Turning Gait Planning of a Quadruped Walking Robot with an Articulated Spine

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Abstract: We suggest a turning gait planning of a quadruped walking robot with an articulated spine. Robot developer has tried to implement a gait more similar to that of natural animals with high stability margin. Therefore, so many types of walking robot with reasonable gait have been developed. But there is a big difference with a natural animal walking motion. A key point is the fact that natural animals use their waist–joint(articulated spine) to walk. For example, a crocodile which has short legs relative to a long body uses their waist to walk more quickly and to turn more effectively. The other animals such as tiger, dog and so forth, also use their waist. Therefore, this paper proposes discontinuous turning gait planning for a newly modeled quadruped walking robot with an articulated spine which connects the front and rear parts of the body. Turning gait is very important as same as straight gait. All animals need a turning gait to avoid obstacle or to change walking direction. Turning gait has mainly two types of gaits; circular gait and spinning gait. We apply articulated spine to above two gaits, which shows the majority of an articulated spine more effectively. Firstly, we describe a kinematic relation of a waist-joint, the hip, and the center of gravity of body, and then apply a spinning gait. Next, we apply a waist-joint to a circular gait. We compare a gait stability margin with that of a conventional single rigid body walking robot. Finally, we show the validity of a proposed gait with simulation.

Keywords: Quadruped walking robot, Waist-joint, Discontinuous gait, Zigzag gait, Turning gait,

1. INTRODUCTION

Till now, so many types of walking robot have been developed[1-8]. Recently, a nation-wide walking robot boom was spread, which lead to accelerate a robot development. Walking robots are usually classified according to their number of legs, such as bipeds and quadrupeds. Most human interfaced robots are biped walking robots and Quadruped walking robots are applied to factory automation, which can work effectively in a dangerous area due to their high stability. In 1999, sony marketed an entertainment walking robot which called AIBO.

AIBO can walk and playing with a children. this means that walking robots could process many types of work. To accomplish these object. First, Walking robots must be very stable during walking. Walking Stability mainly depend on gait which is a sequence of leg motion coordinated with a sequence of body motion for the purpose of transforting the body of legged system from one place to another. Generally, the gait is classified into periodic and non-periodic gait

Non-periodic gaits usually provide good mobility and high stability in walking. However, studies in this area mainly rely on complex computer simulation and graphic methods. In contrast, periodic gaits feature simpler control rules and a smooth body motion. So, recent research has focused on discontinuous gaits in periodic gait that move the body with all feet securely placed on the ground. Such gaits exhibit very good properties for legged machines. Previous work in this area Intermittent Crawl Gait(Tsukagoshi)[9], E-sway Gait(Cheng)[10], and Zigzag Gait[11].

But, these gait did not include turning gait. Turning gait is as important as a straight gait. Whenever meet an obstacle, robot must change the moving direction turning their body. Developed turning gait are mostly continuous turning gait, and seldom researched about discontinuous turning gait. In 1995, the phase gait (Santos)[8] proposed a discontinuous turning gait which includes a circular and spinning gait. Though, these gait only consider LSM(longitudinal Stability Margin)which is a little difference in SM(stability margin), they showed the majority of discontinuous gait in comparison of a continuous gait.

In this paper, we suggest a discontinuous zigzag turning gait of a quadruped walking robot with a waist joint(articulated spine).

The big difference of a conventional walking robot and Natural legged animals is a body structure. Natural animals have a waist joint which enables body to be flexible in Fig. 1. This is a very useful to turning gait, which lead to more stable walking. For example, crocodiles and lizards have small legs in comparison with their body scale. However, these animal walk more stable and faster with swing their body using a waist-joint. GEO[13] and SQ43[14] were implemented with an articulated spine. Yet, they are still bound to a periodic straight gait, and the gait was not implemented on the systematic analysis but on the basis of bio-control model.

