An energy-efficient walking for a low-cost humanoid robot PINO

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1 Introduction

The RoboCup Humanoid League [1], which is scheduled to start in 2002, is one of the most attractive research targets. We believe that the success of the humanoid league is critical for the future of RoboCup, and will have major implications in robotics research and industry. Building humanoids that compete at RoboCup requires sophistication in various aspects including mechanical design, control, and high-level cognition.

PINO is a low-cost humanoid platform composed of low-torque servo-motors and low-precision mechanical structures [2][3]. It has been developed as a humanoid platform that can be widely used for many RoboCup researchers in the world. Figure 1 shows the whole view and the mechanical architecture of PINO.

(a) Whole view (b) Mechanism

Fig. 1. Picture and mechanism of PINO

It is intentionally designed to have low-torque motors and low-precision mechanical structures, because such motors and mechanical structures significantly reduce production cost. While most of the existing humanoids use the high-performance motor systems to attain stable walking, such motor systems tend to be very expensive. Motors that are affordable for many researchers have only limited torque and accuracy. Development of a method that allows biped walking using low-cost components would have a major impact on the research community as well as industry.

On the other hand, the most energy efficient walking is passive dynamic walking without any torque control [4]. In such methods, walking motions are determined by the relationship between a gravity potential effect and the parameters of the robot mechanical structure. Therefore, no control of walking behaviors such as speed or dynamic change in step size is possible as its name stands for.

We aim at establishing the design principle for humanoid walking between two extremes, full control and no control, that is, control with less energy consumption. In the conventional bi-ped walking algorithms, knees are always bended so that the walking can be stable, therefore, motors are highly loaded continuously. This is very different from normal human walking postures. It should be noted that most of the existing control methods for humanoid walking are designed independent of the structural properties of the robot hardware. In general, these control methods require extremely large torque to realize the desired walking patterns. Although knees are bended when walking on uneven terrain, humans stretch their knees straight when walking on flat floor. This posture can be modeled easily by an inverted pendulum, which is known to be energy-efficient. In addition, movement of torso affects overall moment of inertia. Then, our inspiration is to mimic human walking posture to minimize energy consumption through the combination of inverted pendulum controlled by a swing leg and feedback control of torso movement.

In this article, we introduce the first step towards the final goal, the establishment of the design principle of the humanoid walking. In order to resolve this trade off between less energy-consumption and more control of speed or dynamic change in step size, we started from the hypothesis that the humanoid can change the walking speed without changing the step length if the moment of inertia of the swing leg at the hip joint has been adequately changed. That is, if the moment of inertia is reduced, the period of the swing leg becomes short. Then, we suppose that if we control the moment of inertia, the walking speed can be changed with lower torque.

We have designed a control method using the moment of inertia of the swing leg at the hip joint. The method was applied to the PINO model with torso in computational simulations, and confirmed that the method enabled stable walking with various speed and dynamic change in step size under limited torque.

2 Kinematic Model

A cycle of bi-ped walking can be sub-divided into three phases; (1) two-legs supporting phase, (2) one-leg supporting phase, and (3) landing phase. Both

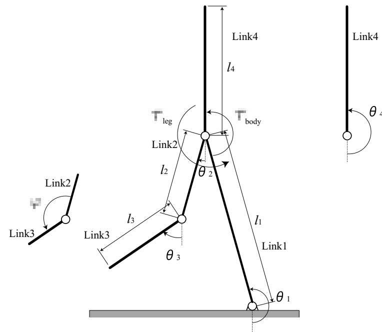

Fig. 2. Planar four-link model of the robot

Table 1. Link parameters

m_1	[kg]	0.718	l_1	[m]	0.2785
m_2	[kg]	0.274	l_2	[m]	0.1060
m_3	[kg]	0.444	l_3	[m]	0.1725
m_4	[kg]	3.100	l_4	[m]	0.4515

legs are grounded in the first two phases whereas only one leg is grounded in the last phase.

The basic idea behind the low-energy walking method is to consider legs of humanoid, during the one-leg supporting phase, as a combination of an inverted pendulum model and a 2 DOF normal pendulum one, assuming the structure of PINO to be a planar walker. In this case, the inverted pendulum and the 2 DOF one represent the supporting leg and the swing one, respectively. The inverted pendulum model is the most energy-efficient model as the supporting leg.

Figure 2 shows the four-link model with torso. This model consists of link i $(i = 1, , 4)$, and link1 has a joint with the ground. Joint angles θ_i $(i = 1, , 4)$ denote the absolute angle of link i. We assume that every joint has a viscosity coefficient of 0.01 [N·m·s/rad], and that the knee joint also has a knee stopper. Each link has uniformly distributed mass m_i $(i = 1, , 4)$, respectively. Table 1 shows the link parameters of the four-link model which are estimated from real PINO.

Given the control method to verify the hypothesis of hip joint control method in **1** (see also [5]), optimal parameter sets are found in the following three cases in the parameter space:

Case 1: Torso movement is controlled by feedback from body and leg movement.
Case 2: Torso is fixed vertically.
Case 3: The three-link model without torso to compare with the four-link model with torso.

3 Technical Results

Figures 3, 4 and 5 show the foot trajectory for each case. Table 2 shows the

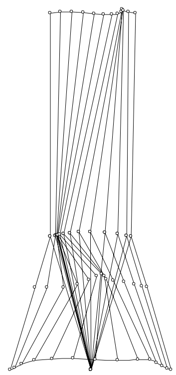

Fig. 3. Result of the foot gait of case 1

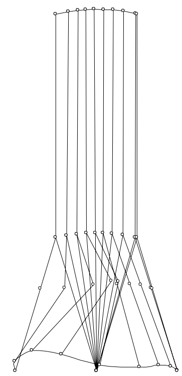

Fig. 4. Result of the foot gait of case 2

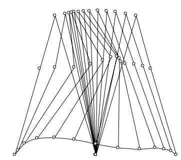

Fig. 5. Result of the foot gait of case 3

Table 2. Results of three cases

Value		Case 1	Case 2	Case 3
$\dot{\theta}_1$	[rad/sec]	1.736	0.962	3.374
$\dot{\theta}_2$	[rad/sec]	1.692	0.223	1.384
$\dot{\theta}_3$	[rad/sec]	0.000	0.000	0.000
$\dot{\theta}_4$	[rad/sec]	1.309	—	—
t_2	[sec]	0.319	0.406	0.296
Energy consumption	[J]	0.064	0.109	0.025

initial angular velocities of $\dot{\theta}_i$ $(i = 1, , 4)$, time to touch down t_2 and energy consumption. From these results, it was confirmed that the proposed control method enables the low-cost humanoid PINO to perform reasonably stable biped walking. Further, in the four-link model with torso, it was verified that appropriate swings of the torso enable the robot to walk with lower energy consumption as low as 0.064 [J] (for the detail see [5]).

4 Conclusion

In this study, we observed the interesting relationship between the control parameters and the walking behaviors, but understanding the details of the mechanism realizing such behaviors is our future work. This study demonstrate that energy-efficiency of humanoid walking can be altered when whole body motion is appropriately used. This is an important insight toward practical humanoid for low-cost production, as well as high-end humanoid seeking for ultra high performance using whole body movement.

5 OpenPINO

All technical information on PINO is now available under GNU General Public License and GNU Free Document License, as OpenPINO (exterior design and trademarks are not subjects of GNU license). It is intended to be entry-level research platform for possible collective efforts to evolve humanoid for further research. Authors expect linux-like community is build surrounding OpenPINO.

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