Proceedings of the 2002 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
EPFL, Lausanne, Switzerland • October 2002

Omni-directional Walking of a Quadruped Robot

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Abstract

In this paper, we propose a successive gait-transition method for a quadruped robot to realize omni-directional static walking. The gait-transition is successively performed among the crawl gaits and the rotation gaits while the foots hold in common positions before and after gait-transition. The gait-transition time is reduced by carefully designing the foot position of the crawl gait and the rotation gait while limiting the foots in rectangular reachable motion ranges. Experiments were executed to show the validity and the limitation of the proposed gait-transition method.

1 Introduction

The legged robot was expected to be an environment-accessible platform because of its environment adaptability. The quadruped walking robot will be one of the most practical locomotion machines to move about on uneven terrain and is stablest while walking in static state [1]. In this study, we limit the discussion on the static walking of a quadrupled robot that is always statically stable. Note that the static stability assumes that the vertical projection of the COG (center of gravity) remains always inside the stability polygon with an adequate stability margin during all phases of movements.

One of static walking gait, named as Crawl gait, was introduced by McGhee [2], that appears to be very close to the walk frequently used by mammals at low speed [3]. For the robot to perform the movement in any decided direction, Hirose extended the crawl gait to a standard side-walking gait, crab gait [4]. We classify this crab gait to crawl gait in this research. Moreover, for the quadruped robot to perform a rotation, a rotation gait was introduced [5] that gives the maximum rotation velocity around any center of turning. To manage transition between the "standing postures" which represent the position and attitude of the platform, the moving speed and the supporting patterns of all four legs, the standing posture transformation gait was proposed [6]. This algorithm, however, connects the walking gaits with a static convergence leg position and must have the torso stop at least of 4 steps. It can not make the robot perform an omni-directional walking with the least time of torso stop. Recently, the semi-autonomous walking of a quadruped robot based on leg transition at the border of the leg work space has been proposed [7], and the gait-transitions between forward, backward, left and right turning and rotation motion have been discussed in cooperation of sideways' motion of torso [8]. The omni-directional walking, however, has not been perfectly performed by the former algorithms. In this study, we thus present an omni-directional walking gait to realize the omni-directional static walking of the quadruped robot. The omni-directional walking discussed in this study is not only performing a given direction walking as crab walking, but also performing the successive walking while the walking direction is changed. The walk gait planning technique chooses the crawl gait or rotation gait from the center of turning and transfers the gaits from one to another continuously when changing the center of turning.

The purpose of this paper is, first introducing the planning technique of the standard gaits (crawl gait and rotation gait) that is for easily performing successive gait-transition; then discussing the successive gait-transition technique that deals with the gait transition between any crawl gait and any rotation gait.

2 Omni-directional Walking Gaits

As mentioned in introduction, the most basic static walking pattern for the quadruped robot is the crawl gait (including crab gait). This gait is not only for straight-line movement but also for a curve movement with small curvature. While the curvature becomes larger or the center of turning is near COG, the rotation gait has better static stability and higher motion speed than the crawl gait. The successive omni-directional walking is generated by continuous gait-transition between these crawl and rotation gaits. In this paper, we present

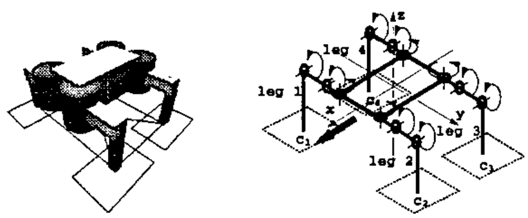
Standard gait planning: After selecting the gait from the turning center, plan the leg positions and trajectories with legs' reachable ranges.

1. Select a gait from the position of the turning center.

2. Derive the landing position of the swinging leg and the lifting position of the supporting leg from the legs' reachable range.
3. Plan the leg trajectories that connect corresponding points.

Successive gait-transition: Transfer gait successively corresponding to the change of the turning center.

1. Select next gait and derive the next-step legs' positions from new position of the turning center.
2. Move the legs from current legs' positions to new legs' positions successively.



(a) Robot model (b) Coordinate

Fig. 1: Robot model and Coordinate located on the robot

In this study, we utilize the robot model shown in Fig. 1 (a) and set the torso coordinate as Fig. 1 (b). The origin of the coordinate is located at COG, its $x-$axis is in the back-to-front direction of the torso, its $y-$axis is in the right-to-left direction and its $z-$axis is in the bottom-to-top direction. The legs are labeled 1 to 4 as shown in Fig. 1. Assume the robot posture shown in Fig. 1 to be basic posture and the corresponding legs' positions as legs' basic positions. While walking, the robot is assumed to control its posture so as to keep the torso horizontally in height of COG, c_{iz}. The supporting leg's motion and the swinging leg's motion are both planned in the coordinate fixed on the robot torso. The duty factor β is assumed to be 0.75 for the crawl gait to allow a maximal speed and the time of swinging leg T_{sw} is fixed to a constant value.

