Self-Excited Walking of a Biped Mechanism

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Abstract

This paper present a self-excited walking of a four-link biped mechanism which possesses an actuated hip joint and passive knee joints. First we manifested that this self-excitation control enables 3-DOF planar biped model to walk on a level ground, by numerical simulation. Next we showed experimental study of a manufactured planar biped walking robot. We demonstrated that stable walking can be realized on a slightly inclined plane by the self-excitation control.

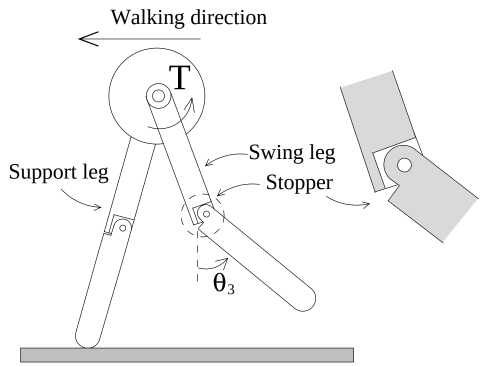

Figure 1: 3-DOF walking mechanism

1. Introduction

Biped locomotion is regarded as a combined motion of an inverted pendulum and a 2-DOF pendulum. Here the inverted pendulum represents motion of a support leg and body, while the 2-DOF pendulum represents motion of swing leg. Only when those movements are synchronized, biped locomotion can be stabilized.

Over the past few decades, a large number of studies have been made on bipedal walking. Among many researchers, McGeer [1] [2] studied passive dynamic walking mechanisms on a downhill slope without actuating and controlling. In connection with his research, a close study on stability and complexity of simple walking model was done by Garcia [3]. Goswami [4] [5] investigated the passive gait of a compass-like biped robot especially about symmetry and chaos. Spong [6] [7] studied on the switching control applied to passive gait. One of the purpose of their researches is to enlarge the basin of the limit cycles. The remarkable feature of these passive gait is its anthropomorphic motion and energy efficiency because those passive mechanisms utilize its inherent natural motion.

Based on the similar idea of utilizing natural mode, one of the authors has already proposed self-excitation control [8] which can efficiently and robustly drive natural mode of the mechanical system. Ono and Okada [9] [10] applied the Van der Pole type self-excitation to drive an insect wing model and the asymmetric stiffness-matrix type to drive a rolling biped mechanism. Further, Ono and Imadu [11] showed a possibility that a human like planar 3-DOF biped mechanism can be driven by the latter method. In this paper, we show this self-excitation control strategy enables 3-DOF planar biped mechanism to walk. Then we verify the numerical simulation experimentally by using a manufactured biped robot.

2. Control Method of Biped Walking

2.1. Conditions for stable walking

Figure 1 shows a planar biped walking mechanism which has no ankle and trunk. This mechanism consists of two legs which are connected in series at hip joint by an actuator. Each leg consists of a thigh and a shank connected at a passive knee joint which has a rotary damper and a knee stopper. By this knee stopper, an angle of knee rotation is restricted like a human knee so that it cannot rotate forward. Five conditions are required to realize a stable biped walking on a sagittal plane by this simple mechanism.

1. The period of the mechanism as a inverted pendulum should synchronize with half period of swing leg as a 2-DOF pendulum.

2. Kinematic energy loss which is consumed during swing leg's foot collision and each knee stopper collision should be actively supplied by the actuator.

3. Synchronized motion of inverted pendulum and 2-DOF swing leg pendulum, and energy supply and consumption have a stable characteristics against deviations from the synchronized motion.

4. At the support leg's knee joint, knee stopper have to be locked (support leg condition).

5. The swing leg should bend to keep the clearance (swing leg condition).

In this study, we show that these requirements can be satisfied by self-excitation control. By the linearized theory and simulation of nonlinear system, we already confirmed that 2-DOF swing link system is efficiently self-excited by asymmetric stiffness-matrix-type self-excitation control. Based on the previous study, we defined feedback torque at the hip joint as such,

$$T = -k\theta_3 \qquad (1)$$

where k is a feedback gain and θ_3 is absolute angle of the swing leg shank. Because it is difficult to analytically show that this control method can generate a walking motion which satisfies the above mentioned requirements, we show this self-excitation control can fulfill the required conditions and make the mechanism walk stably on level plane by numerical simulation.

