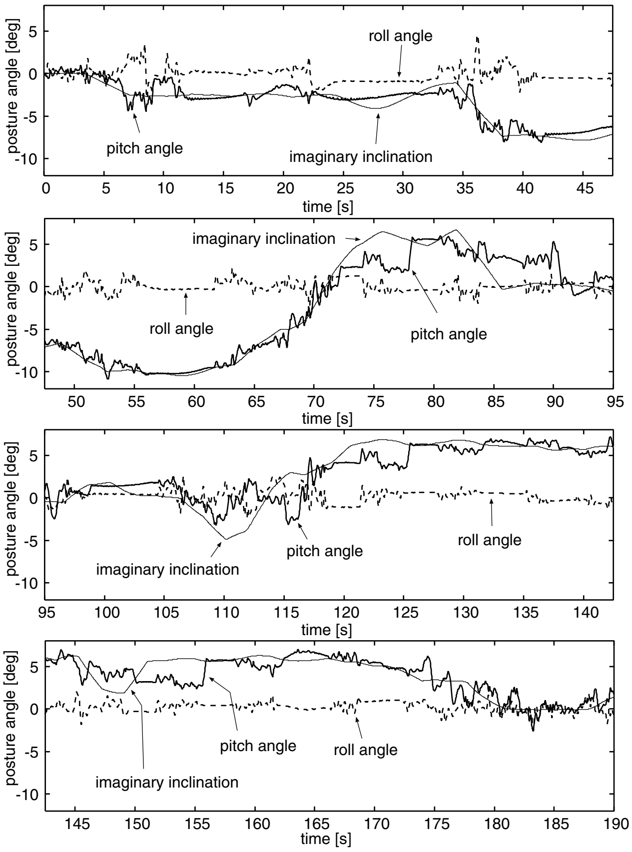


Fig. 9. Body angle in the simulation.

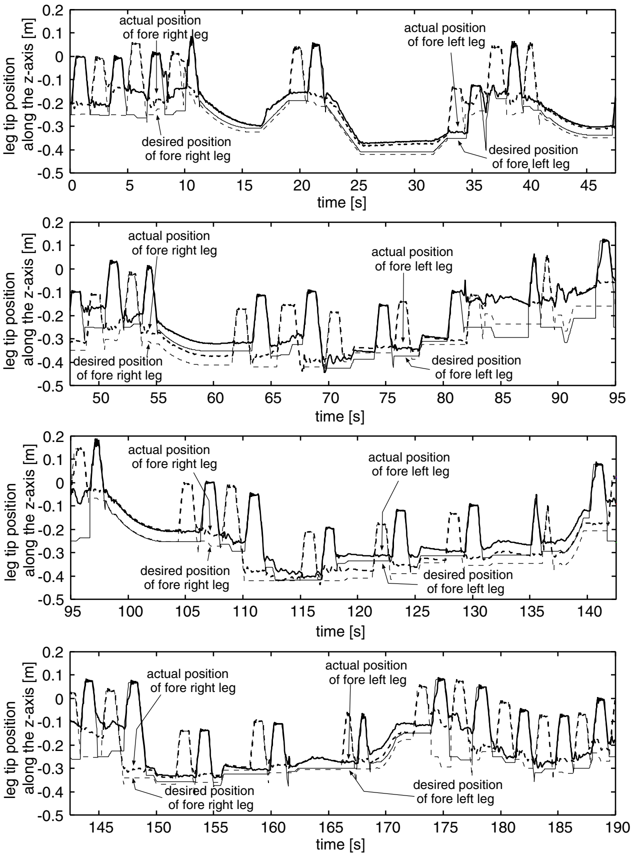


Fig. 10. Leg tip position along the z-axis in the simulation (front legs).

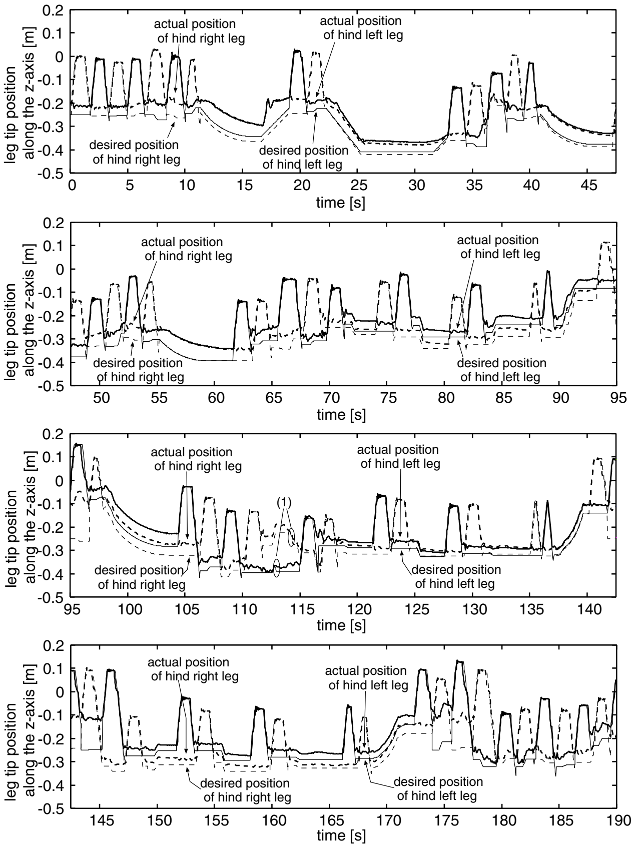


Fig. 11. Leg tip position along the z-axis in the simulation (rear legs).

imaginary surface appears smaller than otherwise.

