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Gait generation and change of direction for the underactuated three-legged robot[†]

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Abstract

This paper describes a three-legged robot that consists of one actuated leg and two passive legs. The active leg has a knee joint and an ankle joint. The passive legs have no knee joint, although they have a passive ankle joint respectively. The passive leg part and the actuated leg part are linked by a hip part. The robot behavior is passive while the robot is supported by its passive legs and swings the actuated leg part. Generally, in the event that an actuator or a transmitting mechanism fails, robots cannot apply torques to the joint. We therefore took up a walking robot with passive knee joints not only for the energy-efficient walking but also with a view to making ambulation failsafe in case of mechanical failures.

Keywords: Failsafe; Passive joint; Underactuated system; Walking robot

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1. Introduction

In the future, life-supporting robots, designed for the declining birthrate and the graying of society, are expected to advance into our living space. Among various locomotive configurations of robots ones with wheels and crawlers, recent research has increasingly focused on robots with legs, such as the HRP, as such robots are superior to those having other configurations for activities in human living spaces [1, 2]. Ensuring safe robot activities is important for walking robots to work nearby human beings.

Legged locomotion can be categorized as active walking and passive walking, depending on whether or not the joints are equipped with actuators. Compared with active walking with actuator-equipped joints, passive walking, in which gaits are automatically generated in accordance with the physical characteristics of a robot, can exhibit smooth and natural motion. In addition, the absence of actuators contributes to lowering the robot's energy consumption and to making them smaller and lighter.

As the focus of the current research on active biped robots has shifted to the subject of systematically coordinated motions to execute tasks, the topic of passive walking robots have recently become popular in studies on legged locomotion. Studies on passive walking date back to the time when McGeer [3] published that it was feasible for an unactuated robot to descend a gentle slope. Goswami et al. [4] analyzed in detail the passive walking of a compass-like biped robot.

What we propose herein is a robot with one jointed leg and two legs which resembles crutches and has no ankles or knee joints (Fig. 1). This is a walking robot possessing the advantages of a biped walking robot with active legs. It can make complex motions such as directional changes and has high efficiency in passive walking. The robot, when supported at three end points of each of its legs, is considered to have a more stable posture at rest than biped walking robots, which need stabilization control even in an upright position.

Research on passive walking, including those with knee joints, often focus on the characteristics of its dynamic system premise of continuous walking. The more the passive robots walk over a long period of time, the more benefits of energy saving they bring. However, in the case when a passive walk mechanism for locomotion of an actual utility robot is used, initiation and break of walking is required.

Additionally, changing of direction is needed. This leads to the conclusion that bare minimum active joints are necessary.

Passive walking resembles a failure in a robot's joints, in that the joints receive zero torque. In the event that an actuator or a transmitting mechanism fails, a robot cannot "apply force to the joints." We therefore take up a walking robot with passive ankle joints not only because energy-efficient walking allows a legged robot powered by a storage battery to be active for prolonged periods of time but also with a view to making ambulation failsafe in case of mechanical failure.

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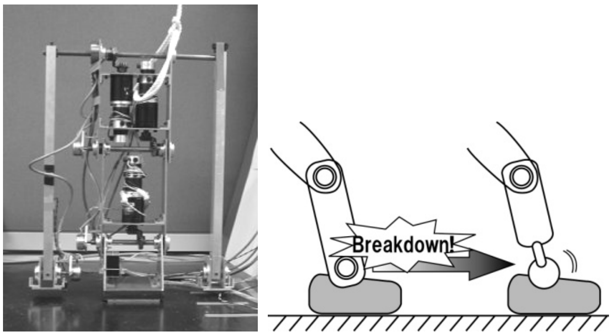

Fig. 1. Three-legged walking robot.

Sometimes joints lock up because of trouble in its reduction gears, but we focus on the case wherein joints rotate freely in this paper.

We have studied this three-legged robot to plan gaits for straight walking [5]. Several gait candidates were applied to a rigid four-linked pendulum as a model of the mechanism. The target trajectory was extracted using dynamics simulation and evaluation function. Moreover, the same method was applied to two other models: the robot whose knee joint of the center leg is passive and that whose hip joint has a magnetic clutch to switch the hip joint from active to passive [6, 7]. The issue of the robot being unable to change direction still remains. In this paper, the direct kinematics analysis explains that additional joints, which give a different angle to the side legs, allow the three-legged robot to change direction. The dynamic simulation of the three-dimensional model of the walking robot is also performed.

