

# Gait Planning for a Robot Dog

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**Abstract:** This paper proposes a gait control algorithm for a commercial quadruped robot pet developed by Dasarobot Co., Korea. Reliable motion and online characteristics are the key requisites for the motion planning algorithm of a commercialized robot. Centroid body sway ensures walking stability to achieve reliability of the proposed gait. By using ground coordinate representation, it is possible to integrate several online gaits to realize a compact and efficient gait planning algorithm. Experimental results are presented to verify the proposed gait planning and control.

**Keywords:** Quadruped; Robot pet; Gait planning; Initial posture

## I. INTRODUCTION

Small-sized robot pets have gained increasing attention for their high industrial potential in recent years. The robot dog AIBO was developed by Sony, Japan, in 1998, and the similar i-Cybie was launched by Silverlit/Tiger Electronics, USA, in 2000 [1]. Recently, DASAROBOT in Korea produced the commercialized robot dog Genibo in 2008 [2]. In contrast to conventional fixed-body industrial robots, robot dogs have the unique feature of quadruped locomotion as well as intelligence and emotion. Thus, smooth and natural walking has an important impact on robot dog behavior.

Quadruped gait control had been studied for several decades. There are two methods for gait design: systematic planning and incremental learning. Gait design by planning is a means of online trajectory generation based on mathematical analysis. Song addressed the well-known static walking stability of the static wave gait in [3], and several gaits such as the crawl gait [4], crab gait, and spin gait have been studied [5][6]. On the other hand, the learning method connects several basic motion behaviors through repetitive trial-and-error to construct a gait [7]. For basic motion behaviors, the tip trajectory for a swinging leg, body sway motion for stable walking, shoulder height, stance, etc. are set, and a genetic evolution algorithm searches and evaluates the connected parameters of motion behaviors to generate the appropriate walking motion. Incremental learning is basically an offline scheme since it requires extra processes to search and optimize the basic motion behaviors. The optimization search process consumes considerable time. Moreover, it is difficult to change gait parameters such as the gait period, duty factor, stride, etc., since a different gait motion needs another learning process; this makes the learning method difficult to apply to commercialized robots.

The main aim of this study is to implement an online gait control algorithm for the commercialized

quadruped robot pet Genibo. For commercial purposes, gait planning should be compact and portable for an embedded controller and satisfactory performance of gait motion should be guaranteed. To realize real-time capability, the proposed gait control algorithm is based on constructive planning rather than incremental learning. Most hitherto developed quadruped gait control algorithms were for research purposes, not commercial purposes.

## II. KINEMATIC STRUCTURE

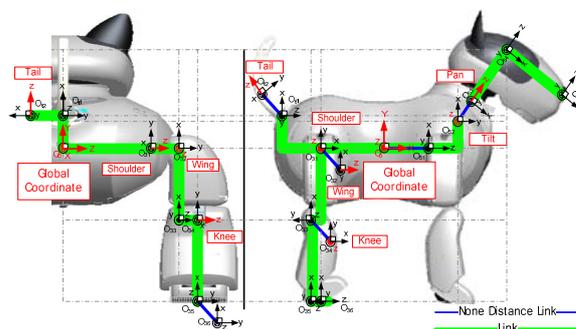


Fig. 1 Kinematic structure

The quadruped pet robot Genibo is 193 mm in height and 1.5 kg in weight. Each leg has 2 DOF (degrees of freedom) at the shoulder joint and 1 DOF at the knee joint. The robot has 2 DOF for the pan and tilt joints on its neck and one tail joint. The total number of joints is 16. The kinematic structure of the robot and the coordinate frame assignment at each joint according to D-H (Denavit-Hartenberg) conventions are shown in Fig. 1. By using an analytic approach, it is possible to derive the inverse kinematics solution (1) of the foot coordinate  $O_{16}$  with respect to the shoulder coordinate  $O_{11}$ :

$$\theta_i = f_i(F_x, F_y, F_z, d, a, \alpha), \quad i = 1, 2, 3 \quad (1)$$

where  $\mathbf{F} = [F_x, F_y, F_z]^T$  denotes the foot position vector in the shoulder coordinates and  $d$ ,  $a$ , and  $\alpha$  are the link parameters for D-H representation.