3 Planning of Standard Gaits

In this section, we give the planning technique of the crawl gait with an arbitrary turning center and the rotation gait that are the standard gaits of omni-directional walking. In order to perform the gait-transition with least of steps, the foots before and after gait-transition are designed to have common positions as shown in Fig. 2. The positions of the supporting legs at the basic posture are defined as the common positions of the standard gaits. The successive gait-transition based on the discussed standard gaits can also be used for starting phase from the basic posture and ending phase to the basic posture without any change. The planning of the crawl gait and that of the rotation gait are almost same beside of

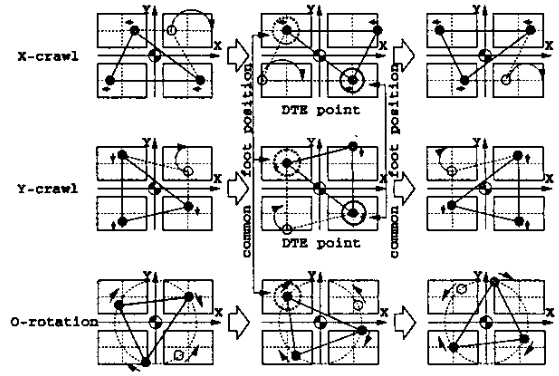


Fig. 2: Common foot position for each walking gait

the position of the turning center and the sequence of leg swinging. The standard gaits are planned through 1) selecting a gait pattern from the position of the turning center, 2) deriving the landing position of a swinging leg and the lifting positions of the supporting legs, 3) planning the leg trajectories that connect corresponding points.

3.1 Selection of gait pattern

In this study, we assume that the walking speed and rotation speed are given by operator or from navigation.

In this section, we first derive the radius of the turning curve, r_g, and the position of the turning center, $\boldsymbol{Q}$, from the given walking speed, $\boldsymbol{v}_{in}$, and the rotation speed, $\dot{\theta}_{in}$. The radius of the turning curve r_g, can be given by

$$r_g = |\boldsymbol{v}_{in}|/|\dot{\theta}_{in}|. \quad (1)$$

If the rotation speed $\dot{\theta}_{in}$ is zero (in the case of straight-line walking), we use a small value instead (in simulation and experiment, 10^{-10} was used). The position of the turning center, $\boldsymbol{Q}$, located at the ground, thus can be described by

$$\boldsymbol{Q} = \boldsymbol{Rot}(\boldsymbol{k}, \frac{\pi}{2}) \left[\begin{array}{cc} \frac{\boldsymbol{v}_{in}}{\dot{\theta}_{in}} & -c_{iz} \end{array} \right]^T \quad (2)$$

where $\boldsymbol{Rot}(\boldsymbol{k}, \frac{\pi}{2})$ is the rotation matrix that rotates $\pi/2$ angle around $z-$axis.

Next, we select the walking gait pattern from the above-derived position of the turning center. Through mapping the position of the turning center and the turning direction onto Fig. 3, the walking gait pattern that should be used can be selected from Fig. 4. For example, if the robot turns in counter-clockwise and the position of the turning center is on the (5) area of Fig. 3 (a), the robot is resulted to select the walking gait pattern (5) of Fig. 4.

It should be pointed out that the rotation gait is selected in the case that the walking speed and the rotation speed are 0 (the robot is stopped). As a result, the starting phase from the basic posture can be seen as the gait-transition

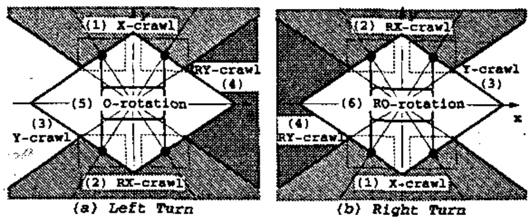


Fig. 3: Gait selection by center of curvature

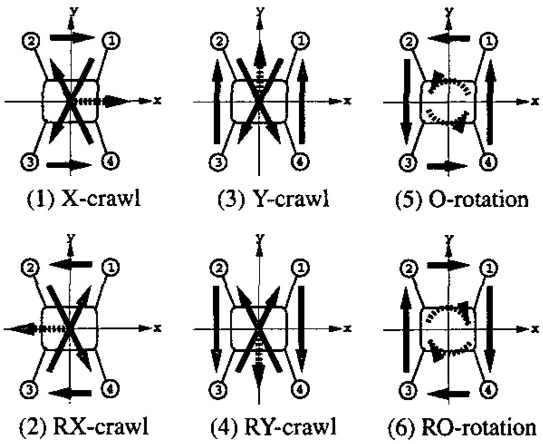


Fig. 4: Each type of the static walking gaits

from the rotation gait, and the ending phase to the basic posture can be seen as the gait-transition to the rotation gait. That is, the walking from start to the limit speed (or from the limit speed to end) can be seen as the gait-transition from (or to) the rotation gait.

