Paper:

Free Gait Algorithm with Two Returning Legs of a Leg-Wheel Robot

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The leg-wheel robot we developed has four legs and two wheels mechanically separated and operates with high mobility and stably on rough terrain. We propose a free gait algorithm for the leg-wheel robot that enables continuous locomotion under random velocity commands. The gait algorithm, based on a predictive event-driven approach, determines leg-lift timing to keep legs within prescribed work areas. The robot is operated remotely by an operator who uses a controller to give straight velocity and angular velocity. Our algorithm fully automates leg control via the operator's commands, and its feasibility was confirmed in simulation and experiments. [1]

Keywords: gait algorithm, free gait, mobile robot, leg-wheel robot, event driven method

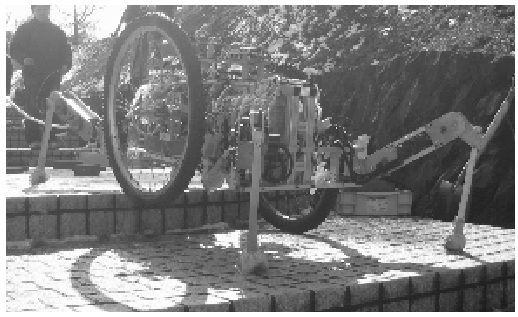

Fig. 1. A leg-wheel robot : Chariot 3.

1. Introduction

Wheels or crawlers are currently used for traversing rough terrain. Wheels are used in many robots due to mechanical simplicity and traveling efficiency but they are generally less adaptable to rough terrain. Compared to wheels, crawlers are highly adaptable to rough terrain but are limited to terrain that enables continuous contact with the land.

Legs enable arbitrary and irregular contact, traversing a wide range of terrain stably, including steps and slopes. Leg travel involves the following problems that must be solved before practical application is possible:

1) Energy consumption is larger than for wheels and crawlers, making it difficult for them to travel a long time using legs alone when energy sources are limited, for example, to batteries.

2) Body stability largely depends on control and the current levels of sensing and control does not provide sufficient reliability on rough terrain.

3) Technology is still being developed to find a desirable coordination of movement for multiple legs, since each leg must both control its own function and work in coordination with the other legs.

We proposed and developed a leg-wheel robot as a platform for traversing rough terrain. The robot (**Fig. 1**) has 4 legs and 2 wheels operating independently depending on terrain requirements. We propose that the robot move in "wheel mode" using wheels alone and legs lifted. As terrain changes, it switches to "leg-wheel mode" [1–3] to speed up travel and maintain stability. Using both wheel mode and leg-wheel mode, it travels in high velocity on paved roads and secure ensurely on rough roads.

Problem 1) is due to robot weight being continuously supported by actuators. Our robot supports weight by wheels in addition to legs, improving energy efficiency.

For problem 2), our robot has continuous wheel support, which, unlike legs, uses simple control for high stability. Passive wheel compliance and active leg compliance enable the robot to absorb terrain changes and leg displacement information provides calculated reaction from the ground, traversing unknown terrain without a need for sensing geographic information in advance [1–3], which suits circumstances in which accurate geographic information is note available, e.g., outdoors or in heavy undergrowth.

For problem 3), we introduced a predictive event-driven gait enabling continuous random travel by predicting when legs reach movement limits and by setting leg-lift timing [4, 5]. Conventional studies on leg coordination are classified into those that:

1) Accept arbitrary velocity commands by changing step length and duty ratios for regular gaits such as wave

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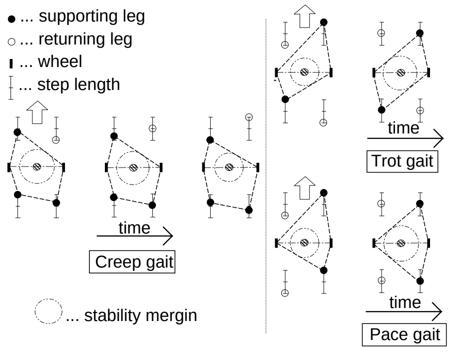

Fig. 2. Stability margin of each gait.

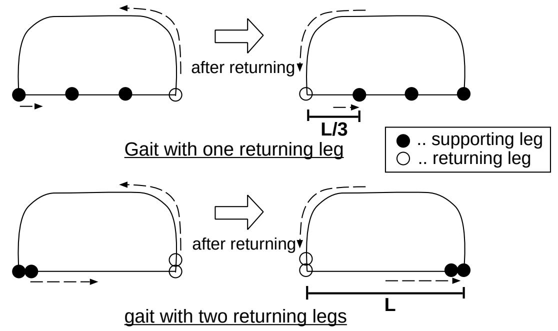

Fig. 3. Movement distance of supporting legs while other legs are returning.

gait [7, 8] or trotting [9].