The phenomena at time (6) (**Fig. 8**) are attributable to the leg relaxation. This resulted from the leg load sharing ratio having exceeded the basic setting value 0.5 to a certain degree, because the robot generated target trajectory in parallel to the imaginary surface, which is ascending due to successive ascending steps, while actual surface the robot is moving on is horizontal.

When the robot encountered a descent at location "E" (**Fig. 5**) at time (7) (**Fig. 8**), it transferred to the step-down gait. The robot detected the descending step start position at the third searching motion for the start position, and then descended during time (8) (**Fig. 8**) with the all-leg-support gait.

At time (8) (**Fig. 8**), the robot obtained $H_e = 0$ (**Table 1** at 89.7 s) because the front leg was already out of the rut. As a result, the robot experienced insufficient body lowering and the body was lowered by leg relaxation at time (9) (**Fig. 8**).

At time (10) (**Fig. 8**), the robot detected an ascending step at location "F" in the state $N_d = 8$, changed $N_u = N_g = 1$, and transferred to the step-up gait based on H_{ei} (**Table 1** at 98.0 s) after preparatory leg repositioning.

When the robot encountered a descent at location "G" (**Fig. 5**) at time (11) (**Fig. 8**), it transferred to the step-down gait. Note that the rear legs detached from the ground at time (12) (**Fig. 8**), the robot stopped and lower the rear legs until the legs contacted the ground (**Fig. 11(1)**).

When the robot encountered a descent at location "H" (**Fig. 5**) at time (13) (**Fig. 8**), it transferred to the step-down gait. The phenomena at time (14) (**Fig. 8**) are attributable to the leg relaxation.

Movement during time (15) (**Fig. 8**) was performed by the normal gait ($N_u = N_d = N_g = 0$), indicating that the robot selected the normal gait for regular terrain such as that after location "H" (**Fig. 5**). As explained above, the integrated gait successively achieved traverse on random rough terrain with heights or depths up to 0.2 m by appropriately selecting proposed gaits [3–6] (except for the exclusion surfaces).

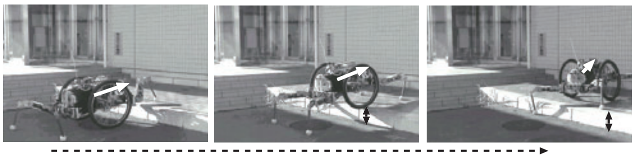
5. Experiments in Outdoor Rough Terrain

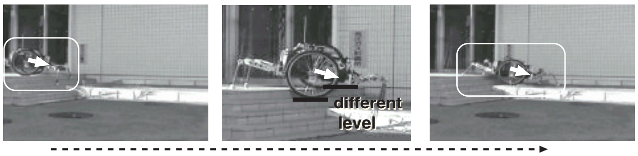
This section describes experiments that verified traverse capability on actual outdoor rough terrain using the proposed integrated gait. The experimental conditions were the same as those with simulation.

Figure 12 shows experimental scenes in outdoor rough terrain. Due to space limitation, a part of them are reported.

Figure 12(a) shows the robot ascending onto a pavement 0.2 m high. The robot detected the pavement and ascended onto it by the step-up gait.

Figure 12(b) shows the robot diagonally descending two consecutive descending steps of the depth of 0.1 m. The picture in the middle indicates that the robot was descending the step keeping its body roll angle about horizontal using the step axis mechanism that positioned the right and left wheels at different height.


(a) an upward step



(b) downward steps


(c) stairs

(d) mountain (normal rough terrain)

(e) mountain (large rough terrain)

Fig. 12. Experimental scenes.

Figure 12(c) shows the robot descending stairs of heights of about 0.1 m. It detected descending steps and then descended by repeating the step-down gait.

Figure 12(d) shows the robot traversing in a forest with undergrowth. It traveled in the normal gait since the degree of the surface was of regular rough terrain. The robot, which moved based on information from internal sensors alone [1] without using external sensors such as ultrasonic sensors or visual sensors, traveled the terrain without being influenced by external disturbance from undergrowth, which would otherwise have affected the robot.

Figure 12(e) shows the robot moving in the step-up gait in large rough terrain in a forest. It successively traversed over rough terrain of an ascending step using the step-up gait, which the normal gait could not have coped with.

As seen in **Figs. 12(a)-(e)**, the robot demonstrated high moving ability over actual outdoor rough terrain.

6. Conclusion

We have described an integrated gait for leg-wheel robots. The integrated gait targets both regular rough terrain with heights up to ±0.1 m and large rough terrain with height of 0.1 to 0.2 m and selects appropriate gaits based on the surface of the terrain to achieve traverse over comprehensive rough terrain that includes both types of terrain. We verified and confirmed the traverse ability of the integrated gait through simulation and experiments on successive rough terrain.

We have achieved basic moving technology for leg-wheel robots for unknown rough terrain using the integrated gait. Individual gaits constituting the integrated gait do not rely on external sensors, providing high reliability without being influenced by erroneous external recognition. At the same time, we will integrate external sensor information into the proposed control method based on internal sensor infomation, which the integrated gait is controlled with, to enable robots to achieve much higher moving ability, function and reliability.

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