Locomotion Control of a Multi-legged Locomotion Robot using Oscillators

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Abstract— **This paper proposes the locomotion control system for a multi-legged locomotion robot. The proposed control system is composed of leg motion controllers and a gait pattern controller. The leg motion controllers drive the actuators of the legs by using local feedback control. The gait pattern controller is composed of non linear oscillators. The oscillators tune the phases through the mutual interactions and the feedback signals from the touch sensors at the tips of the legs. Various gait patterns emerge through the mutual entrainment of these oscillators. As a result, the robot with the controller walks stably by changing its gait patterns in a wide range of locomotion speed. Moreover, it continues to walk even if a part of leg controller breaks down. The performance of the proposed control system is verified by numerical simulations.**

Keywords— **Locomotion control, multi-legged locomotion robot, central pattern generator model.**

I. Introduction

Locomotion is one of the basic functions of mobile robot and the leg mechanism is one of the strategies for accomplishing locomotion. The advantage of legged locomotion is that legs can move on a rough terrain, while the disadvantage of legged locomotion is that each leg supports the body discontinuously, which results in degradation of stability of walk. The multi-legged locomotion overcomes the difficulty, but requires complex body mechanisms. The control system for this class of mechanical system designed by the modern control theory has several drawbacks; since the controller is designed based on the mathematical model, it becomes to be correspondingly complex and is unable to adapt to a changing environment. The walking motion of an animal solves these problems; during a walk, a lot of joints and muscles are organized into a collective unit to be controlled as if it has fewer degrees of freedom but to retain the necessary flexibility for a changing environment. Biological inspired controllers for legged locomotion robot have been studied[1]. Cruse, H. et al. have proposed a controller, walknet, for six-legged walking based on the investigations of the stick insect Carausius morosus[2]. The proposed controller is a distributed one with local controllers interacting with their immediate neighbors. The controller ensures proper spatiotemporal coordination among the legs, taking account of the physical properties of the system by the sensory feedback. It is widely believed that animal locomotion is generated and controlled, in part, by a central pattern generator (CPG)[3]. The CPG is a neuronal ensemble capable of producing rhythmic output in the absence of sensory feedback or brain input, but is highly sensitive to sensory feedback and external control from the brain. The controllers for legged-locomotion have been proposed based on a CPG model. We have also proposed the controller for a quadruped locomotion based on a CPG model[4]. The oscillators are assigned at each leg and drive the periodic motion of legs. The phases of the oscillators are controlled by the signals of the touch sensors at the tips of the legs. It is confirmed by the numerical simulations and the hardware experiments that the robot changes its gait pattern adaptively to variance of the environment and establishes a stable locomotion.

This paper will apply the proposed controller to a multi-legged locomotion robot, ten legged locomotion robot. A robot is five module. A module has two legs. The aim of the paper is to demonstrate that the robot with the proposed controller show considerable adaptability in the sense that the robot changes its behavior in accordance with changing environmental conditions, that is, the robot changes its gait pattern according to a speed of walk during a straight walking. And beyond this, the robot is able to walk even if a part of leg controller breaks down.

II. Equations of Motion

We consider the multi-legged locomotion robot shown in Fig.1. The robot has 5 body modules and each body has two legs. A module has two legs. Each leg is composed of two links which are connected to each other through a one degree of freedom rotational joint and connected to the body module through a one degree of freedom rotational joint. The body modules are connected to each other through a three degree of freedom rotational joint. The inertial fixed coordinate system and the first body module fixed coordinate system are defined as $[\boldsymbol{a}_0] = [\boldsymbol{a}_{01}, \boldsymbol{a}_{02}, \boldsymbol{a}_{03}]$ and $[\boldsymbol{a}_1] = [\boldsymbol{a}_{11}, \boldsymbol{a}_{12}, \boldsymbol{a}_{13}]$,respectively. Axes $\boldsymbol{a}_{01}$ and $\boldsymbol{a}_{03}$ coincide with the direction of locomotion and vertically upward direction, respectively. Axes $\boldsymbol{a}_{11}$ and $\boldsymbol{a}_{13}$ coincide with axes $\boldsymbol{a}_{01}$ and $\boldsymbol{a}_{03}$, respectively. Body modules are numbered from 1 to 5, as shown in Fig.1 and left and right legs are numbered as leg 1 and leg 2, respectively. The joints and the links of each leg are numbered as joint 1 and 2, and link 1 and 2 as shown in the figure. The position vector from the origin of $[\boldsymbol{a}_0]$ to the origin $[\boldsymbol{a}_1]$ is defined as $\boldsymbol{r}_0 = [\boldsymbol{a}_0]r_0$. The angular velocity vector of $[\boldsymbol{a}_i]$ to $[\boldsymbol{a}_{i-1}]$ is defined by $\boldsymbol{\omega}_i = [\boldsymbol{a}_i]\omega_i (i = 1, \cdots, 5)$. We define θ_i as the components of 3-1-2 Euler angle from $[\boldsymbol{a}_{i-1}]$ to $[\boldsymbol{a}_i]$. We also define $\theta_{ik}^{(j)}$ as the joint angle of link k of leg j of module i.