2) Plan optimized gait patterns for given conditions including stability and travel speed [10, 11].

3) Follow rule-based gait pattern generation based on simple rules on leg return and landing timing [4, 5, 12–16].

Studies in 3) are divided into hexapod [12–14], quadruped [15, 16], and quadruped double-wheeled robots [4, 5].

For hexapod robots [12–14], Alexandre et al. realized a free gait by monitoring leg movement phases in which only when a leg relationship met a certain condition, two adjacent legs would not swing simultaneously [14].

For quadruped robots, most studies concern gaits with one swing leg to maintain stability [15, 16].

For leg-wheel robots, Kumagai et al. realized predictive event-driven creep that limits swing to one leg at a time [4] among 4 legs, i.e., 1 swinging and 3 supporting. Stability is sufficient, however, ensured with 2 swing legs in leg-wheel mode (**Fig. 2**).

Figure 2 shows transitions of the static stability margin while one leg is in swinging phase.

For creeping, leg arrangement with a minimum stability margin is sufficient. Minimum stability margins with 1 swing leg are the same as that with 2 swing legs. 1 and 2 legs with leg-wheel robots. We evaluated gait stability using the minimum stability margin when the location of rough terrain is unknown.

Figure 3 shows distance moved in one return for returning gaits with 1 and 2 legs, with swing leg speed assumed to be constant. Since the gait with 1 returning leg advances by L/3 while the gait with 2 returning legs advances by L, the maximum straight velocity is three times higher with 2 legs than with 1 leg.

Considering that the maximum straight velocity becomes three times by changing the number of swing legs from one to two without compromising the minimum stability margin, the predictive event-driven gait uses 2 swing legs.

Gaits are divided into regular, in which leg-lift and landing timing is cyclically fixed, and free, in which timing is not cyclic and is determined based on an index. Animals use both depending on conditions. When traversing flat land at constant speed, they use regular gaits and when traversing rough terrain or changing direction, they use noncyclic gaits, because leg-lift and landing timing is fixed in cyclic gaits, limiting leg movement. We thus propose a free gait algorithm for 2 swing legs.

The algorithm forbids two front or hind legs from swinging at the same time, taking advantage of wheel support – typical of leg-wheel robots making our study differ from others. The proposed gait gives the maximum number of swing legs among gaits achieving continuous traveling with arbitrary velocity commands, including direction, and ensuring the stability margin.

2. Two-Leg-Returning Free Gait Algorithm

We used passive compliance for wheels and active compliance for legs [3], and focus here on the leg movement algorithm, excluding posture control. For details, see [3].

The robot is controlled by operator commands instructing translational and rotational speed. The proposed gait-generating algorithm immediately responds to command changes. In the proposed algorithm, if an instructed velocity exceeded the maximum traveling velocity of the robot, velocity restriction is activated.

2.1. Conditions for Lifting Legs

In leg-wheel mode, maintaining least one front and back leg in support ensures the minimum stability margin as in creeping (**Fig. 2**). More than 3 legs among 4 that swing generate a zero stability margin, meaning that the gaits in the leg-wheel mode that ensure the same minimum stability margin as creep with a maximized number of swing legs is the gait in which maximum simultaneously swinging legs number two having at least one support leg in front and back (two-leg-returning free gait). Conditions hold that at least one front and back leg must be a support leg, as follows: Two front or back legs cannot swing simultaneously.

Leg-lift and landing timing in front legs is determined by comparing the time to reach the movable limits and the timing for finishing leg swinging, which are detailed after. As for back legs, each timing is determined by the same way.

Leg-lift and landing timing of front legs is independent from that of back legs.

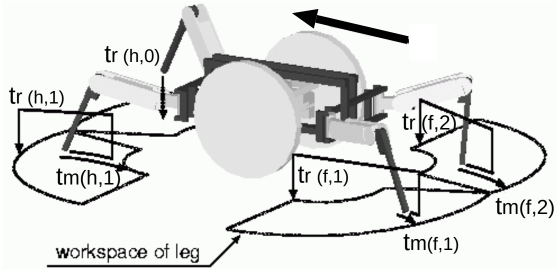

Fig. 4. An assignment of the timing parameters.

