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Legged Robot design applying the behavior of Passive Dynamic Walking

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Abstract– In this paper we propose new legged robot design applying its dynamical behavior. In concrete terms, we focus the dynamical properties of Passive Dynamic Walking and try to apply them to design legged walking robot hardware.

1. Introduction

Several researches on the legged walking robot have been conducted, and many robots show incredible performances as the research results [1-5]. Many of such the robots are designed by calculating the statics same as the industrial robot-manipulator design [6]. However, when we try to realize the mechanical legged walking system, it must be important to understand and apply the dynamical properties and behaviors to design mechanical hardware which are suitable for legged walking [7].

For example, as shown in Fig.1, reference [8] compares the legged walking robot design as the aircraft design. Thereby, it is thought that we are able to realize "good legged walking robot" which walks efficiently and naturally by applying the principle of Passive Dynamic Walking.

In this paper we propose one legged robot design method applying the idea described above, and try to realize the design procedure. In concrete terms, we focus the properties of Passive Dynamic Walking and try to apply them to design the legged walking robot hardware.

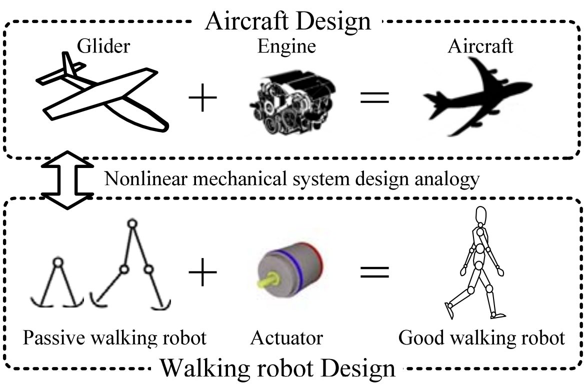


Fig.1 An idea of legged robot design which we suppose

2. Passive Dynamic Walking and its behavior

2.1. Passive Dynamic Walking and its characteristic behavior

Passive Dynamic Walking propounded by [8] is a kind of legged walking operation which walks by the mechanical dynamics and gravity force. Passive Dynamic Walking enables the legged robots to walk stably without actuators by giving the proper initial conditions such as leg angles and angular velocities.

The simplest system model of Passive Dynamic Walking is shown in Fig.2, and its dynamical equation is described as Eq.(1), where $\boldsymbol{\theta} = [\theta_p, \theta_w]$, $\mathbf{M}(\boldsymbol{\theta})$ is the inertia matrix, $\mathrm{N}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})$ is the centrifugal and Coriolis term, $\mathbf{g}(\boldsymbol{\theta}, \alpha)$ is the gravity term.

$$\mathbf{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{N}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} + \mathbf{g}(\boldsymbol{\theta},\alpha) = \mathbf{0} \quad (1)$$

This equation is equivalent to a double pendulum system essentially.

Supposing that a transition of the support leg and the swing leg occurs instantaneously and the impact of the swing leg with the ground is inelastic without sliding. Then the transition equation at the collision of the swing leg with the ground can be derived as

$$\mathbf{P}_b(\beta)\dot{\boldsymbol{\theta}}^- = \mathbf{P}_a(\beta)\dot{\boldsymbol{\theta}}^+ \quad (2)$$

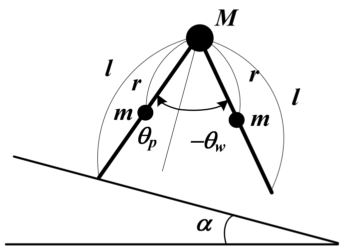


Fig.2 The simplest system model of Passive Dynamic Walking robot ; hip mass: M [kg]leg mass: m [kg], leg length: l [m], distance between hip center and leg's centroid: r [m], G-forces: g = 9.8[m/s^2], slope angle: α [rad], support leg angle: θ_p [rad], swing leg angle: θ_w [rad].

by using the angular momentum conservation conditions, where $\dot{\theta}^-$, $\dot{\theta}^+$ are the pre-impact and post-impact angular velocities and β is the contact angle of each leg.

It is well known that Passive Dynamic Walking shows characteristic behaviors which are similar to nonlinear dynamical system by using the theoretical model.