2.2. Algorithm of self-excitation control

In order to derive basic equation of motion to simulate the walking gait of the 4-link biped mechanism, we divide one step walking motion into three phases from view point of difference of freedom and governing equation. Figure 2 shows three different phases of one step walking.

1. From start of swinging leg to collision of knee stopper (First phase).

2. From collision of knee stopper to touchdown of swing leg (Second phase).

3. Double support phase and exchange between support leg and swing leg (Third phase).

In the following analysis, we assumed that during the first and second phases, the knee stopper of support leg can be locked by negative internal force. The validity of this assumption is discussed in the next chapter. From this assumption we can regard the biped mechanism as 3-DOF which consists of 1-DOF support leg and 2-DOF swing leg.

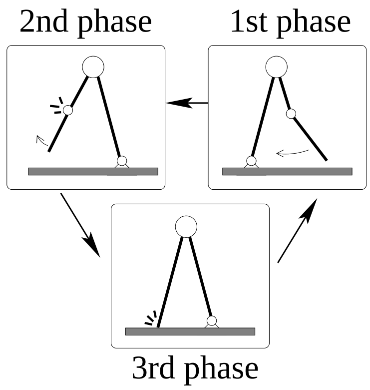

Figure 2: Different phases of biped walking

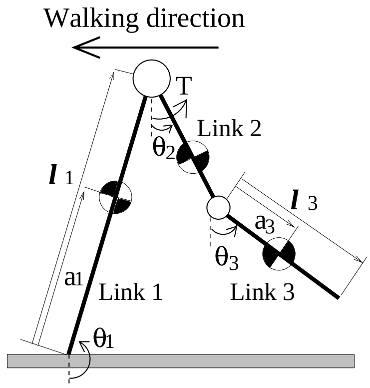

Figure 3: Analytical model of 3-DOF walking mechanism

In the first phase, the feedback torque $T = -k\theta_3$ is applied at hip joint. By this feedback torque, swing leg is naturally bent at knee joint. Then it can swing forward without hitting the ground.

In the second phase, the feedback torque is not supplied ($T = 0$). Therefore it moves freely until it collides with a ground. We considered these foot collision and knee stopper collision as perfect inelastic one. Hence we calculate angular velocity of each links just after the collisions by the law of conservation of angular momentum.

2.3. Analysis of the model

First Phase: Figure 3 shows the analytical model of the biped mechanism. Equation of motion of

Table 1: Link parameter values

m_1	$[kg]$	4.0	$m_{2,3}$	2.0	2.0
l_1	$[m]$	0.8	$l_{2,3}$	0.4	0.4
I_1	$[kgm^2]$	0.21	$I_{2,3}$	0.027	0.027
a_1	$[m]$	0.2	$a_{2.3}$	0.2	0.2

this system is written as follows:

$$[M]\begin{pmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\\ \ddot{\theta}_3\end{pmatrix}+[C]\begin{pmatrix}\dot{\theta}_1^2\\ \dot{\theta}_2^2\\ \dot{\theta}_3^2\end{pmatrix}+\begin{pmatrix}K_1\\ K_2\\ K_3\end{pmatrix} = \begin{pmatrix}k\theta_3\\ -k\theta_3\\ 0\end{pmatrix} \quad (2)$$

Second Phase: During the second phase there is no feedback torque, and the swing leg can be considered as 1-DOF because the knee stopper is naturally locked by walking motion.

Third Phase: We assumed this phase takes place instantaneously. From the law of conservation of momentum and angular momentum, we derive the angular velocity just after the foot collision.

3. Results of Numerical Simulation

3.1. Nature of self-excited walking

Based on the analysis described above, we performed numerical simulations. In this self-excitation control strategy, the variable parameter is only feedback gain k. Therefore we examined the effect of feedback gain on characteristics of biped walking motion.