Fig. 3, shown the region for gait selection by center of curvature, is obtained from the relation between the position of the turning center and the stability margin while using the rotation gait, and from the critical angle between the $X-$crawl gait and the $Y-$crawl gait. Since there has no DTE (diagonal triangle exchange) point [9] in the rotation gait, the robot can always walk with a positive stability margin while the turning center is near the center of the torso. Thus the rotation gait is better used in the case that the turning center is near the center of the torso. The boundary for clarifying the use of the rotation gait and the crawl gait is not quit clear, we here derive the border, where the stability margin of the rotation gait is zero, by computer simulation. In the computer simulation, the parameter of the robot model mentioned in section 5 was utilized and the rotation speed was set to 0.06[rad/s]. As the robot model is symmetric in fore-aft and right-left direction, we only show the obtained contour of the stability margin of the second phase in Fig. 5. From this result, we know that

- the border of zero stability margin is almost a straight line,
- the stability margin is inverse proportion of the distance of the turning center from the COG,
- the stability margin decreases in highest speed along the line that connects the origin of torso coordinate and the leg's basic position.

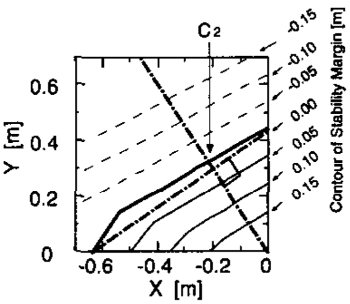


Fig. 5: Contour of stability margin for rotation gait

The boundary for clarifying the use of the rotation gait, thus, can be approximately given by a line

$$y = -\frac{c_{ix}}{c_{iy}}x + \frac{c_{ix}^2 + c_{iy}^2}{c_{iy}}. \tag{3}$$

This line is passing through the leg's basic position c_i and normal to the line that connects the origin of torso coordinate and the leg's basic position. The line obtained by substituting the parameter of the used robot model for Eq. (3) is passing through the leg's basic position c_i and is very near the line connected the points on $x-$axis and $y-$axis with the zero stability margin. If the turning center is on the torso side of this line, the stability margin of the rotation gait is never smaller than zero. This line can be thus used as the border to select the rotation gait. If the turning center is on the outside of the line against the torso, the crawl gait is better selected. Depending on the walking direction angle, select one crawl gait from $X-$crawl, $RX-$crawl, $Y-$crawl, and $RY-$crawl.

After selecting the used gait pattern from the position of the turning center, then give the time phase t_i for each leg corresponding to the selected gait. $t_i = 0$ is for start of the legs' swinging and $t_i = T_{sw}$ is for its end.

3.2 Derivation of leg's landing position and leg's lifting position

The landing position of the swinging leg and the lifting position of the supporting leg can be derived from the rotation speed whose maximum value is determined by the position of the turning center, the selected gait, and the legs' reachable ranges. In this study, we assume that the reachable ranges of the legs are symmetric about COG and rectangles for simplicity, as shown in Fig. 1 and Fig. 2. The scheme proposed in this paper, however, can also be used for any shape of reachable range of legs.

3.2.1 Maximum rotation speed From the constraint that the trajectories of the supporting legs must pass through the basic positions of legs in order for the foots to have common positions in the transition from one gait to another gait, we can have the curvature radius r_i given by

$$r_i = ||\boldsymbol{c}_i - \boldsymbol{Q}||. \tag{4}$$

As shown in Fig. 6, the basic position of each leg, $\boldsymbol{c}_i$, can

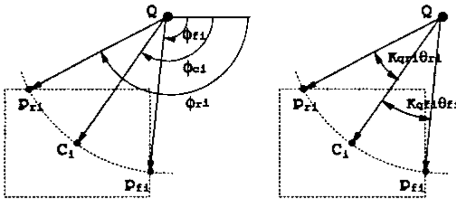


Fig. 6: Reachable angles of a leg around curvature center

be described by the inclining angle ϕ_{ci}. It is given by

$$\phi_{ci} = \text{atan2}((c_{iy} - Q_y), (c_{ix} - Q_x)). \tag{5}$$

If setting the intersection of the trajectory of the supporting leg and the boundary of the reachable range by $\boldsymbol{p}_{fi}$ for walking direction, $\boldsymbol{p}_{ri}$ for anti-walking direction, we can have the inclining angles corresponding to $\boldsymbol{p}_{fi}$ and $\boldsymbol{p}_{ri}$ as

$$\phi_{fi} = \text{atan2}((p_{fiy} - Q_y), (p_{fix} - Q_x)), \tag{6}$$
$$\phi_{ri} = \text{atan2}((p_{riy} - Q_y), (p_{rix} - Q_x)). \tag{7}$$

In order to derive the trajectories of the supporting legs that make the foots have the common positions before and after the gait transition, we introduce the trajectory-partition coefficients K_{qfi} and K_{qri}. These two coefficients are the coefficients that divide the trajectories corresponding to the gait, and use the values listed in Tab.I.