With a view to planning a discontinuous zigzag gait with articulated spine, We added three parameters(θ_u, θ_r, JP) to propose a kinematic modeling of a waist-jointed quadruped walking robot, and then we analyzed the relationship between COG(the center of gravity of body) and waist joint position in Turning gait. Turning gait is classified into spinning and circular gait according to the turning radius. Spinning gait only rotate body at the center of arbitrary point in body and circular gait contain rotate and straight gait. These gait cannot define moving direction. So we give moving directions, and find an optimal gait under given moving direction. Finally, we prove the validity of suggested turning gait with a simulation.

Fig.1. turning motion with a waist-joint.

2. Robot modeling and assumption

In gait planning, we need so many parameters such as hip position, swing-leg sequence, COG position, walking terrain, and so forth. Therefore, to describe the problem more accurately , following assumption were made:

1. The robot walks on a flat terrain and its body moves parallel to the ground.
2. The kinematically reachable range of each leg is rectangular and the same size.
3. The initial and final leg footholds as well as the COG are given.
4. The non-singular crawl [1] gait is considered.
5. The legs are assumed to be massless in comparison to the weight of the vehicle body.
6. The upper and lower body is distributed with a uniform mass.
7. The spine-joint rotates according to the z axis.

The assumption 1 to 6 have shown generality and validity in previous researches. We added one assumption 7 in given assumption. Natural animals have a 3 degree of freedom in waist. But, we only consider 1 degree of freedom because a proposed gait is accomplished in a plat terrain, which mean that the others rarely affect stability in walking than the one.

When we planning a gait, the most important parameter is stability. the stability in walking state is determined by gait stability margin. The gait stability is minimum stability margin at each event. There are so many types of method to measure stability margin. We consider a SM(stability margin) because this is more meaningful than LSM(longitudinal Stability Margin). SM is the shortest length from COG to support polygon. A conventional walking robot can be known to hip position given COG.

But, waist-jointed walking robot has many solutions given same COG. To find an optimal hip position, we added three parameters, the upper waist-joint angle(θ_u), the rear waist-joint angle(θ_r), and the position of waist-joint (*JP*) in Fig.2.

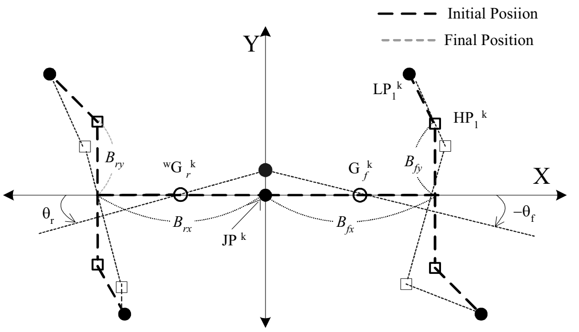


Fig.2. Kinematic modeling of an articulated spine robot.

A hip position(HP^k) at *k'th* event is described in equation (1-1), (1-2)

$$\begin{bmatrix} HP_{xi}^k \\ HP_{yi}^k \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} C(\theta_f{}^k) & -S(\theta_f{}^k) & 0 & JP_x^k \\ S(\theta_f{}^k) & C(\theta_f{}^k) & 0 & JP_y^k \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} B_{fx} \\ (-1)^{i+1} \cdot B_{fy} \\ 0 \\ 1 \end{bmatrix} \tag{1-1}$$

$i = 1, 2.$

$$\begin{bmatrix} HP_{xj}^k \\ HP_{yj}^k \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} C(\theta_r{}^k) & -S(\theta_r{}^k) & 0 & JP_x^k \\ S(\theta_r{}^k) & C(\theta_r{}^k) & 0 & JP_y^k \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -B_{rx} \\ (-1)^{j+1} \cdot B_{ry} \\ 0 \\ 1 \end{bmatrix} \tag{1-2}$$

$j = 3, 4.$

Using equation (1), the COG(G^k) is described in equation (2)

$$\begin{aligned} G_x^k &= l_1 \cdot C(\theta_f^k) - l_2 \cdot C(\theta_r^k) + JP_x^k \\ G_y^k &= l_1 \cdot S(\theta_f^k) - l_2 \cdot S(\theta_r^k) + JP_y^k \end{aligned} \tag{2}$$

In equation (2), there are many solution set(θ_u, θ_r, JP) in same COG position. Next chapter, we describe the characteristics of waist-joint robot, and find an optimal solution of equation (2).