2. Modeling of the walking robot

A schematic diagram of the robot that is the subject of this paper is shown in Figs. 2 and 3. There are no knee joints in the side legs, and the ankle joints are passive. The center leg consists of an active knee joint and an active ankle joint. The hip link connects the center leg and side legs. It is considered that the hip link has active joints, and relative angles among the three legs can be set arbitrarily. The robot behavior is passive while the robot is supported by its side legs and swings its center leg part. To change the walking direction, the right and left hip joint angles are treated differently. Differently angled side legs allow the hip link to turn and the center leg to swing obliquely.

Although there are also several possible solution approaches to change the walking direction, we select the above-mentioned method from the viewpoint of performing locomotion by using the supporting leg much like a person uses crutches.

The standing posture shown in Fig. 4 is a reference posture, and the position of the origin is set at the center of the central leg sole. Therefore, the position coordinate of the end of the right leg link ${}^0\boldsymbol{P}_\mathrm{R}$ and left leg link ${}^0\boldsymbol{P}_\mathrm{L}$ is expressed by the following equations [8]:

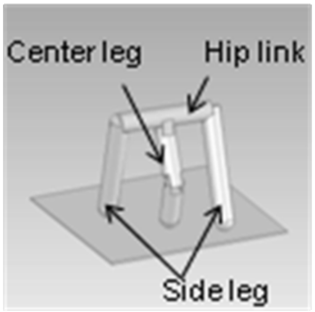

Fig. 2. The center leg and two side legs resembling crutches.

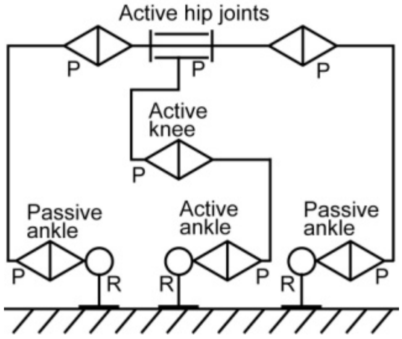

Fig. 3. The link model of the robot.

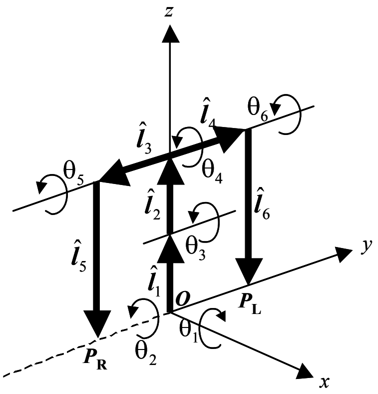

Fig. 4. Joint angle definitions.

$$ {}^0\boldsymbol{P}_R = \boldsymbol{E}^{i\theta_1}\boldsymbol{E}^{j\theta_2}\left(\hat{\boldsymbol{l}}_1 + \boldsymbol{E}^{j\theta_3}\left(\hat{\boldsymbol{l}}_2 + \boldsymbol{E}^{j\theta_4}\left(\hat{\boldsymbol{l}}_3 + \boldsymbol{E}^{j\theta_5}\left(\hat{\boldsymbol{l}}_5\right)\right)\right)\right) \tag{1} $$

$$ {}^0\boldsymbol{P}_L = \boldsymbol{E}^{i\theta_1}\boldsymbol{E}^{j\theta_2}\left(\hat{\boldsymbol{l}}_1 + \boldsymbol{E}^{j\theta_3}\left(\hat{\boldsymbol{l}}_2 + \boldsymbol{E}^{j\theta_4}\left(\hat{\boldsymbol{l}}_4 + \boldsymbol{E}^{j\theta_6}\left(\hat{\boldsymbol{l}}_6\right)\right)\right)\right) \tag{2} $$

where $\boldsymbol{E}^{a\theta_n}$ is the rotation transform matrix, $(i : x\ axis,\ j : y\ axis)$ is the rotation axis, and $\theta_n(n : 1 \sim 5)$ is the rotation angle

$$ \boldsymbol{E}^{i\theta} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \tag{3} $$

$$ \boldsymbol{E}^{j\theta} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \tag{4} $$

and $\hat{\boldsymbol{l}}_m \ (m:1\sim 6)$ are the vectors of each link as follows:

$$\begin{aligned} \hat{\boldsymbol{l}}_1 &= \begin{bmatrix} 0 & 0 & l_1 \end{bmatrix}^T, & \hat{\boldsymbol{l}}_2 &= \begin{bmatrix} 0 & 0 & l_2 \end{bmatrix}^T \\ \hat{\boldsymbol{l}}_3 &= \begin{bmatrix} 0 & -l_3 & 0 \end{bmatrix}^T, & \hat{\boldsymbol{l}}_4 &= \begin{bmatrix} 0 & l_4 & 0 \end{bmatrix}^T \\ \hat{\boldsymbol{l}}_5 &= \begin{bmatrix} 0 & 0 & -l_5 \end{bmatrix}^T, & \hat{\boldsymbol{l}}_6 &= \begin{bmatrix} 0 & 0 & -l_6 \end{bmatrix}^T \end{aligned} \tag{5}$$