Using K_{qfi} and K_{qri}, we can have

$$\theta_{fi} = |\phi_{fi} - \phi_{ci}|/K_{qfi},\ \theta_{ri} = |\phi_{ri} - \phi_{ci}|/K_{qri}. \tag{8}$$

Among all of θ_{fi} and θ_{ri}, the smallest one is the feasible maximum rotation angle $\theta_{\max}$ and $\theta_{\max}/T$ is the feasible maximum rotation speed $\dot{\theta}_{\max}$. That is, we can have maximum rotation speed $\dot{\theta}_{\max}$ given by

$$\theta_{\max} = \min\{\theta_{fi}, \theta_{ri} \mid i = 1, 2, 3, 4\}, \tag{9}$$
$$\dot{\theta}_{\max} = \theta_{\max}/T, \tag{10}$$

where T is the time of one cycle in 4 steps.

3.2.2 Landing position of the swinging leg The start position of the swinging leg $\boldsymbol{p}_{si}$ is the leg's position at $t_i = 0$ and its end position $\boldsymbol{p}_{ei}$ is the leg's position at

Table I: Partition coefficient for each walking pattern

X-crawl

leg i	K_{qfi}	K_{qri}
1	0.5	0.25
2	0.25	0.5
3	0.25	0.5
4	0.5	0.25

RX-crawl

leg i	K_{qfi}	K_{qri}
1	0.25	0.5
2	0.5	0.25
3	0.5	0.25
4	0.25	0.5

Y-crawl

leg i	K_{qfi}	K_{qri}
1	0.5	0.25
2	0.5	0.25
3	0.25	0.5
4	0.25	0.5

RY-crawl

leg i	K_{qfi}	K_{qri}
1	0.25	0.5
2	0.25	0.5
3	0.5	0.25
4	0.5	0.25

O(RO)-rotation

leg i	K_{qfi}	K_{qri}
1, 2, 3, 4	0.5	0.25

$t_i = T_{sw}$. The inclining angle of the landing position of the swinging leg, ϕ_{ei}, is described as

$$\phi_{ei} = \phi_{ci} + K_{qi}\theta \tag{11}$$

through the inclining angle of the legs' basic position ϕ_{ci}, the trajectory-partition coefficient K_{qi} (K_{qfi} or K_{qri}), and the rotation angle θ ($\theta = \dot{\theta}_{in}T$. Therein, $\theta \le \theta_{\max}$) of one cycle. Note that K_{qi} is K_{qfi} (or K_{qri}) corresponding to θ_{fi} (or θ_{ri}) which is $\min\{\theta_{fi}, \theta_{ri}\}$. For example, if $\theta_{f1} = \min\{\theta_{fi}, \theta_{ri} | i = 1, 2, 3, 4\}$, K_{qf1} must be used. The landing position of the swinging leg, $\boldsymbol{p}_{ei}$, can be thus derived by

$$\boldsymbol{p}_{ei} = \boldsymbol{Q} + \begin{bmatrix} r_i \cos\phi_{ei} \\ r_i \sin\phi_{ei} \\ 0 \end{bmatrix}. \tag{12}$$

3.2.3 Lifting position of the supporting leg The start position of the supporting leg is the landing position of the swinging leg $\boldsymbol{p}_{se}$ and its end position $\boldsymbol{p}_{hi}$ is the leg's position at $t_i = T$. The inclining angle of the supporting leg at end of supporting phase, ϕ_{hi} can be described as

$$\phi_{hi} = \phi_{ei} - \dot{\theta}(T - T_{sw}) \tag{13}$$

by the inclining angle of the swinging leg at end of swinging phase, ϕ_{ei}, and the rotation speed $\dot{\theta}$ ($\dot{\theta} = \dot{\theta}_{in}$. Therein, $\dot{\theta} \le \dot{\theta}_{\max}$). The lifting position of the supporting leg, $\boldsymbol{p}_{hi}$, is thus given by

$$\boldsymbol{p}_{hi} = \boldsymbol{Q} + \begin{bmatrix} r_i \cos\phi_{hi} \\ r_i \sin\phi_{hi} \\ 0 \end{bmatrix}. \tag{14}$$

3.3 Planning of leg trajectories

The leg trajectory of the swinging leg is a curve connected its start position $\boldsymbol{p}_{si}$ and its end position $\boldsymbol{p}_{ei}$ with account of height h_{sw}. We use a cos function to define the command position of the swinging leg, p_{di}, and its command velocity $\dot{p}_{di}$, as

$$p_{di} = \begin{bmatrix} \frac{p_{six}-p_{eix}}{2}\cos(\frac{\pi}{T_{sw}}t_i) \\ \frac{p_{siy}-p_{eiy}}{2}\cos(\frac{\pi}{T_{sw}}t_i) \\ \frac{h_{sw}}{2}\{1-\cos(\frac{2\pi}{T_{sw}}t_i)\} \end{bmatrix} + \frac{1}{2}(p_{si}+p_{ei}),$$

$$\dot{p}_{di} = \begin{bmatrix} -\frac{1}{2}(p_{six}-p_{eix})\frac{\pi}{T_{sw}}\sin(\frac{\pi}{T_{sw}}t_i) \\ -\frac{1}{2}(p_{siy}-p_{eiy})\frac{\pi}{T_{sw}}\sin(\frac{\pi}{T_{sw}}t_i) \\ h_{sw}\frac{\pi}{T_{sw}}\sin(\frac{2\pi}{T_{sw}}t_i) \end{bmatrix}.$$