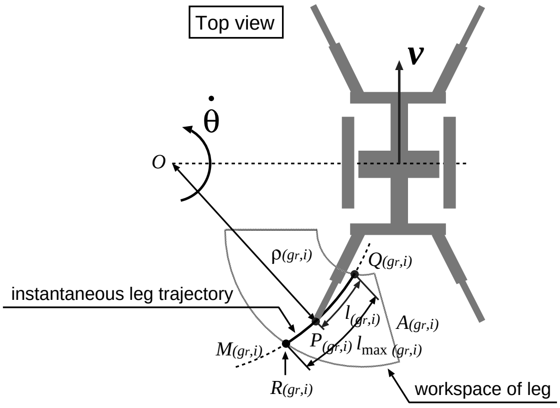

Fig. 5. Notations used in the gait algorithm description.

2.2. Leg-Lift and Landing Timing

Leg-lift and landing timing is determined by defining and comparing two indices, time to reach the movable limit and timing for finishing leg swinging. Both are predicted assuming that the robot moves at the same speed. (1) "Time to reach the movable limit" (t_m) and (2) "time to finish the swing leg movement" (T_r) are key elements of this study (**Fig. 4**). In regard to t_m, suppose a leg robot is moving and current time is T_{curr}. Focusing on a leg, it repeatedly goes back and forth in support and swing phases. In a support phase, the leg moves backward to drive the body forward. Since the leg cannot continue moving backward indefinitely, it eventually reaches a limit at time T_{lmt}. $T_{lmt} - T_{curr}$ indicates how soon a leg reaches this limit. Regarding t_r, when a leg is in a swing phase (the same as a return phase), it reaches an end point at time T_{end}, lands, and moves backward as a support leg. "Time to finish the swing leg movement" t_r is defined as $T_{end} - T_{curr}$, indicating how soon a leg ends the swing phase. Since a support leg is switched to a swing leg when it reached the movable limit as explained above, t_r can also be defined for a support leg. As with t_m, t_r is specific to each leg and the value changes with time. Note that neither t_m nor t_r indicate time points or timing. They represent the time distance from now.

The predicting time range is up to when the support leg farthest from the movable limit (a support leg having the largest t_m) at the time of prediction reaches the movable limit. The time range corresponds to one robot movement cycle, which includes all movement of support legs.

In modeled movement (**Fig. 5**), the model represents turning and a momentary leg movement (g_r,i), the back left leg, showing circular trajectory $M_{(g_r,i)}$ with the turning center O. "g_r" in leg (g_r,i) takes either "f" for the front leg or "h" for the back leg, and "i" takes 1 or 2 in each group (front and back legs) representing time wise proximity to the movable limit for the leg. When one of the front or back legs swings, it is represented by i=0 and the support leg by i=1 (no i=2). "g_r" represents a group in which not all legs in the group swing simultaneously and "i" a leg number in the group ("leg number") in the order closer to the limit, or having a smaller t_m. Our study limits a group to two legs, but the discussion is not limited to two in application. The arc segment of the trajectory within the fan-shaped leg workspace $A_{(g_r,i)}$ is called "momentary leg trajectory." In straight movement, the momentary leg trajectory becomes a line segment. The length of momentary leg trajectory $l_{\max(g_r,i)}$ represents the momentary full leg stroke(g_r,i) and leg position $P_{(g_r,i)}$ on the trajectory is expressed by length $l_{(g_r,i)}$ from an end point $Q_{(g_r,i)}$ to the position in the direction of leg movement (from $Q_{(g_r,i)}$ to $R_{(g_r,i)}$). Leg speed is expressed by Eq. (1) using body straight velocity v for straight movement, and both angular velocity $\dot{\theta}$ and turning radius $\rho_{(g_r,i)}$ for rotating movement.

$$\dot{l}_{(g_r,i)} = \begin{cases} |v| & \text{(straight movement)} \\ \rho_{(g_r,i)}|\dot{\theta}| & \text{(rotating movement)} \end{cases} . \quad (1)$$

Assuming that the robot continues to move at the same velocity, time $t_{m(g_r,i)}$ for leg(g_r,i) to reach movable limit $R_{(g_r,i)}$ is defined by Eq. (2). The momentary trajectory is updated each processing cycle and variables immediately respond to a command change in velocity (with velocity restriction, stated later).

$$t_{m(g_r,i)} = \frac{l_{\max(g_r,i)} - l_{(g_r,i)}}{\dot{l}_{(g_r,i)}}. \quad (2)$$

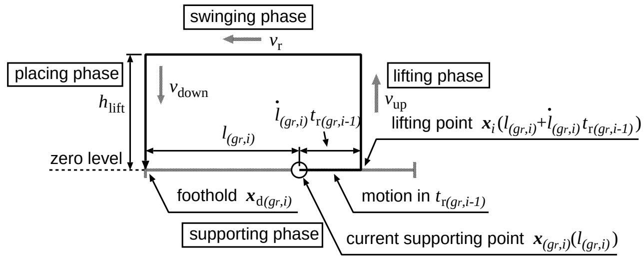

Fig. 6. Calculation of the returning time.