3. Method used to change the walking direction

As the joints of the walking robot used in this study are all rotational joints, behaviors of the robot are determined by changes in the angle of the joints. While the robot is supported by the center leg, its posture can be changed comparatively freely through the active link system. In the phase where the robot is supported by its side legs whose ends are passive, the robot's posture cannot be determined arbitrarily. We therefore divide walk cycle into the following three stages for each support phase, generate the desired trajectories for the respective stages, and complete a desired walking trajectory for one walk cycle by connecting the respective desired trajectories.

The walking sequence to walk straight is shown in Fig. 5.

(1) Side legs are positioned forward from the upright position (Forward Stooped Stepping: Fig. 5(1)).
(2) The center leg is swung forward using passive legs for support (Leg Swinging: Fig. 5(2)).
(3) Return to the initial posture using the center leg for support (Rising Upright: Fig. 5(3)).

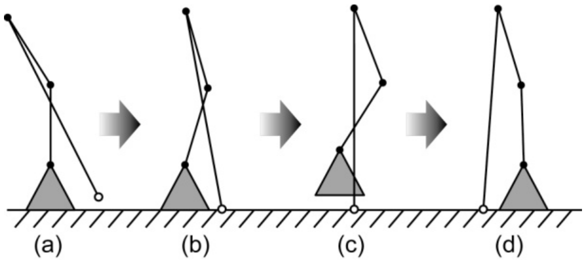

Fig. 5. Walking sequence of the robot.

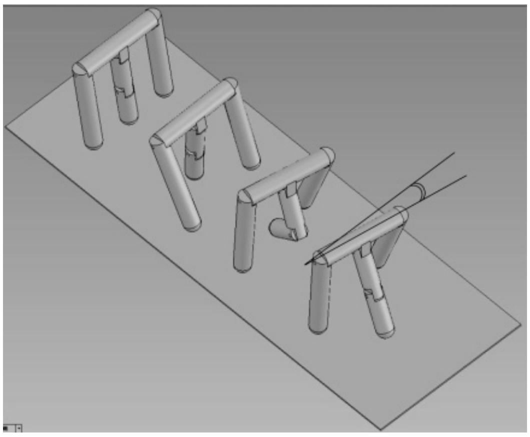

Fig. 6. Change in the walking direction.

To make the three-legged robot turn while walking, we consider giving the side legs a different angle $(\theta_5 \text{ and } \theta_6)$. The hip link $\hat{\boldsymbol{l}}_3$ and $\hat{\boldsymbol{l}}_4$ is parallel with y-axis when the robot walks straight. In contrast, in the case when the side legs have different angles while walking, the hip link is angled to the y-axis, allowing the robot to change its walking direction. The center leg has a hip joint and a knee joint to control the distance between the hip joint and the end of the center leg link. Flexion of the knee joint during the center leg swings prevents the collision between the sole and the ground. That motion is also used so the walking robot can assume the posture wherein all the front end portions of the links touch the ground even if the side legs have different angles to each other. For these reasons, the unfavorable collision between the center leg and the ground is not considered in this paper.

The effectiveness of the angle difference between the side legs on the directional change of the hip link is then analyzed. ${}^{R}\boldsymbol{P}_L$ is the vector from $\boldsymbol{P}_R$ to $\boldsymbol{P}_L$ as follows:

$$\begin{aligned} {}^{R}\boldsymbol{P}_L &= {}^{0}\boldsymbol{P}_L - {}^{0}\boldsymbol{P}_R \\ &= \begin{bmatrix} l_5 S_{2345} - l_6 S_{2346} \\ -l_5 S_1 C_{2345} + l_3 C_1 + l_4 C_1 + l_6 S_1 C_{2346} \\ l_5 C_1 C_{2345} + l_3 S_1 + l_4 S_1 - l_6 C_1 C_{2346} \end{bmatrix} \end{aligned} \tag{6}$$

where $\sin(\theta_1+\theta_2)=S_{12}$ and $\cos(\theta_1+\theta_2)=C_{12}$. In Eq. (6), the condition for both side legs standing on the ground is as follows:

$$\begin{aligned} {}^{R}\boldsymbol{P}_{L\_z} &= l_5 C_1 C_{2345} + l_3 S_1 + l_4 S_1 - l_6 C_1 C_{2346} \\ &= (l_3 + l_4) S_1 - C_1 (l_6 C_{2346} - l_5 C_{2345}) \\ &= 0 \end{aligned} \tag{7}$$