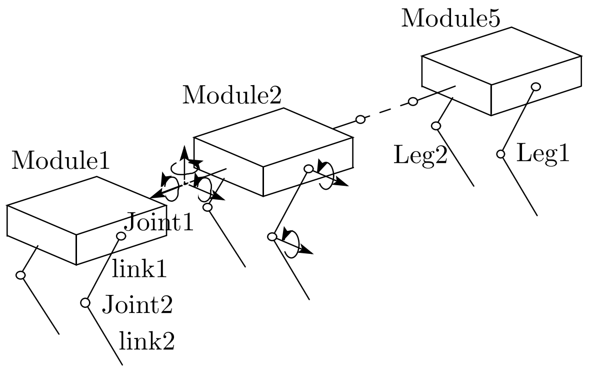

Fig. 1. Schematic model of a multi-legged locomotion robot

The state variable is defined as follows;

$$q^T = [\ r_{0m}\ \theta_{im}\ \theta_{ikm}^{(j)}\ ] \qquad (1)$$
$$i = 1, \cdots, 5,\ j = 1, 2,$$
$$k = 1, 2,\ m = 1, 2, 3$$

Equations of motion for state variable q are derived using Lagrange's equation of motions as follows;

$$M\ddot{q} + H(q, \dot{q}) = G + \sum(\tau_{ik}^{(j)}) + \Lambda \qquad (2)$$

where M is the generalized mass matrix and $H(q, \dot{q})$ is the nonlinear term which includes Coriolis forces and centrifugal forces. G is the gravity term. $\tau_{ik}^{(j)}$ is the input torque of the actuator at joint k of leg j of module i. Λ is the reaction force from the ground at the point where the tip of the leg makes contact.

III. Locomotion control

The control system is composed of leg motion controllers and a gait pattern controller(Fig.2). The leg motion controllers drive the joint actuators of the legs so as to realize the desired motions commanded by the gait pattern controller. The gait pattern controller is composed of non linear oscillators corresponding to each leg. The gait pattern controller receives the commanded signal of the nominal gait pattern as the reference. It also receives the feedback signals from the touch sensors at the tips of the legs. A modified gait pattern is generated from the nominal gait pattern through the phase dynamics of the oscillators, which is served to the leg motion controller as the commanded signal