Since the trajectories of the supporting legs are a circle, the command positions of the supporting legs and their command velocities can be given by

$$p_{di} = Q + \begin{bmatrix} r_i\cos\phi_{di} \\ r_i\sin\phi_{di} \\ 0 \end{bmatrix},$$

$$\dot{p}_{di} = \begin{bmatrix} -r_i\sin(\phi_{di})\dot{\phi}_{di} \\ r_i\cos(\phi_{di})\dot{\phi}_{di} \\ 0 \end{bmatrix} = \begin{bmatrix} r_i\sin(\phi_{di})\dot{\theta} \\ -r_i\cos(\phi_{di})\dot{\theta} \\ 0 \end{bmatrix}$$

by the command inclining angle ϕ_{di} defined by

$$\phi_{di} = \phi_{ei} - \dot{\theta}(t_i - T_{sw}). \tag{15}$$

Through tracking the planned legs' trajectories, the robot can walk in any standard gait around any turning center. Note that the straight-line walking can also be easily performed by setting the radius of the turning center a large value (in simulation and experiment, 10^{10} was used)

4 Successive Gait-transitions

In section 3, we have made the gait-transition performed within least of steps possible, through designing the foots before and after gait transition to have common positions, and through planning the leg trajectories to make the 2 supporting legs formed a diagonal line locate at the basic legs' positions at DTE point. In this section, we assume that the gait-transition is executed at one step before DTE point and propose the successive gait-transition procedures while changing the turning center.

While the position of new turning center is given, we first select the corresponding gait and derive the corresponding legs' positions, then move the legs from the current positions to new positions, to perform the successive gait-transition. The gait-transition between the gaits shown in Fig. 4 can be mainly classified to

- Gait-transition from crawl to crawl
- Gait-transition from crawl to rotation
- Gait-transition from rotation to crawl
- Gait-transition form rotation to rotation

Next, we discuss the successive gait-transition procedures that can perform the above 4 gait-transitions stably and continuously with least of steps.

4.1 Gait-transition from crawl to crawl

The gait-transition from crawl to crawl is divided to following two cases based on which leg is first swung at start of gait-transition.

Case 1: the front leg is the first swinging leg in the walking direction of new gait

Case 2: the back leg is the first swinging leg in the walking direction of new gait

The gait-transitions for these two cases are shown in Fig. 7. Therein, 'U' describes the swinging leg at step 1, 'C' is the leg opposite to the leg U, 'A' describes the front leg in the walking direction of old gait except the leg U and the leg C, and 'B' is the opposite leg of the leg A, respectively.

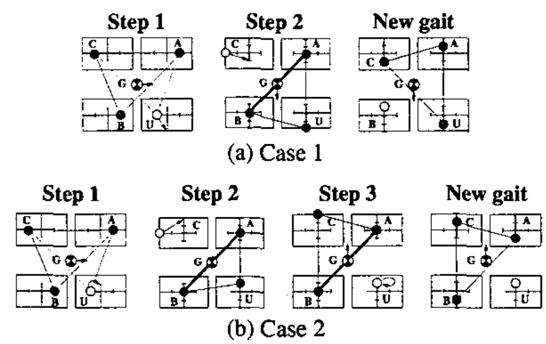
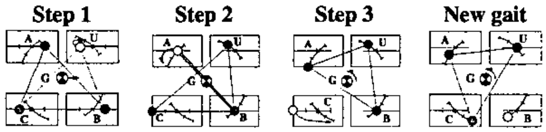


Fig. 7: Gait-transition from Crawl gait to Crawl gait

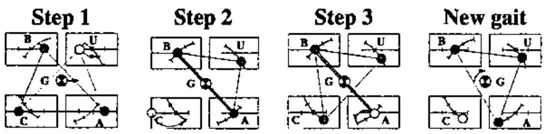
Step 1 is the state right before DTE point. The gait-transition starts at this step while the leg U is firstly lifted up. Step 2 is at DTE point. At this step, the leg A and the leg B are in the basic legs' positions, three legs are thus already at the legs' position of new gait. Since COG is on the line connecting the leg A and the leg B, the leg C is possibly swung at this time. Moving the leg C to its position of new gait finishes the gait-transition. For case 1 and case 2, the gait-transition is performed in this way, but following difference between case 1 and case 2 is existed. In the case 1 as shown in 7 (a), since the polygon of supporting legs is formed in the walking direction, the gait-transition can be performed successively without stopping the torso. In the case 2 as shown in Fig. 7 (b), however, the polygon of supporting legs is not formed in the walking direction. The torso must stop in one step in order for the polygon of supporting legs to be generated in the walking direction.