Assuming that the walking robot has side legs with the same length, $l_5 = l_6$, $-\theta_5 = \theta_6$ is considered the solution for the posture to change walking direction. The locus of both ends of the hip link is shown in Fig. 7.

The distance D between both ends of the hip joint is given by using several assumptions:

$$D = \sqrt{2l_c^{\,2} - 2l_c^{\,2}\cos(\theta_5 - \theta_6) + l_t^{\,2}} \tag{8}$$

$$\begin{cases} l_5 = l_6 = l_c \\ l_3 + l_4 = l_t \\ \theta_1 = 0 \\ \theta_2 + \theta_3 + \theta_4 = 0 \end{cases} \tag{9}$$

The distance D becomes long as the relative angle of the side legs is great. The side legs have to flare to change walking direction. Therefore, a mechanism is necessary so the link ends can slide to maintain its contact with the ground. The rigidity of the leg links can be changed or a special elastic joint can be used to absorb the displacements. In this paper,

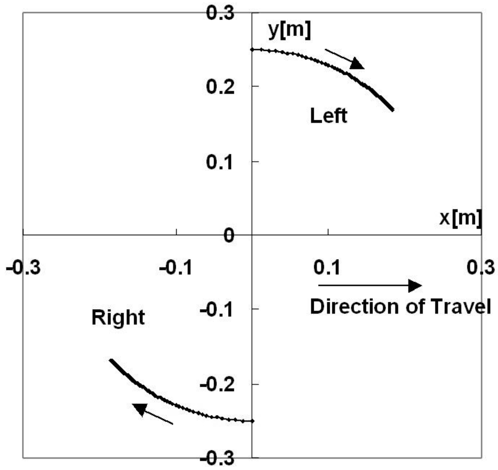

Fig. 7. Locus of ends of both hip links.

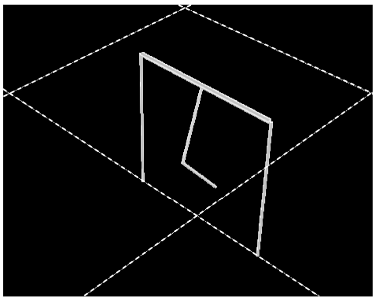

Fig. 8. Swing posture of the center leg for straight walking.

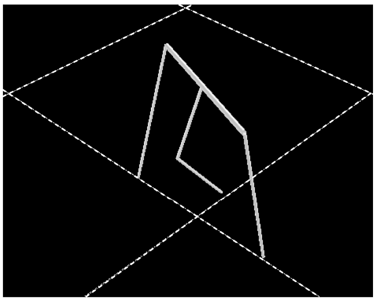

Fig. 9. Twisted posture for change in direction.

we consider the relative angle to be less than 0.5 rad and assume that the link ends of the side legs and the ground are constrained by the frictional force.

The dynamics simulation was performed under the condition of $\theta_5 = 0.4\,\text{rad}, \theta_6 = 0.2\,\text{rad}$. The walking robot model turned 0.055 rad to the right, and the length of the stride was 0.304 m. By way of comparison, the length of the stride was 0.35 m in the case where the angle of both side legs was set to 0.2 rad. The case where the angle was 0.4 rad resulted in the length of the stride to be 0.27 m.

4. Conclusions

In order to change the walking direction of the three-legged robot with passive joints at the end of each link, side legs are placed forward at different angles. The direct kinematics analysis of a link model as a walking robot indicates that the walking direction can be changed by making an angle difference between the side legs. The dynamics simulation of the walking robot evaluates the motion of the directional change in walking. The distance from one of the side legs to the other increases at the same time. Future research should consider the effects on the turning motion from the swing motion of the center leg and the utilization of the deflection of the side leg.

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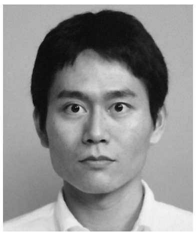

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