Stable Quadrupedal Dynamic Walking using Phase Modulations based on Leg Unloading

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SUMMARY

Dynamic walking at lower Froude number (Fr) is difficult to realize than that at higher Fr, since both posture control and rhythmic motion control are important and should be integrated. We are developing a general quadrupedal locomotion controller by using a neural model involving a CPG (Central Pattern Generator) utilizing normal ground reaction force (leg loading) sensory feedback for both rolling motion (posture) and gait (rhythmic motion) control. Especially, while using a non-oscillator-typed CPG and generating the self-excited physical oscillation as a result of local feedback, we could be able to integrate sensor-dependent posture control and sensor-driven rhythmic motion control. Currently, we succeeded in simulations of dynamic walking under disturbances while using a CPG with phase modulations based on leg unloading.

PHASE MODULATIONS BASED ON LEG UNLOADING

Respectively, HL and HR are for the left and right hind legs, and FL and FR are for the left and right forelegs. Each leg is actuated by a control unit called the Leg Controller (LC). Each LC has two phases: *swing* and *stance*.

The desired trajectories are calculated using the oscillator[1] phase ϕ (Fig.1), where $r_{sw}(\phi)$ and $r_{st}(\phi)$ are swing and stance phases trajectories, respectively. Each leg has three (hip, knee and ankle) joints which move within the pitch plane. The positions of the foot at the swing-to-stance and stance-to-swing transition are named as AEP (anterior extreme position) and PEP (posterior extreme position). We consider dynamics of an oscillator phase ϕ, where $\dot{\phi} = \hat{\omega}$ in the stance phase and the following in the swing phase.

$$\dot{\phi} = \begin{cases} \hat{\omega} + \omega_{mod} & \text{if } 0 \leq \phi < \hat{\phi}_{AEP} \\ 0 & \text{if } \phi \geq \hat{\phi}_{AEP} \end{cases}$$

Resetting of ϕ is employed so that $\phi = \hat{\phi}_{AEP}$ and $\phi = \hat{\phi}_{PEP}(= 0)$ at the onset of stance and swing phases, respectively. The conditions of phase transition are

$$\begin{aligned} &\text{swing to stance:} && f_n > 0 && \text{and} && \phi > \hat{\phi}_{AEP}/2 \\ &\text{stance to swing:} && f_n < \chi && \text{and} && \phi > (\hat{\phi}_{AEP} + \pi/2) \end{aligned}$$

where normal ground reaction force (leg loading) f_n is used at the phase transition from stance to swing[1] and χ is the force threshold.

Even though the model has *no roll joint*, still rolling motion of the whole body is naturally generated since unstable motion of an inverted pendulum occurs during the two-legs stance phase. Such rolling motion (lateral posture) can be stabilized by using leg phase modulations based on leg unloading.

[1]Actual stance phase duration and duty ratio of each leg are widely variable according to body rolling motion, terrain irregularities and so on, since we use leg unloading for the phase transition from stance to swing. In the sense that the actual walking cyclic period is determined by dynamics of the whole body and environment, we call it "non-oscillator-typed CPG."

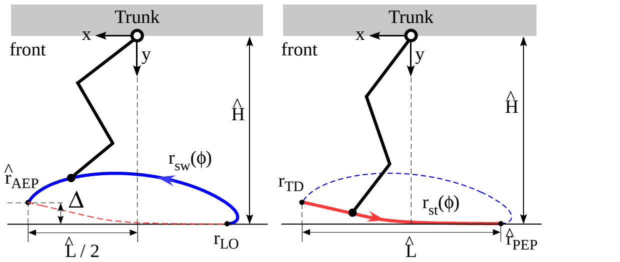

Figure 1. Stance and swing trajectories. L(0.1m), H(0.18m) and Δ(0.01(m) for fore and 0(m) for hind legs) are body height, stride length and AEP vertical offset to generate appropriate rolling motion, respectively.

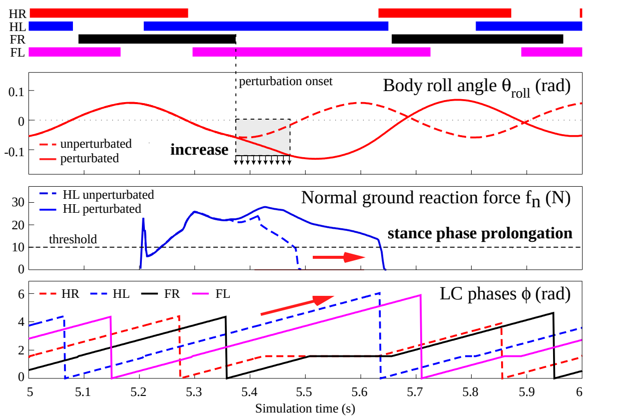

Figure 2. Recovery from a perturbation increasing the amplitude of the rolling motion (a lateral force of 15 N is applied at the onset the swing phase in FR. Without the disturbance, the walking cyclic period and duty ratio are 0.40(s) and 0.625, respectively.

ASCENDING COORDINATION MECHANISM

We made simulations using above described LCs *independent of each other* under small disturbances. We mostly succeeded in simulations of stable walking under lateral perturbations (Fig.2). But, we found that additional mechanisms were needed to help the system to recover in some special lateral perturbations. Therefore, we implemented a two-fold ascending coordination mechanism. Those are adjustments of the force threshold:χ and ω_{mod} of a fore leg LC based on the oscillator phase ϕ of a same-lateral hind LC.

When adding this ascending coordination mechanism between same-lateral legs, simulation results showed good resistance ability against lateral perturbations at all the timings considered and against various terrain irregularities, both with a short and a longer walking periods *without explicit reflexes such as a vestibulospinal reflex for posture control*[2].

Now, we are making a new quadruped robot to validate the results obtained in simulations.

REFERENCES

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