### III. GAIT PLANNING

#### 1. Gait integration

The leg motion for a gait can be represented by (i) moving coordinates on a robot body, i.e. body coordinates; and (ii) reference coordinates fixed on the ground, i.e. ground coordinates. For body coordinates, the foot positions of all supporting legs move in the opposite direction of the body motion. However, for ground coordinate representation, the foot positions of the supporting legs are fixed onto the ground regardless of body motion. It is easy to integrate various gaits-such as forward, backward, spin, crab, etc.-into ground coordinate representation since the fixed foot positions of the supporting legs are common to all gait types. Easy integration implies memory reduction and compact implementation in small embedded controllers.

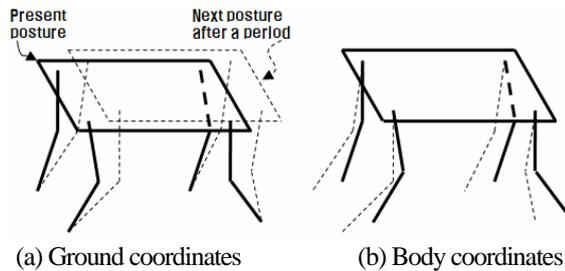


Fig. 2 Representation in the ground and the body coordinates

Since the inverse kinematics solution in Section 2 was described with respect to the shoulder coordinates  $T_s$ , the leg motion represented in the ground coordinates should be transformed into the shoulder coordinates as in (2).

$$ft_w = T_{wb} \cdot T_{bs} \cdot ft_s \equiv ft_s = T_{bs}^{-1} \cdot T_{wb}^{-1} \cdot ft_w \quad (2)$$

where  $ft_w$  and  $ft_s$  are foot positions for the ground and shoulder coordinates. This coordinate transformation is illustrated in Fig. 3, where  $T_w$ ,  $T_b$ , and  $T_s$  denote the ground, body, and shoulder coordinates.  $T_{wb}$ ,  $T_{bs}$ , and  $T_{st}$  imply the ground-to-body, body-to-shoulder, and shoulder-to-foot transformations, respectively.

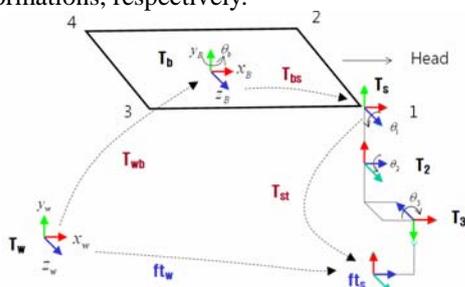


Fig. 3 Coordinate transformation

#### 2. Gait planning

Quadruped walking is a state transition process between three-leg and four-leg support states. A gait diagram of the well-known standard wave gait [3] was modified as shown in Fig. 4 to allow a long enough time

interval for all four-leg support states, so that a landing foot has firm ground contact to maintain a stable stance.

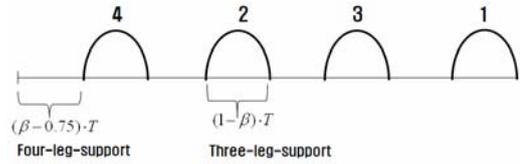


Fig. 4 Gait diagram

In Fig. 4,  $\beta (> 0.75)$  denotes the duty factor, time ratio between the support interval to a walking period. Here, the 4-2-3-1 swing sequence is assumed from several possible leg sequences.