4.2 Gait-transition from crawl to rotation

Depending on the leg's position at Step 2 of gait-transition, we can divide the gait-transition from crawl to rotation to two cases as shown in Fig. 8. Therein, 'U' describes the swinging leg at step 1, 'C' is the leg opposite to the leg U, 'A' describes the leg swung right after the leg U of new gait, and 'B' is the leg opposite to the leg A, respectively.



(a) Case 1



(b) Case 2

Fig. 8: Gait-transition from Crawl gait to Rotation gait

Step 1 is the the state just before DTE point, and the gait-transition starts at this step while the leg U is firstly lifted up. The following two cases have, for the gait-transition from crawl to rotation, depending on the fact if the leg A can be lifted up or not while shifting step 1 to step 2.

Case 1: As shown in Fig. 8 (a), the leg A is possibly lifted up at step 2 and can be moved to the new leg's position. The leg B is on the basic leg's position at this moment and still at the leg's position of the new gait. At step 2, in order to guarantee the leg C within its reachable range, the torso must stop in one step. After that, the leg C is moved to the position of the new gait at step 3, and the gait-transition is finished.

Case 2: As shown in Fig. 8 (b), since the leg A can not be lifted up at the moment of step 2, the leg C is thus moved to the position of the new gait. At this step, since the COG is on the line connecting the leg A and the leg B, the leg C is possibly swung. The leg A becomes to be possibly lifted up at step 3, thus move the leg A to the position of the new gait and finish the gait-transition. Same as the case 1, the leg B is on the basic leg's position at step 2 and still at the leg's position of the new gait. Since the leg C is moved to the limit point of the new gait to make the leg A possibly moved at step 3, the torso must stop in two steps, step 2 and step 3. At this case, the same result as that of the standing posture transformation gait [6] is obtained.

4.3 Gait-transition from rotation to crawl

The gait-transition from rotation to crawl can be perform from any state of the rotation gait. Its procedure is shown in Fig. 9. Therein, 'U' describes the swinging leg at step 1, 'C' is the leg opposite to the leg U, 'A' describes the front leg in the walking direction of new gait except the leg U and the leg C, and 'B' is the opposite leg of leg A, respectively.

Since the leg U is possibly lifted up at step 1, thus move the leg U to the basic leg's position and start the gait-transition. While the leg U moved to the basic leg's position, the leg C is also at the basic leg's position. At start moment of step 2, the COG is on the line connecting the leg U and the leg C. The leg A and the leg B are thus possibly lifted up. At step 2, the leg A is moved to the position of new gait while stopping the torso motion. At step 3, move the leg B to the position of new gait and finish the gait-transition. The reason swinging first the leg A but not the leg B is for forming a triangle of supporting legs in the walking direction of new gait.

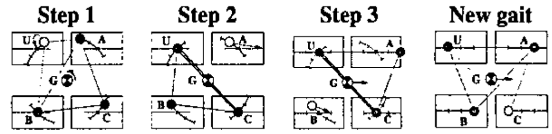


Fig. 9: Gait-transition from Rotation gait to Crawl gait

4.4 Gait-transition from rotation to rotation

Same as the gait-transition from rotation to crawl, the gait transition from rotation to rotation can be perform from any state of the rotation gait. Its procedure is shown in Fig. 10. Therein, 'U' describes the swinging leg at step 1, 'C' is the leg opposite to the leg U, 'A' describes the leg swung right after the leg U of new gait, and 'B' is the leg opposite to the leg A, respectively.

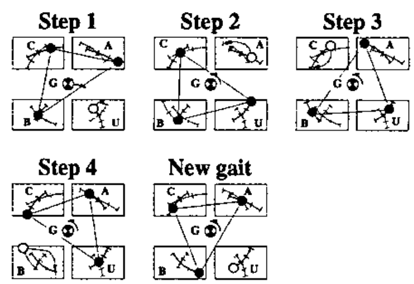


Fig. 10: Gait-transition from Rotation gait to Rotation gait

The gait-transition from rotation to rotation can be easily perform by moving the legs to the position of new gait one by one.