Figure 4 shows a typical result of numerical simulation of stable walking motion by using link parameter values shown in Table 1. Those parameter values are obtained under the assumption that the linear density of the robot's link is 5 [kg/m] and the length of leg l_1 is 0.8 [m]. Figure 5 shows phase plane of the shank during one cycle of the gait. From $t = T_0$ to $t = T_2^-$, the shank is support leg phase, from $t = T_2^+$ to $t = T_4^+$ the shank is swing leg phase. T_1^-, T_3^- and T_1^+, T_3^+ indicate before and after the knee stopper collision, respectively. T_2^-, T_4^- and T_2^+, T_4^+ show before and after the foot collision with the ground, respectively.

If the feedback gain and initial conditions are adequate, the gait of biped mechanism converges to the stable limit cycle. By inverse dynamics of the simulation result, we confirmed that the knee stopper of the support leg is naturally locked by walking motion if there is $1 \sim 2[deg]$ offset at the knee joint. Therefore the knee joint of the experimental robot does not need a locking mechanism.

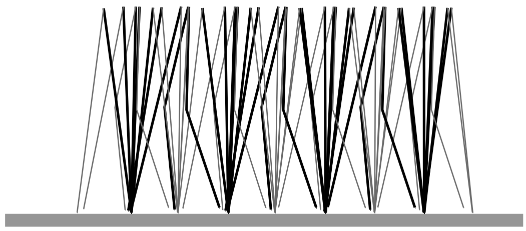

Figure 4: Stick figure of stable walking (k=6.3 [Nm/rad], $r = 0.0$ [m], Period=1.18 [s])

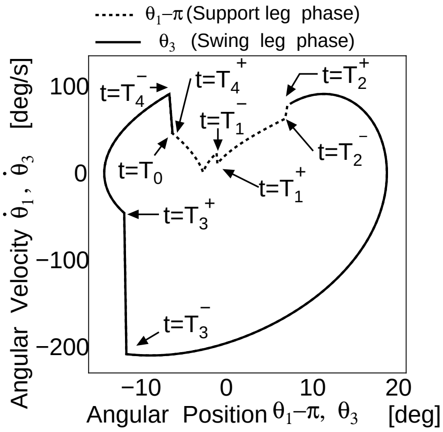

Figure 5: Phase plane of the shank

3.2. Effect of feedback gain

In this section, we explain the effect of feedback gain on biped walking motion. As the result of numerical simulation, we found that stable walking is possible over the wide range of feedback gain value, from $k = 4.8$ to $k = 7.2[Nm/rad]$. Figure 6 shows the effect of feedback torque on walking velocity, input energy and periods. We defined the input energy P such that

$$P = \frac{1}{t_{end}}\int_0^{t_{end}} |\dot{\theta}_2 k\theta_3| dt \quad (3)$$

where t_{end} is simulation term. As seen in this figure, even if feedback gain k increases, the walking periods change little, velocity increases slightly, but input energy increases proportional to the k.

The walking motion of the biped mechanism with high feedback gain become soldier-march-like

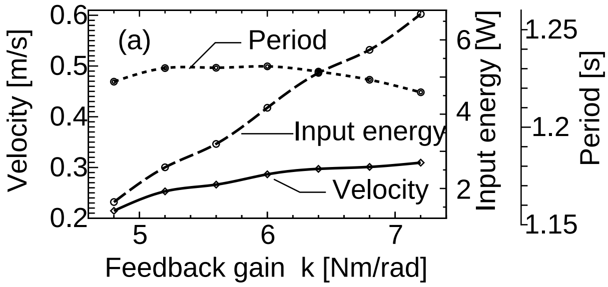

Figure 6: Feedback gain effect on velocity, input energy and period

gait, swinging up the swing leg high. This is the reason why energy consumption increases proportionally to the feedback gain. Therefore it can be said that walking period and velocity are not affected so much by feedback gain, but in terms of energy consumption, a smaller feedback gain walking is better. However the feedback gain should also be determined from the robustness of walking motions against the irregularity of the ground.

4. Experiment

4.1. Manufactured biped walking mechanism

The manufactured biped walking robot is shown in Figs.7 and 8. The Biped Walking Robot (BWR) has a couple of outer leg and single inner leg. These legs are connected in series by AC servo motor. Each leg consists of thigh and shank connected at knee joint which has optical encoder, rotary damper and knee stopper.