3. TURNING GAIT PLANNING OF A WAIST -JOINTED QUADRUPED WALKING ROBOT

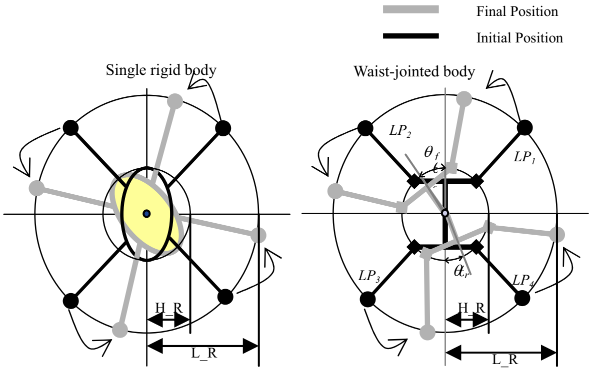
There are main three stages in discontinuous zigzag gait planning. First, select leg sequence. Next, find the maximum stability margin point at each event. Finally generate the optimal COG trajectory include the maximum stability margin point. At arbitrary event, we must know leg position according to swing-leg sequence to find the optimal COG. When leg i is a *j*' th swing order, the position of leg i(LP_i^k) at *k*' th event is described as follows[15]:

$${}^wLP_i^k = \begin{cases} {}^wLP_i^0 & if \quad 0 \le k \le 2i-1 \\ {}^wLP_i^9 & if \quad 0 \le k \le 2j-1 \end{cases} \tag{3}$$

Turning gait has two types of gait, spinning gait and circular gait. From now, we find an optimal gait according to above stage.

3.1 Spinning gait

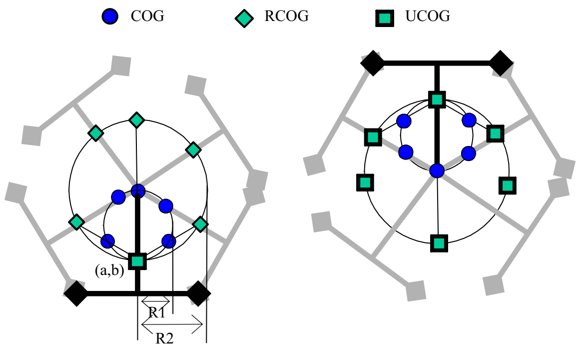
Generally, a spinning gait is a circular gait with no rotation radius. Therefore, this feature was enable to change walking direction in a narrow space.



(a) (b)

Fig. 3. A spinning gait with single rigid body(a) and with a waist-jointed body.

Fig.3-(a) shows a spinning gait with single rigid body and Fig.3-(b) shows a spinning gait with waist-jointed body. In turning, turning radius is H_R(Hip Radius) or L_R(Leg Radius). In case of single rigid body walking robot rotate with B_R, robot turn around on the kinematic center of the body(generally COG point). This means that COG cannot change its position in turning. But, waist-jointed walking robot turn around on the waist-joint position(*JP*). The UCOG(cog of upper body) changes in the shape of circle and the RCOG(cog of rear body) also changes in Fig.4. Therefore, robot could change COG for turning with H_R.



(a) (b)

Fig. 4. Variation of COG corresponding to rotation on waist-joint.

From now, we show above characteristic with simulation. The simulation was processed using Visual C++ in Pentium Ⅵ 2.4C. The reachable range of legs are rectangular with a width of 60cm and a pitch of 100cm and the waist-joint angle allowed to be turn from -15 ° to 15 ° . In fig.5, single rigid body walking robot has a 0 gait stability margin because COG always locate on the line of support polygon in the instant of first-leg lift regardless of swing-leg sequence. But, waist-jointed walking robot turning stable without change JP. First, Fig. 6 shows a gait stability margin according to rotation angle in 24 swing leg sequence. The result shows two characteristics.