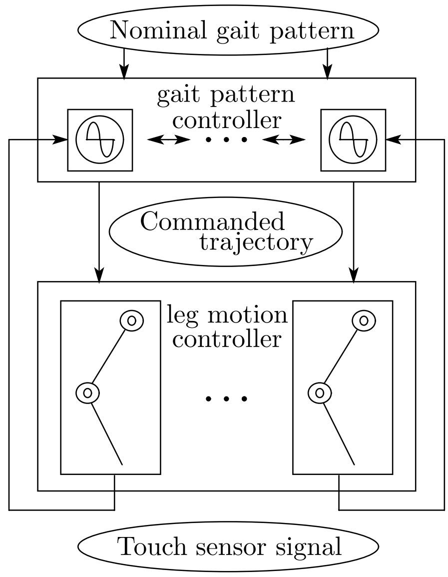

Fig. 2. Control system

A. Design of gait

A.1 Design of leg motion

First, we design the nominal trajectories of the tips of the legs. We define the position of the tip of the leg where the transition from the swinging stage to the supporting stage as the anterior extreme position (AEP) and the position where the transition from supporting stage to the swinging stage as the posterior extreme position (PEP). The nominal PEP and the nominal AEP are expressed as $\hat{\eta}_{iP}^{(j)}$, $\hat{\eta}_{iA}^{(j)}$ in the coordinate system $[\,\boldsymbol{a}_0\,]$. The nominal trajectory for the swinging stage is designed as a closed curve $\hat{\eta}_{iSw}^{(j)}$ which involves the points $\hat{\eta}_{iA}^{(j)}$ and $\hat{\eta}_{iP}^{(j)}$, and the nominal trajectory for the supporting stage is designed as a straight line $\hat{\eta}_{iSp}^{(j)}$ which also involves the points $\hat{\eta}_{iA}^{(j)}$ and $\hat{\eta}_{iP}^{(j)}$.

These trajectories are given as functions of the phases of the oscillators. The state of the oscillator (i, j), oscillator on leg j of module i, is expressed as follows;

$$z_i^{(j)} = \exp(\boldsymbol{j}\phi_i^{(j)}) \tag{3}$$

where $z_i^{(j)}$ is the state of the oscillator and $\phi_i^{(j)}$ is the phase of the oscillator.

The nominal phases $\hat{\phi}_i^{(j)}$ of the oscillator (i, j) at AEP and PEP are determined as follows;

$$\hat{\phi}_i^{(j)} = \hat{\phi}_{iA}^{(j)} \quad \text{at AEP}, \quad \hat{\phi}_i^{(j)} = 0 \quad \text{at PEP} \tag{4}$$

The nominal trajectories $\hat{\eta}_{iSw}^{(j)}$ and $\hat{\eta}_{iSp}^{(j)}$ are given as functions of the nominal phase $\hat{\phi}_i^{(j)}$ of the oscillator as

$$\hat{\eta}_{iSw}^{(j)} = \hat{\eta}_{iSw}^{(j)}(\hat{\phi}_i^{(j)}) \tag{5}$$

$$\hat{\eta}_{iSp}^{(j)} = \hat{\eta}_{iSp}^{(j)}(\hat{\phi}_i^{(j)}) \tag{6}$$

We use one of these two trajectories alternatively to generate the nominal trajectory $\hat{\eta}_i^{(j)}$ of the tip of the leg as follows(Fig.3);

$$\hat{\eta}_i^{(j)}(\hat{\phi}_i^{(j)}) = \begin{cases} \hat{\eta}_{iSw}^{(j)}(\hat{\phi}_i^{(j)}) & 0 \le \hat{\phi}_i^{(j)} < \hat{\phi}_{iA}^{(j)} \\ \hat{\eta}_{iSp}^{(j)}(\hat{\phi}_i^{(j)}) & \hat{\phi}_{iA}^{(j)} \le \hat{\phi}_i^{(j)} < 2\pi \end{cases} \tag{7}$$

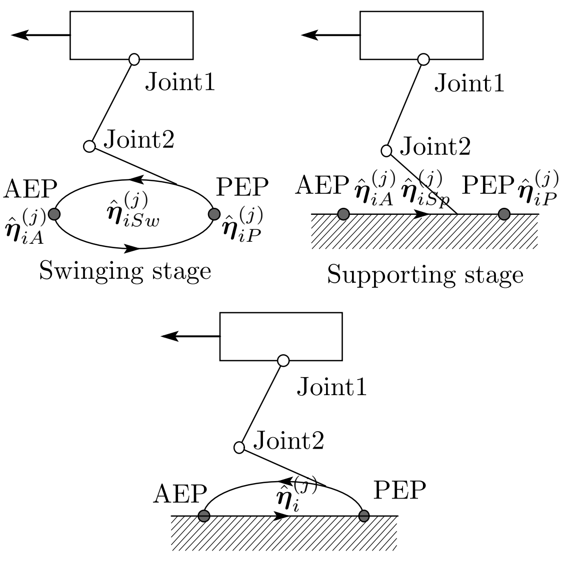

Fig. 3. Nominal trajectory of the leg

Then, we set the nominal phase dynamics of the oscillator as follows;

$$\dot{\hat{\phi}}_i^{(j)} = \hat{\omega} \tag{8}$$

The nominal angular velocity $\hat{\omega}$ of the oscillator and the nominal locomotion velocity $\hat{v}$ are given as follows;