The time required to completely swing a leg for leg (g_r,i) defines 2-dimensional coordinates for a leg using $x_{(g_r,i)}(l_{(g_r,i)})$ and a parameter $l_{(g_r,i)}$ (**Fig. 6**). $x_{d(g_r,i)}$ represents the target landing point. The target landing point is set on the border of the leg workspace so that the leg in a support phase passes the center of the leg workspace (the midpoint in radius and circumferential direction) assuming that the speed of movement is the same after leg landing. The target landing point is updated each processing cycle.

Since both front or back legs cannot swing simultaneously, leg(g_r,i) is ready to swing after leg(g_r,$i-1$) finishes.

When the timing for finishing swinging of leg(g_r,$i-1$)

is represented by $t_{r(g_r,i-1)}$, leg(g_r,i) will move during the time from $x_{(g_r,i)}(l(g_r,i))$ to $x_{(g_r,i)}(l_{(g_r,i)} + \dot{l}_{(g_r,i)} t_{r(g_r,i-1)})$. The destination is the initiating point for leg lifting, i.e., the beginning of swinging for leg (g_r,i), and the timing for finishing leg swinging is discussed based on this point.

When the trajectory is rectangular and consists of a lifting phase in which a leg is vertically lifted to a leg-lift height, a swing phase in which the leg is horizontally moved linearly to $x_{d(g_r,i)}$, and a landing or placing phase in which the leg is vertically lowered to the ground, the timing for finishing swinging for leg(g_r,i) at $x_{d(g_r,i)}$ is expressed by the following recursion formula:

$$t_{r(g_r,i)} = t_{r(g_r,i-1)} + T_{up} + \frac{|x_{d(g_r,i)} - x_{(g_r,i)}(l_{(g_r,i)} + \dot{l}_{(g_r,i)} t_{r(g_r,i-1)})|}{v_r} + T_{down} \quad (3)$$

in which T_{up} and T_{down} represent time required for leg-lift and landing, ignoring leg acceleration and deceleration for simplicity, and defined as $T_{up} = h_{lift}/v_{up}$, $T_{down} = h_{lift}/v_{down}$ using h_{lift}, height of leg-lift, v_{up}, leg-lift velocity, and v_{down}, leg lowering velocity. v_r is horizontal leg moving velocity in a swing phase and assumed to be constant in an effective leg workspace. $t_{r(g_r,0)}$ used for $t_{r(g_r,1)}$ calculation is equal to the time for support leg(g_r,1) to become ready for swinging. With a swing leg, this corresponds to minimum time (Eq. (4)) for the swing leg to land.

$$t_{down(g_r,0)} = \frac{h_{(g_r,0)}}{v_{down}} \quad \ldots\ldots\ldots\ldots \quad (4)$$

in which leg number 0 represents swing legs and $h_{(g_r,0)}$ is the height of the swing leg. $t_{r(g_r,0)}$ is defined by Equation 5 with $t_{down(g_r,0)}$ added by a time margin T_{cr} to prevent excessive access to the movable limit.

$$t_{r(g_r,0)} = \begin{cases} T_{cr} & (\text{no returning leg in the same } g_r \text{ legs}) \\ t_{down(g_r,0)} + T_{cr} & (\text{with a returning leg in the same } g_r \text{ legs}). \end{cases} \quad (5)$$

To avoid legs having the same g_r swinging simultaneously, swinging for a smaller leg number (the leg that would reach the movable limit earlier) must finish movement prior to a leg having a larger leg number reaching the movable limit (Eq. (6)) using time to reach the movable limit $t_{m(g_r,i)}$ and timing for finishing leg swinging $t_{r(g_r,i)}$.

$$t_{m(g_r,i)} > t_{r(g_r,i-1)} \quad (i = 1, 2). \quad \ldots\ldots\ldots \quad (6)$$

When one leg in a group swings, there is no $i = 2$ in the group. Since swinging must satisfy this condition, the initiation of swinging of a support leg is set to the point when Eq. (6) is false or the following equation is true:

$$t_{m(g_r,i)} \leq t_{r(g_r,i-1)} \quad (i = 1, 2). \quad \ldots\ldots\ldots \quad (7)$$

For two support legs and $i = 1$, the leg with leg number 1 has reached movable limit. The leg becoming a swing leg is leg number 1. When no leg is swinging in a group, swinging is initiated, and when a leg is swinging, swinging of the other leg is initiated after the swing leg lands.