In addition to above gait-transition procedures, we add the rule "the swinging motion of the leg is omitted if the lifting position and the landing position of the leg are same" to shorten the gait-transition time. For comparison, we listed up the time of each gait-transition in Tab.II. From the result, it is known that the case 1 of the gait-transition from crawl to crawl takes shortest time. Even though the gait-transition from rotation to rotation takes longest time, the torso starts the motion around new turning center together with the gait-transition and the walk-

Table II: Comparison of the gait-transition time

$\mapsto$	X		RX		Y		RY		O		RO	
Case	1	2	1	2	1	2	1	2	1	2	1	2
X	1/2T	—	—	3/4T	1/2T	3/4T	1/2T	3/4T	3/4T	3/4T	3/4T	3/4T
RX	—	3/4T	1/2T	—	1/2T	3/4T	1/2T	3/4T	3/4T	3/4T	3/4T	3/4T
Y	1/2T	3/4T	1/2T	3/4T	1/2T	—	—	3/4T	3/4T	3/4T	3/4T	3/4T
RY	1/2T	3/4T	1/2T	3/4T	—	3/4T	1/2T	—	3/4T	3/4T	3/4T	3/4T
O	3/4T		3/4T		3/4T		3/4T		T		T	
RO	3/4T		3/4T		3/4T		3/4T		T		T	

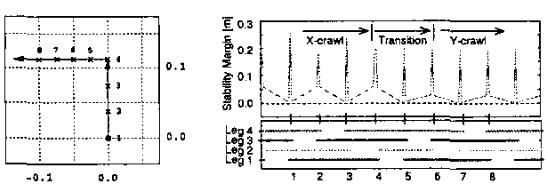
Note: X,RX,Y,RY,O,RO is each gait pattern shown in figure 4.

ing direction is continuously and quickly changed to new one. Therefore, even the stop of the torso in one or two steps is necessary, the gait-transition can be performed continuously. Note that the shorter time is required than that shown in Tab.II for the case where the leg has same lifting/landing positions.

5 Simulations and Experiments

To verify the validity of the proposed omni-directional walking algorithm, the walking experiments by the robot model TITAN-VIII [10] were performed. The robot controller (planning of the gait and the legs' trajectories, the legs' path-tracking control) is built at a PC/AT (Intel MMX Pentium 200MHz, DRAM: 64MB) by RTLinux, and the leg trajectories are tracked by resolved motion rate control. The time of swinging leg is fixed at 1.0[s], and the reachable region is a 0.30[m] × 0.20[m] rectangular region centered at each basic leg's position.

We first show the motion trajectory of the torso, the corresponding stability margin, and the supporting/swinging phase of each leg for each gait-transition pattern in Fig. 11~Fig. 16. In Figs. 11 and 12, Fig. 13 and 14, the COG of torso tracks the same trajectories, but the results for different gait-transitions are shown. It is known that the stability margin is always larger than 0 for each gait transition and the gait-transitions are performed stably.

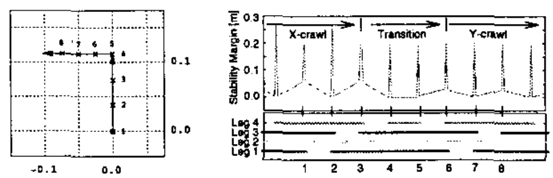


(a) Walking path (b) Stability margin and legs' state

Fig. 11: Walking path of COG, corresponding stability margin and legs' state for the Gait-transition from Crawl gait to Crawl gait (Case 1)

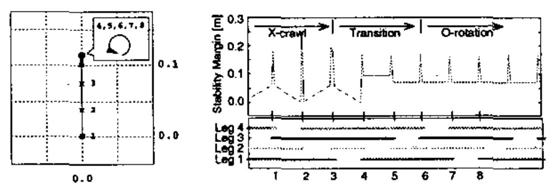
Next, we performed the following experiments

- walking by each standard gait (forward/backward, left/right, left/right turn, left/right rotation, and straight-line walking with an angle)
- gait-transition (crawl→crawl, crawl→rotation, rotation→crawl, and rotation→rotation)
- walking along '8' character



(a) Walking path (b) Stability margin and legs' state

Fig. 12: Walking path of COG, corresponding stability margin and legs' state for the Gait-transition from Crawl gait to Crawl gait (Case 2)

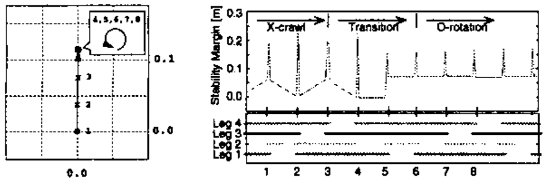


(a) Walking path (b) Stability margin and legs' state

Fig. 13: Walking path of COG, corresponding stability margin and legs' state for the Gait-transition from Crawl gait to Rotation gait (Case 1)

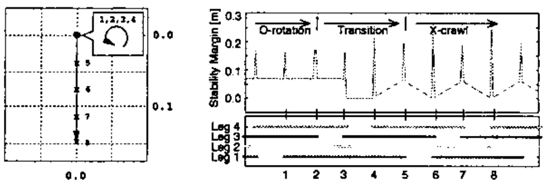
In the walking experiment of the standard gaits, the robot walked stably. Each gait-transition was also checked by the experiment. Fig. 17 shows one example of the gait transition from crawl and crawl. The numbers of the photographs in Fig. 17 is same as that in Fig. 11. The robot is walking forward by $X-$crawl gait in 1, 2, and 3, at 4 the left-forward leg starts swinging toward left and the gait-transition starts. At 5 the right-back leg swings to left and lands at 6 to finish the gait transition. The robot walks left by $Y-$crawl gait in 6,7,8.