Firstly we can ascertain "pull-in effect" in PDW behaviors. The walking stride (hereafter we describe it 'gait') settles to the steady value with several steps after a walk start, as if the gaits are pulled in. Secondly we can ascertain "gait-bifurcation" in Passive Dynamic Walking behaviors. According to the changes of the parameters such slope angle, mass, and leg length of PDW system, walking gaits changes and bifurcates to several values. These properties are certainly confirmed by computer simulations and experiments [8][9][10][11].

And last, we can ascertain a phenomenon same as "lock-effect" in Phase Locked Loop circuit system (PLL). PLL circuit technology is applied for electrical circuits which need to synchronize two cyclic signals. The circuit can keep synchronizing when the deviation of reference signal increases. The limit of deviation increase is called Lock-range and this behavior is called as "lock-effect".

Same kind of phenomenon is confirmed in Passive Dynamic Walking by computer simulation [12]. When the slope angle or mass of the body and leg length changes continuously after a walk start and the gait becomes fixed, the gait changes automatically and continuously according to the amount of changes of the slope angle, body mass, leg length. The phenomenon is checked only in the computer simulation. This behavior can be interpreted as a kind of adaptive function to change gaits by itself according to the environmental change automatically in walk operation.

As described above, same kind of properties and characteristic behaviors of a nonlinear dynamical system are shown in Passive Dynamic Walking.

2.2. Verification of the properties by some experiments

It is confirmed that there are same characteristic properties and behaviors of a nonlinear dynamics system as described in the foregoing section. Especially, existence of "pull-in effect" and "bifurcation" are shown by both the computer simulation and experiments, and it is thought that these properties are applicable to analyze real legged walking robot system.

On the other hand, the adaptive function is checked only by the computation simulation. Therefore, it is necessary to verify the theoretical model used for the computer simulation whether the model really describes the behaviors of Passive Dynamic Walking by the experiments. Moreover it is also necessary to verify the model whether the adaptive function appears or not by the experiments.

Therefore, in this section, we try to verify the validity of the theoretical model by some actual experiments.

2.2.1. Verification of the Passive Dynamic Walking dynamical model by experiments

In this subsection we try to verify the validity of Passive Dynamic Walking dynamical model [13]. It is difficult to carry out the experiment and measure the parameters by using the simplest Passive Dynamic Walking model shown in Fig.2, so we apply the prototype robot with soles shown in Fig.3. Acceleration sensors are attached to legs of the prototype to measure the leg angles. Experimental results are shown in Fig.4 and Fig.5.

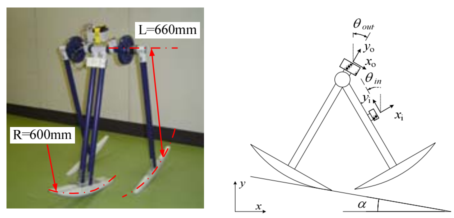


Fig.3 Prototype PDW robot to verify the system model

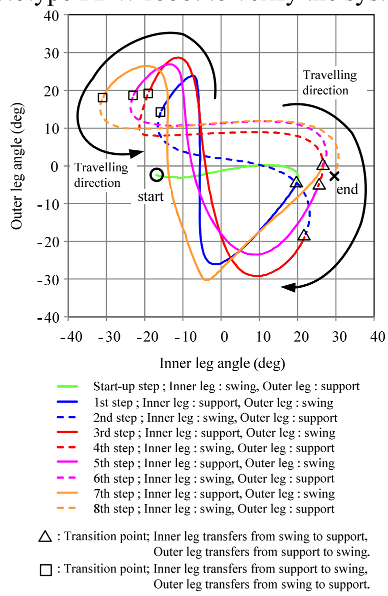


Fig.4 Configuration space trajectories of leg angle θ_{out} and θ_{in} ; the trajectories are going to settle to a constant orbit.

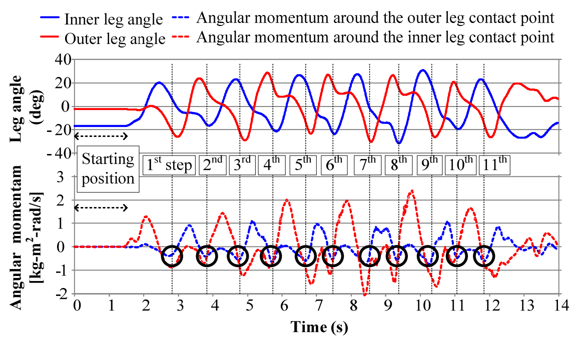


Fig.5 Time-series data of the inner and outer leg angles, and their angular momentums around the contact point to the walking floor surface. The black line circles show values of the angular momentum of each leg at the leg transition moment. After pull-in, the values are approximately equal.