The above algorithm is applied to groups of legs, i.e., front and back legs, independently.

2.3. Velocity Restriction

With the algorithm in Section 2.2 alone, if the velocity command exceeds the maximum velocity, swinging cannot catch up, and the support leg reaches its movable limit before the swing leg completely returns, causing narrow step widths and frequent step changes. If this continues, the step width eventually becomes zero and the robot halts.

To prevent this, velocity restriction is introduced so the swing can returns completely.

We defined the timing for finishing swinging for leg(g_r,0) as Eq. (5), revised to Eq. (8) to assume the complete time to finish swinging $t'_{r(g_r,0)}$. Leg(g_r,0) is a swing leg and margin T_{cr} is given, as in Eq. (5), to the case in which there is no swing leg in the same group.

$$t'_{r(g_r,0)} = \begin{cases} T_{cr} & (\text{no returning leg in the same } g_r \text{ legs}) \\ t_{up(g_r,0)} + \frac{|x_{d(g_r,0)} - x_{(g_r,0)}|}{v_r} + T_{down} + T_{cr} & (\text{with a lifting or swinging leg in the same } g_r \text{ legs}) \\ t_{down(g_r,0)} + T_{cr} & (\text{with a placing leg in the same } g_r \text{ legs}). \end{cases} \quad (8)$$

$t_{up(g_r,0)}$ represents the remaining time of lifting for the swing leg, and is defined the same as $t_{down(g_r,0)}$ in Section 2.2. When there is a swing leg in the same group, time to reach the movable limit $t_{m(g_r,1)}$ of a support leg need only be greater than the timing for finishing leg swinging $t'_{r(g_r,0)}$ for the swing leg to ensure complete timing for finishing swinging, as follows:

$$t_{m(g_r,1)} \geq t'_{r(g_r,0)}. \quad \ldots\ldots\ldots\ldots\ldots \quad (9)$$

The restricted velocity must satisfy the above equation for g_r.

When there is a swing leg, approximate solutions of Eq. (9) for the restricted target velocity are given by Eqs. (10) and (11) by changing magnitude of the vector while maintaining the direction of the vector [4]. When there is no swing leg or the absolute value of the command velocity is smaller than Eq. (10) or (11), the command velocity is not restricted and the velocity command velocity is taken as the target velocity without restriction.

$$|v_{max}| = \min\left(\frac{l_{max(g_r,1)} - l_{(g_r,1)}}{t'_{r(g_r,0)}}\right) \quad (g_r = f, h) \quad (10)$$

(straight movement (with returning legs))

$$|\dot{\theta}_{max}| = \min\left(\frac{l_{max(g_r,1)} - l_{(g_r,1)}}{\rho_{(g_r,1)} \cdot t'_{r(g_r,0)}}\right) \quad (g_r = f, h) \quad (11)$$

(rotating movement (with returning legs)).

3. Verification by Simulation

In simulation to verify the effectiveness of the proposed gait algorithm, we used a dynamics simulator Open Dynamics Engine (ODE) for simulation. **Table 1** indicates physical parameters of the leg-wheel robot used in the

Table 1. Physical parameters of Chariot 3

link length of the legs		
	1st, 2nd, 3rd link	0.08, 0.30, 0.38 m
wheels		
	diameter	0.6 m
	tread	0.58 m
workspase of the legs		
	internal, external radius	0.30, 0.60 m
	angle	-20 – 60 deg
distance between bases of the legs		
	front and back	0.92 m
	right and left	0.4 m
actuator (DC servo motor)		
	legs' 1st joint, wheels	40 W
	legs' 2nd, 3rd joint	60 W
total mass		65 kg

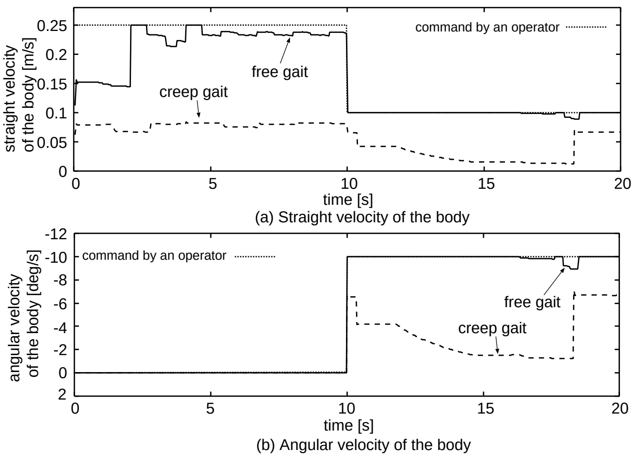

Fig. 7. Comparison between creep gait and free gait (velocity of the body).

simulation. Parameters in **Fig. 6** are set as h_{lift} = 0.15 m, $|v_{\mathrm{up}}| = |v_{\mathrm{r}}| = |v_{\mathrm{down}}| = 0.5$ m/s, body straight and angular speed are given as command speed.