1. As a rotation angle increases, Gait Stability Margin decrease.
2. Most stable swing-leg sequence is 2-1-3-4 or 3-4-2-1 when rotation angle is larger than 0, and 1-2-4-3 or 4-3-1-2 is most stable in the case of minus rotation angle.

Table 1 shows the stability margin, the upper waist-joint angle, the rear waist-joint angle and COG at each event when rotation angel is 5 ° . Fig. 7 shows the walking order in discontinuous spinning gait. At first step, move to COG(which maximum stability margin point of 1’th event) in 4 legged support state, and then lift and place leg. The next step is similar to early step.

We also simulated the relation waist-joint angle and gait stability margin in arbitrary rotation angle. Fig. 8 show the variation of gait stability margin in corresponding to the waist-joint angle of body at turning with rotation angle 5 ° . We conclude that as large as the waist-joint angle, the gait stability margin increase to bounded value, but Gait stability margin saturation to bounded value in regardless of waist-joint angle increase

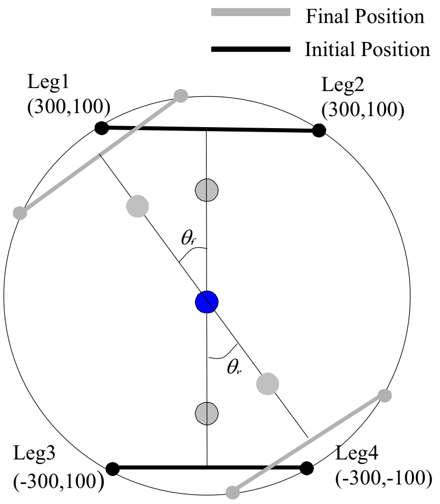


Fig. 5. Spinning gait with H_R.

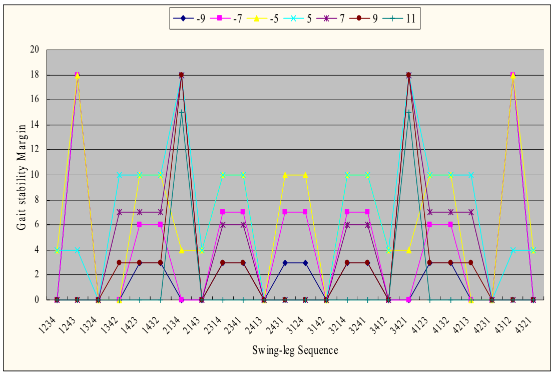


Fig. 6. Gait stability margin corresponding to the swing-leg sequence.

Table 1. Parameters of a waist-jointed robot each event(rotatjion angle =5 °).

Event	θ_u	θ_r	COG position	Gait Stability Margin
0	0	0	(0, 0)	100
1	5.5	-5.5	(0, 19.3)	18.3
2	5.5	-5.5	(0, 19.3)	18.3
3	-0.6	5.6	(0.4, -10.8)	24.0
4	-0.6	5.6	(0.4, -10.8)	24.0
5	-0.6	5.6	(0.4, -10.8)	24.0
6	-0.6	5.6	(0.4, -10.8)	24.0
7	10.5	-0.6	(-1.6, 19.2)	18.3
8	10.5	-0..6	(-1.6, 19.2)	18.3
9	0	0	(0, 0)	100

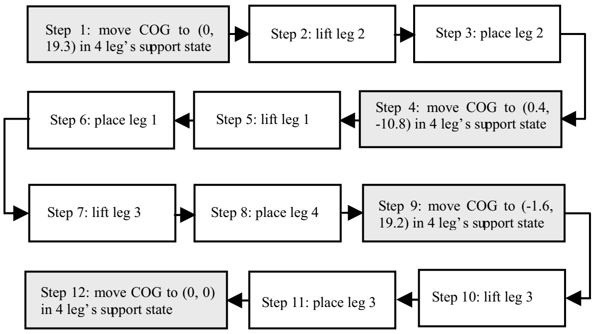


Fig. 7. Walking step in discontinuous spinning gait.