$$\hat{\omega} = 2\pi \frac{1 - \hat{\beta}_i^{(j)}}{\hat{T}_{Sw}} \tag{9}$$

$$\hat{v} = \frac{1 - \hat{\beta}_i^{(j)}}{\hat{\beta}_i^{(j)}} \frac{\hat{S}_i^{(j)}}{\hat{T}_{Sw}} \tag{10}$$

where $\hat{S}_i^{(j)}$ is the nominal stride of leg j of module i which is given as

$$\hat{S}_i^{(j)} = \hat{\eta}_{iA1}^{(j)} - \hat{\eta}_{iP1}^{(j)} \tag{11}$$

,$\hat{T}_{Sw}$ is the nominal time of the swinging stage, which is assumed to be constant and $\hat{\beta}_i^{(j)}$ is the nominal duty ratio of leg j of module i, the ratio between the nominal time for the supporting stage and the period of one step of the nominal locomotion, which is given by

$$\hat{\beta}_i^{(j)} = 1 - \frac{\hat{\phi}_{iA}^{(j)}}{2\pi} \tag{12}$$

A.2 Design of gait pattern

Then, we design the gait patterns, the phase relations of oscillators. There are many gait patterns. Figure 4 shows the typical examples in the case where two oscillators on a same module oscillate in a same phase, where L$*$ means legs of module $*$ and the thick lines indicate the footprints of the legs. Pattern #1 is in phase pattern in which all the oscillators oscillate in a same phase and Pattern #2 is metachronal wave pattern in which the phase differences of oscillators on adjacent bodies are same.

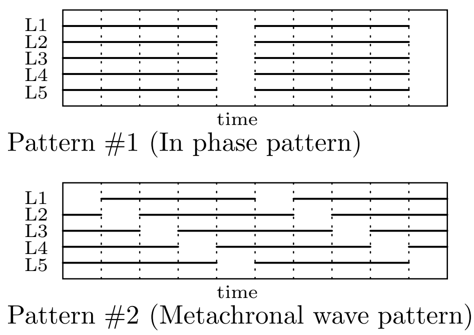

Fig. 4. Gait pattern(Foot print)

B. Control of gait

B.1 Leg motion controller

The angle $\hat{\theta}_{ik}^{(j)}$ of joint k of leg j of module i is derived from the geometrical relationship between the trajectory $\hat{\eta}_i^{(j)}(\hat{\phi}_i^{(j)})$ and is written as a function of phase $\hat{\phi}_i^{(j)}$ as follows;

$$\hat{\theta}_{ik}^{(j)} = \hat{\theta}_{ik}^{(j)}(\hat{\phi}_i^{(j)}) \tag{13}$$

The commanded torque at each joint of the leg is obtained by using local PD feedback control as follows;

$$\tau_{ik}^{(j)} = K_{Pk}(\hat{\theta}_{ik}^{(j)} - \theta_{ik}^{(j)}) + K_{Dk}(\dot{\hat{\theta}}_{ik}^{(j)} - \dot{\theta}_{ik}^{(j)}) \tag{14}$$

where $\tau_{ik}^{(j)}$ is the actuator torque at joint k of leg j of module i, and K_{Pk}, K_{Dk} are the feedback gains, the value of which are common to all joints of all legs.

B.2 Gait pattern controller

We design the phase dynamics of the oscillators as follows;

$$\dot{\phi}_i^{(j)} = \hat{\omega} + g_{1i}^{(j)} + g_{2i}^{(j)} \tag{15}$$

where $g_{1i}^{(j)}$ is the term which is derived from the interactions with other oscillators and $g_{2i}^{(j)}$ is the term caused by the feedback signal of the touch sensor at the tip of the leg.

Function $g_{1i}^{(j)}$ is designed in the following way: We define the potential function as

$$V(\phi_i^{(j)}, \gamma) = \frac{1}{2}K\sum_i(\phi_i^{(2)} - \phi_i^{(1)} - \gamma)^2 \tag{16}$$

Function $g_{1i}^{(j)}$ is then derived from the potential function V as follows;

$$g_{1i}^{(j)} = -(-1)^j K(\phi_i^{(2)} - \phi_i^{(1)} - \gamma) \tag{17}$$

Function $g_{2i}^{(j)}$ is designed in the following way: Suppose that $\phi_{iA}^{(j)}$ is the phase of leg j of module i at the instant when leg j of module i touches the ground, and $\eta_{iA}^{(j)}$ is the position of leg j of module i at that instance. Then, when leg j of module i touches the ground, the following procedure is undertaken.