We carefully designed and adjusted the robot so as to meet the requirement of "dynamically equivalent to the analytical model". Therefore both the outer leg thighs are connected by the hip joint shaft. The shanks are also connected by the light weight frame which does not interfere the motion of inner leg. By means of the connected outer leg, the rolling motion of the robot was perfectly constrained so that the robot could behave as a biped mechanism on a sagittal plane.

4.2. Experimental results

In experiment the most difficult problem is to learn how we lead the initial state of BWR into a basin where BWR's walking motion converges to a limit cycle. Another problem is to reduce disturbances from ground, cable and irregularity of the mechanism.

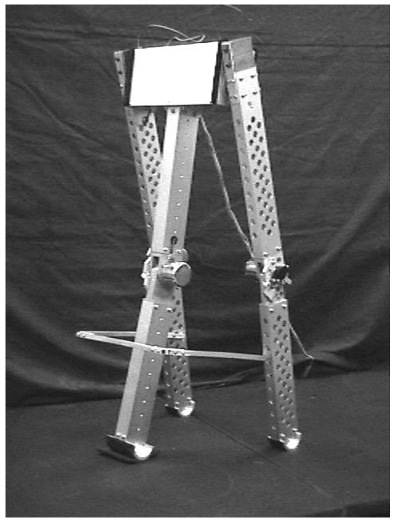

Figure 7: Picture of biped walking robot (BWR)

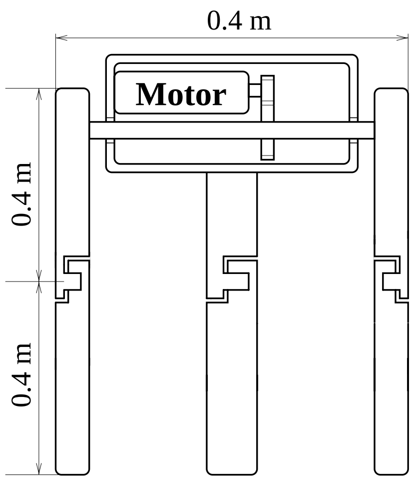

Figure 8: Outline of biped walking robot (BWR)

Optimization and symmetry of mechanical parameters are also important. As the results of trial learning of the initial condition and modification of the system, we have finally succeeded in realizing biped walking on a slightly inclined plane of about $0.8[deg]$. Video of the self-excited biped walking will be shown in the presentation. Figure 9 shows experimental data and simulation data of relative angle α between support leg and swing leg. This experimental result approximately agreed with simulated one. Although it is not clear why the robot cannot walk on a complete level plane, main reason seems to be that the energy consumption at collision is much larger than the simulation results.

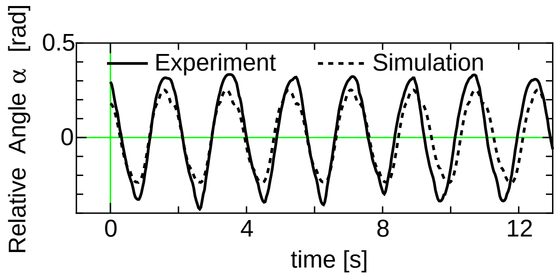

Figure 9: Experimental and simulation data of robot's walking

5. Conclusion

We proposed a self-excited biped walking mechanism which can generate its natural walking motion on a level ground. The control strategy is based on the asymmetric stiffness-matrix-type self-excitation.

Using simple analytical model and basic equation in each phase, we numerically showed self-excited biped walking. As a result, it was found that stable walking motion is possible over the wide range of feedback gain. The walking velocity and period were not so affected by feedback gain because this control strategy utilize the natural motion of the biped mechanism.

To verify the simulation results, we manufactured planar biped robot which has a couple of outer leg, inner leg and one actuator between them. After adjusting the mechanical parameters, we succeeded in making BWR walk on a plane with $0.8[deg]$ inclination. Our future goals are realization of biped walking on complete level plane and improvement of robustness against disturbances.

Acknowledgments

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