3.1. Velocity Comparison with Creep

Figure 7 shows creep speed [4] and target speed after the restriction of Section 2.3 in the proposed two-leg-returning free gait. **Fig. 8** shows normalized positioning of all legs, defined as $l_{(g_{\mathrm{r}},i)}/l_{\max(g_{\mathrm{r}},i)}$ (**Fig. 5**). Normalized leg positioning of 0 represents the point at which swinging has finished (support leg movement initiating point) and position of 1 represents when the leg has reached movable limit. Increasing lines represents legs in support phases, and decreasing lines those in swing phases. Normalized leg positioning in lifting and landing are represented by beginning and end points of the support leg and those in swing phases are represented by a line segment connecting lifting and landing. The discontinuity at 10 s is attributable to the change of the command velocity, which changes momentary leg trajectories (**Fig. 8**).

A straight velocity command of 0.25 m/s was given between 0 and 10 s and then the straight velocity was changed to 0.10 m/s added with angular velocity of -10.0 deg/s (turn to the right) (above: straight speed; below: angular speed, **Fig. 7**). Time-averaged ratios between 0 and 20 s of straight velocity in the two-leg-returning free gait to that of creeping is 3.59, and the ratios between 10 and 20 s of angular velocity to that of creeping is 4.40.

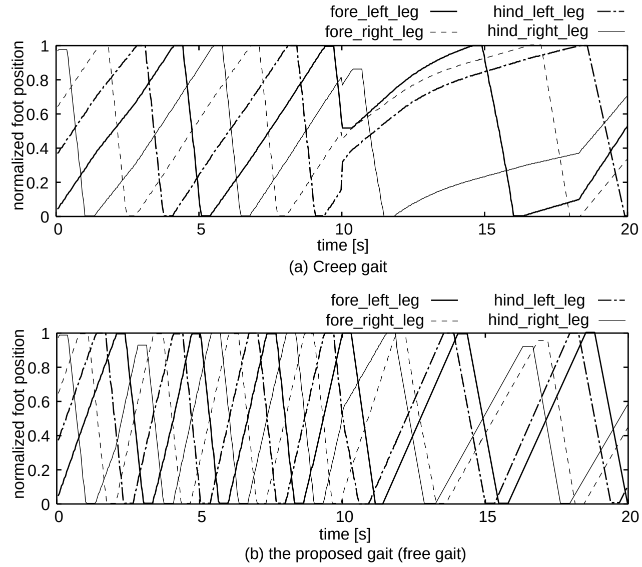

Fig. 8. Normalized foot position.

These results indicate that the proposed gait moves more than three times faster than creeping. The above ratios may vary by command velocity because velocity restriction varies by leg arrangement. One of the reasons that the ratios more than three was yielded is that, while the study [4] restricts movement of support legs by themselves even though all legs are supporting, our proposal does not restrict speed for two legs in a group if both are supporting.

3.2. Verification of Continuous Travel with Command Speed in Arbitrary Directions

We verified by simulation that the proposed gait immediately responds to velocity changes with arbitrary direction and travels continuously.

Figure 9(a) shows target straight and angular speed after the restriction of Section 2.3 when speed was given as indicated by dotted lines. **Fig. 9(b)** shows a trace of the center of gravity (COG) driven by the target velocity after restriction, and **Fig. 9(c)** shows normalized positions for all legs.

The robot traveled straight between t=0 and 5 s, turned to the left in place (betw. t=5 and 10 s), then traveled making a curve to the right (betw. t=15 and 25 s) and to the left (betw. t=28 and 33 s) (**Fig. 9(a)**(b)). During the time between t=28 and 33 s, the target straight speed was gradually reduced from 0.12 to 0.06 m/s.

The robot travel continuously in response to arbitrary velocity commands even though the velocity restriction is activated (**Fig. 9(a)**).