1. Set the phase of the oscillator for leg j of module i from $\phi_{iA}^{(j)}$ to $\hat{\phi}_{iA}^{(j)}$.
2. Switch the nominal trajectory of leg j of module i from the swinging trajectory $\hat{\eta}_{iSw}^{(j)}$ to the supporting trajectory $\hat{\eta}_{iSp}^{(j)}$.
3. Replace parameter $\hat{\eta}_{iA}^{(j)}$ in the nominal trajectory $\hat{\eta}_{iSp}^{(j)}$ with $\eta_{iA}^{(j)}$.

Function $g_{2i}^{(j)}$ is written with a mathematics as follows;

$$g_{2i}^{(j)} = (\hat{\phi}_{iA}^{(j)} - \phi_{iA}^{(j)})\delta(t - t_{hsi}^{(j)}) \tag{18}$$

where $t_{hsi}^{(j)}$ is the time when leg j of module i touches the ground.

The designed phase dynamics becomes a dynamic system where the oscillators affect each other through two types of interactions; one is continuous interactions derived from the potential function V, and the other is the pulse-like interactions caused by the feedback signals from the touch sensors. Through these interactions, the oscillators can generate phase patterns adapted to the change of the environment. The proposed controller has the distinctive feature in utilizing term g_2, which leads the system to rely heavily on the sensory feedbacks, and this makes the system adaptive to changing environments. The controller proposed by Cruse et al.[2] has the same feature, but their controller has two nets, the swing net and the stance net, and changes them by sensory input.

IV. Numerical Analysis

Table I shows the physical parameters of the robot which are used in the numerical analysis.

TABLE I
Physical parameters of the robot

Length of Body	0.13	[m]
Mass of Body(Module 1,5)	0.25	[kg]
Mass of Body(Module 2,3,4)	0.50	[kg]
Length of Link 1,2	0.07	[m]
Mass of Link 1,2	0.050	[kg]

Numerical simulations are carried out under the condition that the nominal stride $\hat{S}_i^{(j)}$ is set to be 0.03 [m], and the band width of joints 1,2 is set to be 2 [Hz]. The term $g_{1i}^{(j)}$ is designed so that the two oscillators on body j oscillate in phase, that is, phase difference γ is set to be zero and feedback gain K is set to be sufficiently large. The nominal duty ratio $\hat{\beta}$ is selected as a parameter which expresses the change of the environment, the speed of locomotion. The nominal time $\hat{T}_{Sw}$ of the swinging stage is set to be 0.3 sec. As a initial conditions in the phase dynamics, the phase difference of two adjacent oscillators is set to be $2\pi/5$.

The performance of the control system is evaluated by the energy consumption E_c of actuator and realized locomotion velocity. The energy consumption E_c is defined as

$$E_c = \frac{\int_t^{t+T_\beta} \sum_{i,j,k} \tau_{ik2}^{(j)}\omega_{ik2}^{(j)}\,dt}{S_\beta} \tag{19}$$

where S_β is the distance of locomotion during time T_β.

As a comparison of performance, a locomotion control system with a fixed gait pattern is analyzed. As the fixed gait pattern, a metachronal wave pattern is used where the phase difference of two adjacent oscillators is set to be $2\pi/5$.

Figure 5 shows the time history of parameter $\hat{\beta}$ where the horizontal line is the number of steps. First, parameter $\hat{\beta}$ is decreased and then is increased. That is, first the robot walks fast and then slow. Figure 6 shows the performance of the controllers, the locomotion velocity and the energy consumption as the function of parameter $\hat{\beta}$. In the figures, "Prop. ac." and "Prop. dec." mean the case where the locomotion velocity of the robot with the proposed controller is increased and decreased, respectively, "Fix." means the controller with a fixed gait pattern and "Theor." means the nominal locomotion velocity based on Eq.(10). In Fig.6(a), the locomotion velocities of the proposed controller are on the nominal velocity curve in a wide velocity range, while the locomotion velocity of the controller with a fixed gait pattern is under the nominal velocity curve in the higher velocity range. In Fig.6(b) the energy consumption of the proposed controller is constant in a wide velocity range, while the energy consumption of the controller with a fixed gait pattern increases in the higher velocity range. From these figures, it may be suggested that the robot controlled by the proposed controller can walk without stick or slip in a wide velocity range, while the robot controlled by the controller with a fixed gait pattern cannot walk smoothly in a higher velocity range.