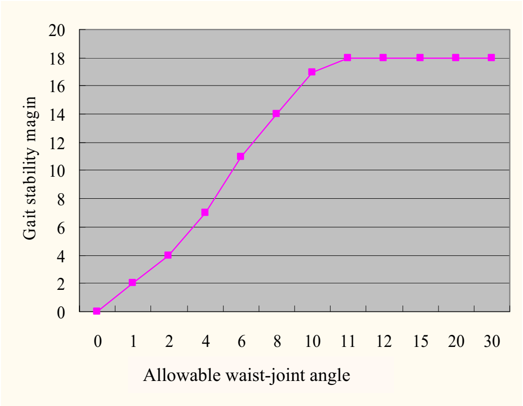


Fig. 8. Gait stability margin corresponding to the allowable waist-joint angle increases.

Till now, we simulated and find the optimal gait with the maximum gait stability margin in turning around with H_R(we call type Ⅰ spinning gait). We find the other type of spinning gait which turning with radius L_R. This type of spinning gait(type Ⅱ) expands a movable body range, so body moves any direction within radius L_H.

Given the same configuration as shown in Fig. 5, we simulated type Ⅱ spinning gait. As shown in Fig 9, Gait stability margin is larger than that of type Ⅰ spinning gait, and turning angle at once is larger too. But, this gait needs more turning space than that o type Ⅰ spinning gait.

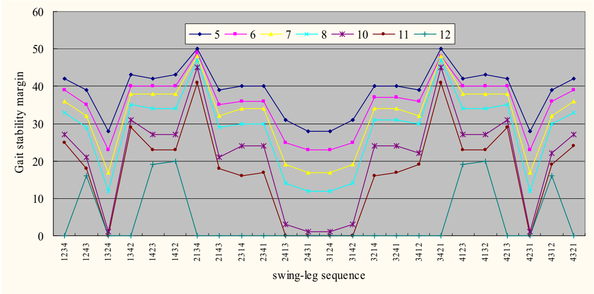


Fig. 9. Gait stability margin in type Ⅱ spinning gait.

4.2 Circular gait

Circular gait include transformation and rotation of body. Rotation angle is θ, and transformation of x direction is dx, and transformation of y direction is dy as shown in Fig. 10.

Therefore, walking direction could be θ or *atan2(dy, dx)* or anything else. Monotonicity[15] to moving direction is very important factor to gait planning. When COG move to inverse direction to final moving direction. COG must come back to reach final position. This fact leads to decrease walking speed or energy efficiency.

To find optimal gait with maximum gait stability margin on the condition that it guarantee monotonicity to moving direction. We find a stability margin graph and select maximum stability margin point at each event.

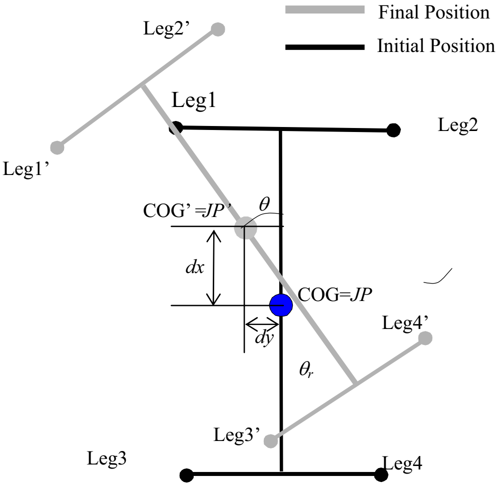


Fig. 10. Circular gait of waist-jointed walking robot.

At first, to find optimal swing-leg sequence, we simulated gait planning 24 swing-leg sequence. The simulation was processed using Visual C++ in Pentium Ⅵ 2.4C. The reachable range of legs are rectangular with a width of 40cm and a pitch of 60cm. To guarantee monotonicity, we selected x-axis as moving direction in convenience.