The decrease in straight velocity around 15 s is due to a command change from straight to right turn. Since leg trajectory differs for straight and turning movement, nor-

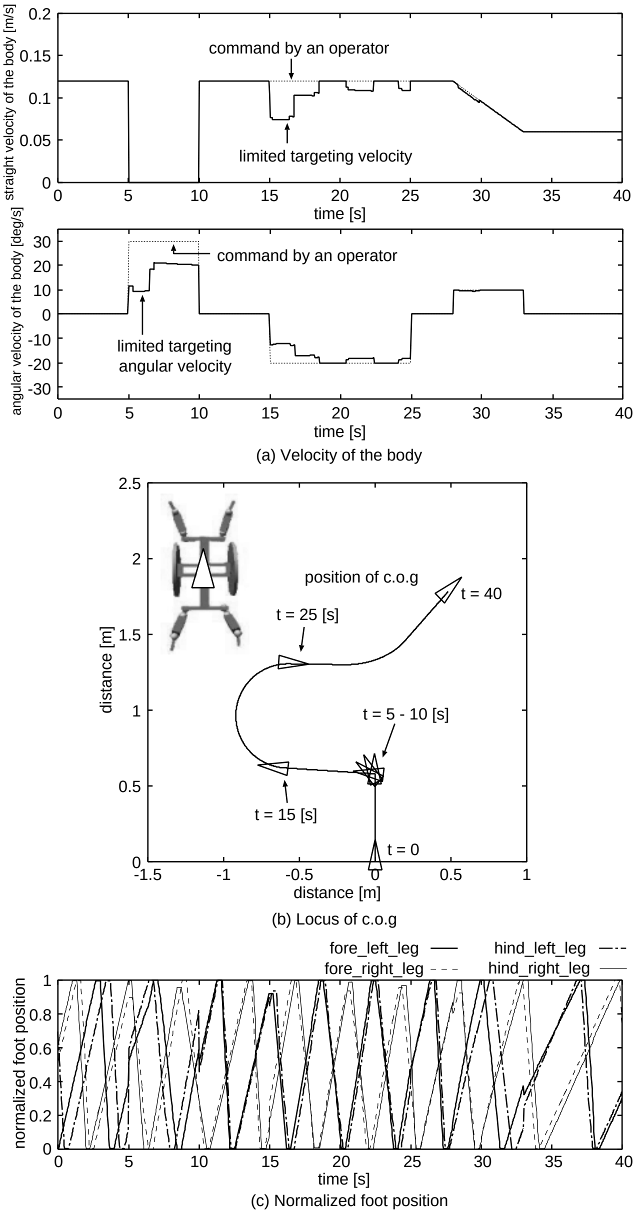

Fig. 9. A result of simulation.

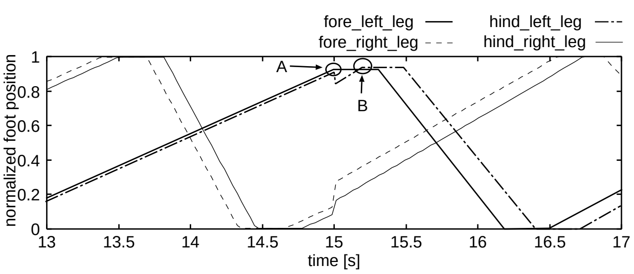

Fig. 10. Normalized foot position at 13-17 s.

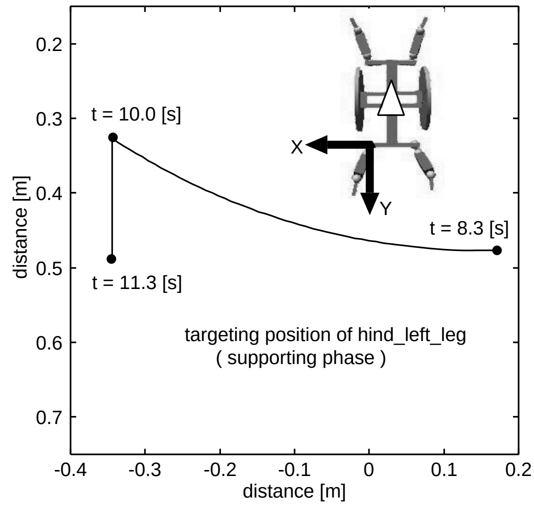

Fig. 11. A trajectory of hind-left leg at 8.3-11.3 s.

malized leg positions for legs other than the left front leg discontinuously change (**Fig. 10**), magnifying the section between 13 and 17 s in **Fig. 9(c)**. With a velocity command change at 15 s, $t_{\mathrm{m}(f,2)} \leq t_{\mathrm{r}(f,1)}$ becomes true with the left front leg (leg(f,1)) and right front leg (leg(f,2)), and according Eq. (7), swinging is initiated even though the left front leg has not yet reached movable limit (point A in **Fig. 10**). As a result, velocity restriction was activated to ensure complete swinging for the left front leg. At point B, under the velocity restriction, $t_{\mathrm{m}(h,2)} \leq t_{\mathrm{r}(h,1)}$ becomes true with the left back leg (leg(h,1)) and right back leg (leg(h,2)), so swinging is initiated even though the left back leg has not yet reached movable limit.