Under this framework, gait planning determines the body trajectory and the next foothold of each leg for each gait period. According to a given walking distance  $\lambda$  and heading angle change  $\phi$ , the body trajectory in ground coordinates can be described as

$$T_w^b(h) = T_w^b(0) \cdot \begin{bmatrix} \cos(h\phi) & 0 & -\sin(h\phi) & h\lambda \cos(\phi) \\ 0 & 1 & 0 & 0 \\ \sin(h\phi) & 0 & \cos(h\phi) & -h\lambda \sin(\phi) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where  $T_w^b(0)$  implies the initial body coordinates and

$h = \frac{t}{T}$ ,  $0 \leq h \leq 1$  denotes the normalized time for a gait period  $T$ . Here, the robot is assumed to keep its body balance during walking.

One possible condition for foothold design is to maintain the robot posture after a gait period. With this condition, it is relatively easy to determine the next footholds as illustrated in Fig. 5, where all swing legs contribute the same amount of body motion for a period.

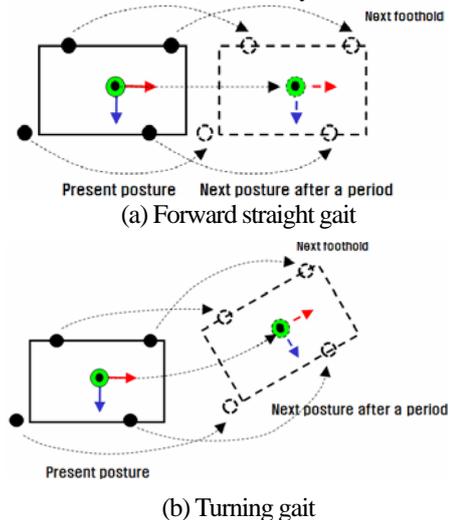


Fig. 5 Body trajectories and next footholds of several gaits

#### 3. Body sway for stable walking

Due to an unbalanced body weight and reaction force from a swing leg, the quadruped robot could fall down while walking. In order to ensure walking stability, the body should sway towards a stable position inside the support polygon. The most stable position is the

centroid of the support polygon [8]. In this study, body sway moves the body center to the centroid of the upcoming support polygon at each four-leg-support state in advance. The body sway motion could conflict with walking commands. For example, when the walking command is the forward gait, body sway moves the body center backwards while a front leg swings. In this case, the front leg is liable to violate the admissible kinematic range. Weighting factors compromise body sway to the admissible kinematic range as shown below:

$$\begin{aligned} v_x &= \mu_x \cdot (c_x - p_x) / \tau \\ v_z &= \mu_z \cdot (c_z - p_z) / \tau \end{aligned} \quad (4)$$

where  $v$  denotes body velocity,  $\mu$  implies the weighting factor,  $\tau$  is the time interval for the four-leg support state, and  $c$  and  $p$  represent the centroid and body center respectively. Here, the weighting factors can be determined empirically.

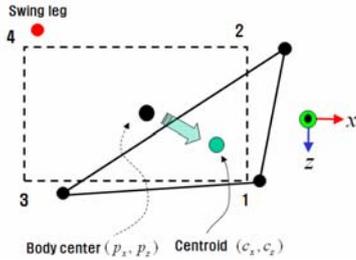


Fig. 6 Centroid body sway

#### 4. Initial posture

In general, a quadruped robot places all feet at the same positions on the ground in the shoulder coordinates at first. Since each leg starts swinging at mutually different time instants, as in the gait diagram shown in Fig. 7, the swing ranges of all legs are different, and the length of a stride is limited by the admissible kinematic range, as illustrated in Fig. 7 (a). It is possible to produce a longer stride by a proper initial posture that places each foot as shown in Fig. 7 (b), which makes the swing ranges of all legs even in the shoulder coordinates. According to the gait diagram in Fig. 4, feet positions of the proper initial posture for the forward straight gait can be described in the shoulder coordinates as follows:

$$\begin{aligned} \text{First swing leg: } ft_s^x &= -\left(\frac{1}{2} - \frac{\beta - 0.75}{\beta}\right) \cdot \lambda \\ \text{Second swing leg: } ft_s^x &= -\left(\frac{1}{2} - \frac{\beta - 0.5}{\beta}\right) \cdot \lambda \\ \text{Third swing leg: } ft_s^x &= \left(\frac{\beta - 0.25}{\beta} - \frac{1}{2}\right) \cdot \lambda \\ \text{Fourth swing leg: } ft_s^x &= \frac{1}{2} \cdot \lambda \end{aligned} \quad (5)$$

where  $\lambda$  is the stride and  $ft_s^x$  denotes  $x$  axis of foot position in the shoulder coordinates.

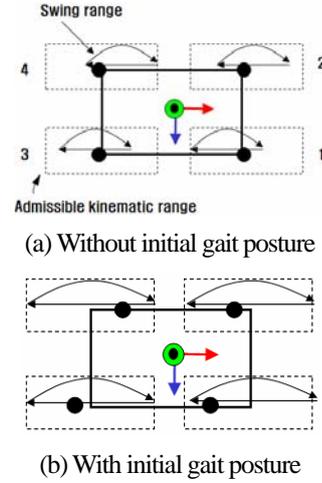
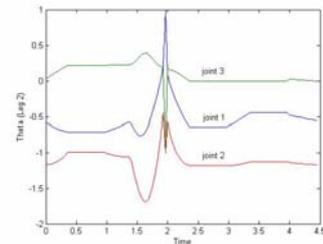


Fig. 7 Work range of tip position

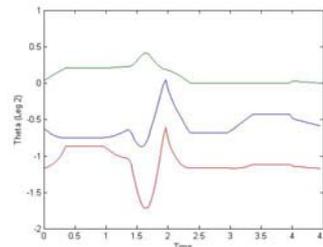
## IV. EXPERIMENTS

### 1. Effect of the initial posture

As described in Section 3.4, it is possible to maximize the stride through a proper initial posture, which makes the swing range of the legs even with respect to the origin of the shoulder coordinates. Fig. 8 shows the effect of the initial posture on maximum stride. Without the initial posture, the inverse kinematic solution of a foot trajectory when  $\lambda = 60 \text{ mm}$  reaches singularity, as shown in Fig. 8 (a). However, as in Fig. 8 (b), the inverse kinematic solution of foot trajectory with the initial posture is smooth enough for the same stride. With the initial posture, the inverse kinematic solution of the foot trajectory reaches singularity when  $\lambda = 75 \text{ mm}$  as shown in Fig. 8; this implies a 25% improvement in stride and consequently walking speed.



(a) Without the initial posture:  $\lambda = 60 \text{ mm}$



(b) With the initial posture:  $\lambda = 60 \text{ mm}$

Fig. 8 Improvement of stride with the proper initial posture

### 3. Walking stabilization by centroid sway

In order to verify the effect by experiments, an

inclinometer on the robot measured the body slope in the  $x$  and  $z$  axes during walking. Fig. 9 (a) is the inclinometer measurement without sway, and Fig. 9 (b) is the measurement with sway. The walking motion with sway is much more stable, as implied in the figure.

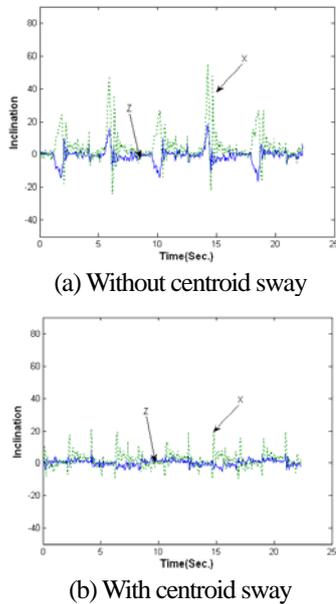


Fig. 9  $x$  and  $z$  inclinometer data

#### 4. Gait motion

The proposed gait planning algorithm was verified through experiments for several gaits. Due to space limitations, some snapshots of the forward and rotation gaits are presented only briefly in this paper.