The dynamical system which is described as Eq. (1) has the couple of solutions which draws a symmetric phase diagram in the second and fourth quadrant of the configuration space as shown in Fig.4 [14]. As shown in Fig.4, we can confirm that the experimental trajectories are equal to the theoretical trajectories. About the angular momentum at the collision and leg transitions, the values of legs are approximately equal after the gaits are pull-in state (after 2nd step) , as shown in Fig.5.

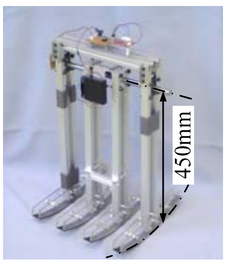
These results show that the system model which is described as Fig.2, Eq. (1) and Eq. (2) certainly expresses the walking motions and behaviors. Therefore it is thought that results of past researches studied by applying this system model are valid. And it is thought that the adaptive function of PDW is revealed also with the system.

2.2.2. Validation of Adaptive function by some experiment

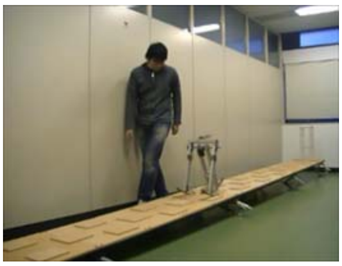
In this section we try to verify whether the adaptive function of Passive Dynamic Walking really exist or not by some actual experiments.

Fig.6 shows the prototype Passive Dynamic Walking robot and its experimental conditions and procedure. Experimental trajectories are shown in Fig.7, and the gait changes of each step are shown in Fig.8.

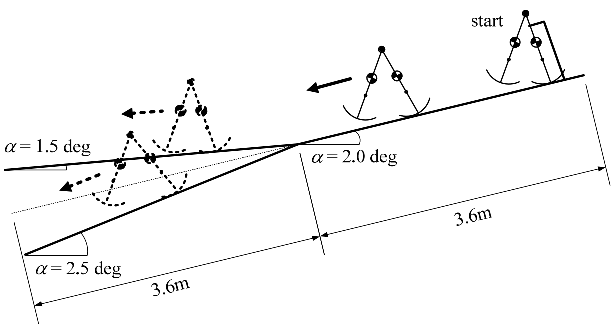
Those results show that the gaits change continuously and automatically when the slope angle changes during walk operation. Therefore, it is thought that revelation of the adaptive function of PDW is also checked in the experiments.



(a) Prototype for experiment



(b) Walking experiment



(c) Experimental conditions and procedure

Fig.6 Experimental apparatus and conditions to verify the adaptive function which indwells in PDW. The prototype robot always starts to walk with the same posture by applying the starting fixture.

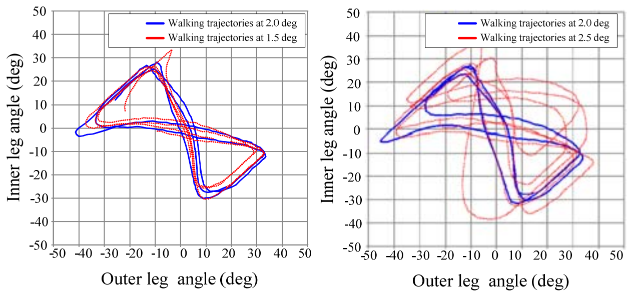


Fig.7 Configuration space trajectories of leg angle θ_{out} and θ_{in}. The trajectories experimented at the slope angle 2.0 to 1.5 deg settle to small orbit. On the other hand, the trajectories experimented at the slope angle 2.0 to 2.5 deg diverge and generate various orbit.