Figure 11 shows a target trajectory of the left back leg between t=8.3 and 11.3 s. The command velocity at t=10 s changes from turning in place to straight movement (**Fig. 9(a)**), with the left back leg as support, indicating that the robot immediately changed to straight movement at t=10 s (**Fig. 11**).

4. Verification by Experiments

To confirm that the free gait algorithm verified by simulation effectively works with a real machine, experiments were conducted using leg-wheel robot Chariot 3.

A single-board computer (Intel Pentium III 1 GHz) and ART-Linux were used for real-time control. The computer and the robot are connected via a FPGA board, which converts torque information from the computer to PWM pulses and counts pulses from rotary encoders installed at joints of the robot. The gait algorithm is processed every 30 ms and robot hardware is controlled every 5 ms. The experimental conditions were the same as those with simulation.

Figure 12(a) shows an experiment and **Fig. 12(b)** and **(c)** shows results. **Fig. 12(b)** shows target straight and angular speed after restriction in Section 2.3 and **Fig. 12(c)** shows the trajectory of COG.

Comparing **Fig. 12(b)** to **Fig. 9(a)**, experimental results are almost the same as in simulation, indicating the appropriateness of simulation. As in simulation, the robot immediately responded to random command changes in velocity including turns and realized continuous traveling. Comparing **Fig. 12(c)** to **Fig. 9(c)** shows a similar trace.

Experimental results thus demonstrate that the algorithm realized continuous traveling responding to velocity commands in arbitrary directions and timing.

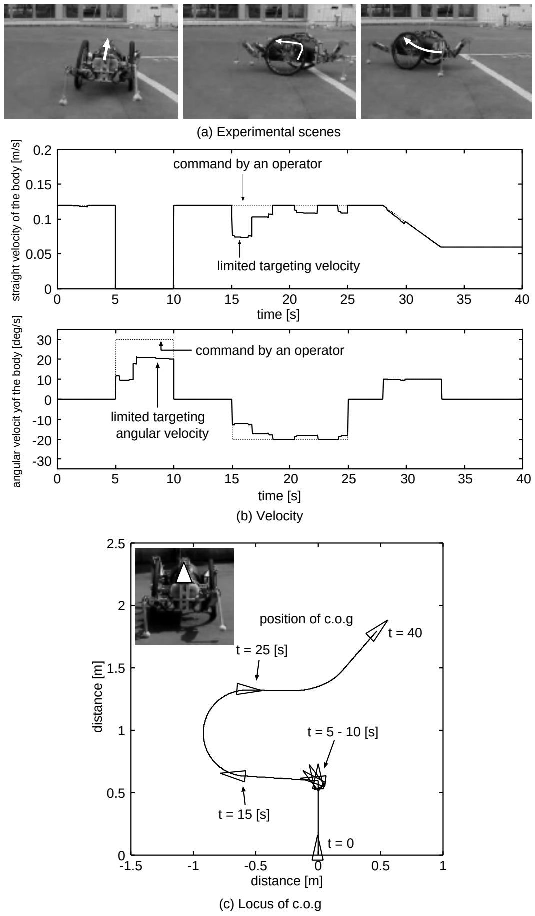

Fig. 12. An experimental result.

5. Conclusions

We have developed a predictive event-driven free gait algorithm with two swinging legs and demonstrated by simulation and experiments that it enabled a leg-wheel robot to realize continuous traveling with velocity commands in arbitrary directions.

The proposed gait realized high speed movement while maintaining the same minimum stability margin as that obtained by creeping, whose maximum simultaneous swing legs is one. We have presented a concept of legs to swing for leg-wheel robots and proved that leg-lift and landing timing could be determined by comparing the time to reach the movable limit and the timing for finishing leg swinging only within a group of legs. Our approach is thus applicable to any robot that maintains the stability margin by making only one leg in the group support.

The travel speed of the robot, however, is dictated by a slower group of legs due to Eqs. (10) and (11) in our algorithm, which determines leg-lift and landing timing only assuming that legs reached movable limits. This means the limitation of a slower group influences other groups, possibly introducing a new velocity restriction to the system. We must include velocity in evaluation factors to improve the leg-lift and landing algorithm for higher speed.

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