From the gait-transition experiments, we know that the



(a) Walking path (b) Stability margin and legs' state

Fig. 14: Walking path of COG, corresponding stability margin and legs' state for the Gait-transition from Crawl gait to Rotation gait (Case 2)



(a) Walking path (b) Stability margin and legs' state

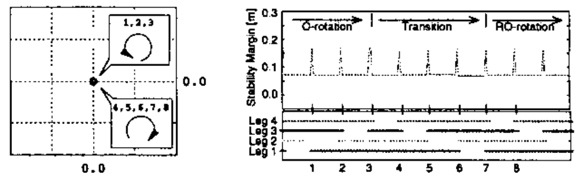
Fig. 15: Walking path of COG, corresponding stability margin and legs' state for the Gait-transition from Rotation gait to Crawl gait

robot totally walked stably as the simulation, at the step 2 of the gait-transition, in case 2 from crawl to crawl and in case 2 from crawl to rotation, however, the torso leaned occasionally. This is because the COG is on the diagonal line at the case, torso leaning is caused by the difference of the COG between the real and simulation models.

For the experiment walking along '8' character, the robot walks only by the X −crawl gait and its walking direction is changed through the rotation gait, thus is always stable. As a result, we can conclude that the omni-directional walking of the quadruped robot can be well generated by the proposed algorithm.

6 Conclusion

In this paper, we proposed a successive gait-transition method for a quadruped robot to realize omni-directional static walking. Experimental test was executed to show that the omni-directional walking of the quadruped robot is possibly generated for most cases. However, since the standard gaits were planned on basis of the basic legs' positions, the stability margin becomes 0 if the robot walks along the direction near the diagonal line of the basic legs' positions. This problem can be solved by selecting X −crawl gait and rotation gait as frequently as possible, but not the crawl gait along the diagonal line. In addition, since the difference of the COG between the real and simulation model existed, the torso leaned occasionally. Giving a 4 legs' supporting period by setting duty factor larger than 0.75 can solve the stated problem. In our future study, we will discuss more stable omni-directional walking of the robot by keeping the stability margin in a positive value.



(a) Walking path (b) Stability margin and legs' state

Fig. 16: Walking path of COG, corresponding stability margin and legs' state for the Gait-transition from Rotation gait to Rotation gait

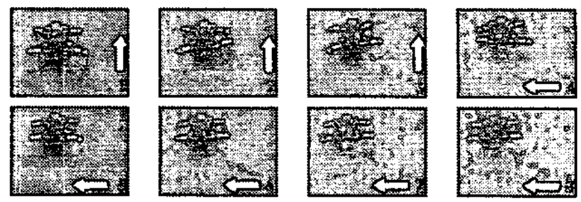


Fig. 17: Photographs to show robot motion for the gait-transition from Crawl gait to Crawl gait (Case 1)

References

[1] S. Hirose: *A study of design and control of a quadruped walking vehicle*, Int. J. of Robotics Research 3-2, (1984) 113—133

[2] R. B. McGhee: *Some finite state aspects of legged locomotion*, Mathematical Biosciences 2, (1968) 67—84

[3] R. B. McGhee and A. A. Frank: *On the stability properties of quadruped creeping gaits*, Mathematical Biosciences 3, (1968) 331—351

[4] S. Hirose, Y. Fukuda and H. Kikuchi: *The gait control system of a quadruped walking vehicle*, Advanced Robotics 1-4, (1986), 289—323

[5] S. Hirose, H. Kikuchi and Y. Umetani: *Standard circular gait of a quadruped walking vehicle*, Advanced Robotics 1-2, (1986), 143—164

[6] S. Hirose and K. Yokoi: *The standing posture transformation gait of a quadruped walking vehicle*, Advanced Robotics 2-4, (1988), 345—359

[7] H. Adachi, N. Koyachi, T. Arai, K. Homma, Y. Shinohara, and K. Nishimura: "Semi-Autonomous Walking Based on Leg Transition at the Border of the Leg Work Space", J. of the Robotics Society of Japan, Vol.16, No.3, pp.329-336, 1998 (in Japanese)

[8] V. Hugel and P. Blazevic: *Towards efficient implantation of quadruped gaits with duty factor of 0.75*, Proc. IEEE Int. Conf. on Robotics and Automation, 2360—2365, 1999

[9] S. Hirose and O. Kunieda: *Generalized standard foot trajectory for a quadruped walking vehicle*, Int. J. of Robotics Research 10-1, (1991), 3—11

[10] K. Arikawa and S. Hirose: *Development of quadruped walking robot TITAN-VIII*, Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, 208—214, 1996