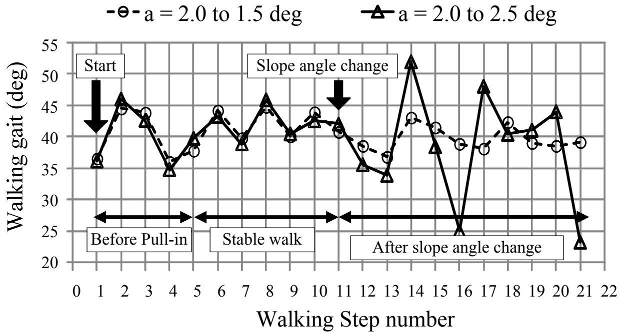


Fig.8 Experimental results of walking gaits which are averages of 5-times experiments. The prototype robot starts to walk on the same initial condition by using starter implement. As shown in the figure, the gaits are very good match before the slope angle change. Then each condition's gait change and continue to walk after the slope angle change.

3. Actual design of legged robot applying the characteristic behaviors of Passive Dynamic Walking

As mentioned above, our goal is to develop a good Passive Dynamic Walking robot design method in order to develop a good legged robot. For the mechanical system design such as legged robot, it is necessary to determine the parameters; size of leg length, mass of each part, required driving force (or torque), etc. So we try to determine the parameters by applying the adaptive function of Passive Dynamic Walking.

Here we assume the changes of robot's parameters which are described above as the environmental changes. And then, we make the robot's parameters to change little by little and continuously during a walk [7]. In addition, in order to examine the essence of the robot design as simply as possible, we adopt the simplest system model of PDW which showed in Fig. 2 and examine the design method.

The outline of the design is described in Fig.9, and the simulative results are shown in Fig.10. From these results, it turns out that the size and mass of the robot's leg can be determined by using the adaptive function. Moreover, in order to determine the robot's gaits, we can search the desired slope angle by changing the angle during the walking simulation. Then we accomplish the needed drive force or torque of robot by calculating the effect of the gravity which is adjusted by the slope angle.

As stated above, it turns out that the legged robot design can be realized by applying the adaptive function of PDW; determining the desired leg length, leg mass, hip mass, and gait.

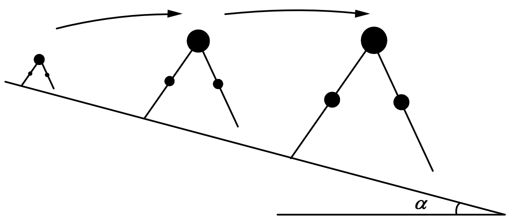


Fig.9 Legged robot design applying the adaptive function of Passive Dynamic Walking. At first, the reference walking model walks passively. Then we continuously increase the masses of legs and hip by degrees, according to the leg's length extension. The first reference model's parameters are M =10.0[kg], m =1.0[kg], l = 0.3[m], r = 0.15[m], and the design objective parameters are M =10.0[kg], m =5.0[kg], l = 1.5[m], r = 0.75[m]. Slope angle is fixed at 0.035 [rad].

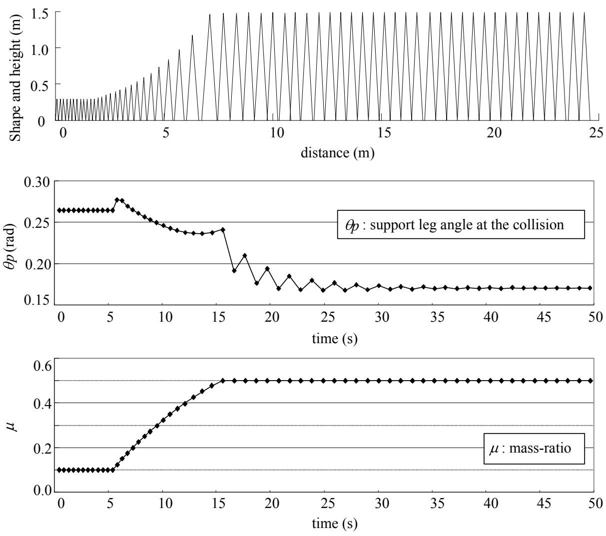


Fig.10 Simulation results of the design procedure. Five seconds after the start walking, leg's mass and length of the Passive Dynamic Walking model starts to increase by degrees. And then, according to the increases of the parameters, walking gaits period decrease. However the robot simulation model continues to walk.

4. Conclusion

We proposed one legged robot design method applying the properties of Passive Dynamic Walking, and tried to realize the design procedure. We focus the properties of Passive Dynamic Walking and try to apply them to design the legged walking robot hardware. Then we verify the validity of the method by some experiments and computer simulation.

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