- Forward gait: Fig. 10 shows the robot posture at the beginning and after one walking period of the forward gait. The robot posture at the beginning is the proper initial posture described in Section 3.4. Here, the walking period and walking distance were 4s and 65 mm respectively.

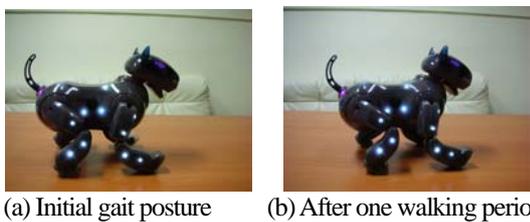


Fig. 10 Forward straight gait

- Rotation gait: Fig. 11 shows the rotation gait with  $15^\circ$  heading angle change command. After 6 steps, the robot changed its heading angle by  $90^\circ$  as shown in Fig. 11 (b).

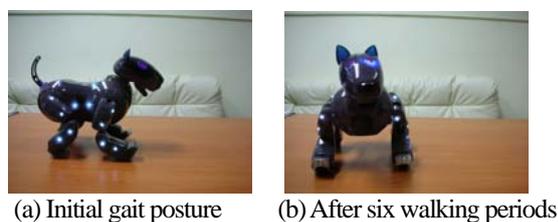


Fig. 11 Rotation gait

## VI. CONCLUSION

Reliability and online characteristics are indispensable for the gait planning algorithm of a commercialized robot. In addition, gait planning should be compact and portable for an embedded controller.

In this study, which is based on systematic planning, a reliable gait control is proposed for the quadruped robot pet Genibo developed by DASA, Korea. The reliability of the proposed algorithm is ensured at two levels: trajectory planning and joint control. At the planning level, centroid sway is able to ensure walking stability for gait control. At the joint control level, sample-based interpolation is proposed to make the joint trajectories obtained at the planning level tractable for the small joint motor-controller of the miniaturized robot. Ground coordinate representation helps to integrate various gaits, and it is possible to maximize a stride by means of a proper initial posture that places all feet at appropriate positions, taking into account the admissible kinematic range in advance. Through experiments on the joint control and gait, it is possible to verify the performance of the proposed gait control algorithm.

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## REFERENCES

- [1] Sony Corporation, Model information for ERS-7, OPEN-R SDK, 2004
- [2] D. Choi et al., Intelligent Robot Pet Genibo, Korea Robotics Society Review 2008, 5(2), 4–11 (in Korean)
- [3] S. Song et al., An Analytical Approach for Gait Study and Its Applications on Wave Gaits, The International Journal of Robotics Research 1987, 6(2), 60–71
- [4] H. Hwang and Y. Youm, Steady Crawl Gait Generation Algorithm for Quadruped Robots, Advanced Robotics 2008, 22(13–14), 1539–1558
- [5] B. Min, Analysis of Quadruped Crab Gait and its Application on Adaptive Gait Control, Ph.D. Thesis, KAIST, 1993
- [6] Y. Lee et al., A Hierarchical Strategy for Planning Crab Gaits of a Quadruped Walking Robot, Robotica 1994, 12(1), 23–31
- [7] G. Golubovic and Huosheng Hu, Parameter Optimization of an Evolutionary Algorithm for On-line Gait Generation of Quadruped Robots, Proceedings of the IEEE International Conference on Industrial Technology Dec. 2003, 1, 221–226
- [8] J. Rebula et al., A Controller for the LittleDog Quadruped Walking on Rough Terrain, Proceedings of 2007 IEEE International Conference on Robotics and Automation, April 2007, 1467–1473