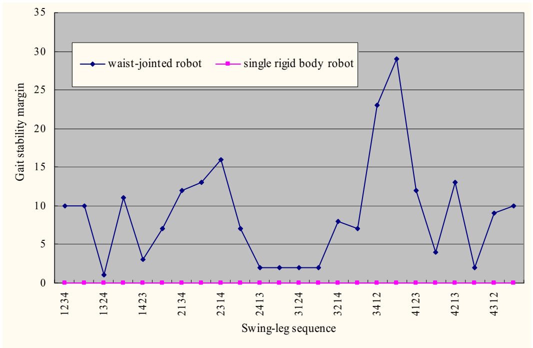


Fig. 11. Gait stability margin corresponding to swing-leg sequence.

Fig. 11 shows that waist-jointed walking robot is more stable than conventional walking robot and optimal swing-leg sequence is 3-4-2-1 in circular gait(rotation angle(5.7˚), transformation(30, 3)). This result is very similar to that of the continuous circular gait. We know that optimal swing-leg sequence in forward gait is 4-2-3-1 or 3-1-4-2. That is to say, as rotation angle increase, optimal swing-leg sequence change and gait stability margin is decrease. Simulation result as shown in Fig. 12 proves the prescribed sentence.

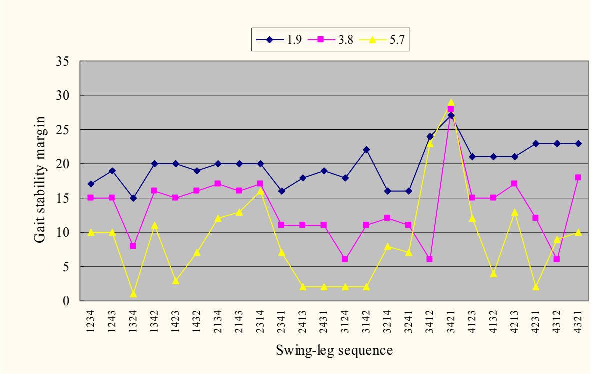


Fig. 12 Gait stability margin corresponding to the rotation angle increases.

As the rotation angle increases from 1.9° to 5.7° , 3-4-2-1 swing-leg sequence has uniformly the maximum gait stability margin and the others decrease or change steeply. Table 2 shows parameters at event in optimal circular gait with rotation angle 1.9° .

Table 2. Parameters of a waist-jointed robot each event (rotation angle =1.9°,translation=(30,3)).

Event	θ_u	θ_r	COG position	Gait Stability Margin
0	0	0	(0, 0)	100
1	10.5	-10	(4,-36)	36
2	13	-12	(4.8,-38)	38
3	7	13	(4.8,19.6)	29
4	-10	15	(18,25.3)	39
5	-10	15	(18,25.3)	37
6	-6	11	(21.4,19.3)	30
7	12.5	-1.5	(21.4,-29)	33
8	14	-4	(25.6,-32)	35
9	0	0	(0, 0)	100

Fig.13 also shows a gait stability margin as waist-joint angle increases. In circular gait, waist-joint increase the gait stability margin.

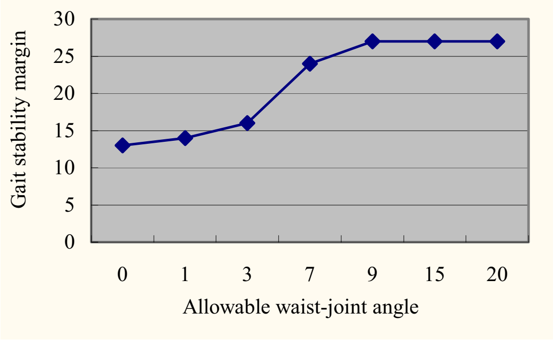


Fig. 13. Gait stability margin corresponding to waist-joint angle increase

5. CONCLUSION

We suggested the waist-jointed walking robot to improve gait stability margin. A waist-jointed walking robot implements so many walking motions in the same COG position and expand reachable range of legs which lead to increase gait stability margin. To prove the majority of waist-jointed walking robot, we applied the waist-jointed walking robot to 2 types of gait(spinning gait, circular gait). These are only a simulation using a numerical computation. In the future, we will prove the relationship between waist-joint and gait parameter more specifically.

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