Figures 7 and 8 show that the gait patterns of the robot with the proposed controller change according to the locomotion velocity. This clarifies that the good performance of the proposed controller lies in the fact that the proposed controller can adapt the gait patterns to the environments, while the controller with a fixed gait pattern cannot adapt the gait pattern to the environment.

Lastly, the degradation of performance is analyzed when a part of the controllers is broken down. The failure of the controllers is assumed so that the leg motion controllers of module # stops to work and then, the legs of the module move freely. As a result, the oscillators of the module lose the feedback signals and oscillate freely.

Figure 9 shows the fall of the locomotion velocities where "normal" and "failure (L#)" mean the normal state of the controller and the failure state of the controller of the legs of module #, respectively. The degradation of performance is suppressed low in the case of the proposed controller compared with the case of the controller with a fixed gait pattern.

Figure 10 shows the changes of the phase difference of the oscillators with the oscillator of module 5 where the arrow indicates the time when the failure occurs. From the figure, it is revealed that degradation of performance is suppressed by changing the phase pattern of the oscillators.

V. Conclusions

We proposed a control system for a multi-legged locomotion robot composed of leg motion controllers and a gait pattern controller. The leg motion controller drives the actuators at the joints of the legs by use of local high gain feedback with the commanded signal from the gait pattern controller. Whereas with the mutual interactions and feedback signals from the touch sensors at the tips of the legs, the gait pattern controller modulates the nominal gate pattern adaptively and serve them to the leg motion controller as the commanded signals. As a result, the robot with the proposed controller can adapt to changing environments. In the following paper, modifying the system so that the modules are connected each other by the joints with three degrees of freedom of rotation, we will analyze the performances of the system during curve walking and walking on highly irregular terrain.

Acknowledgments

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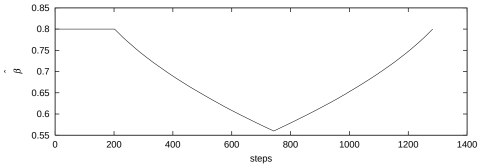
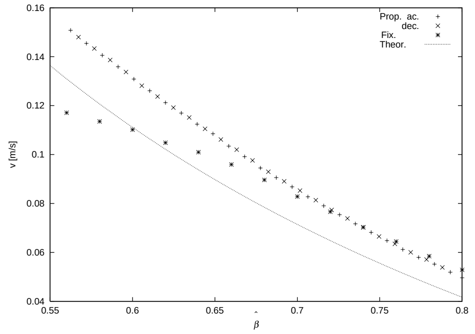
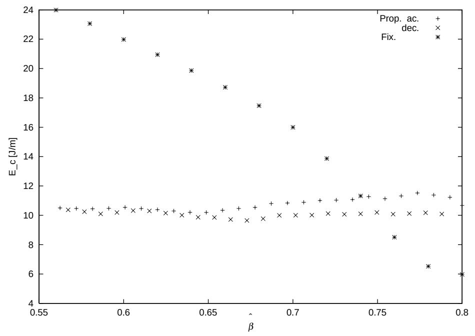


Fig. 5. Time history of $\hat{\beta}$



(a) Locomotion velocity



(b) Energy consumption

Fig. 6. Performance of controller

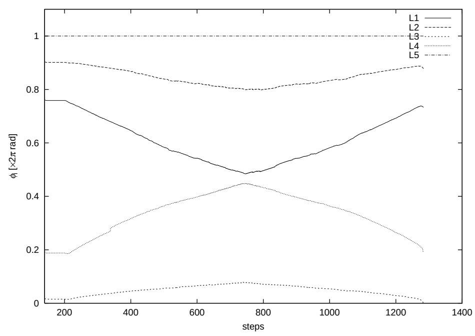
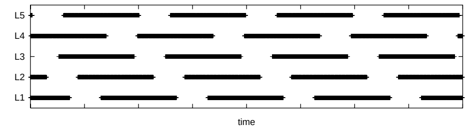
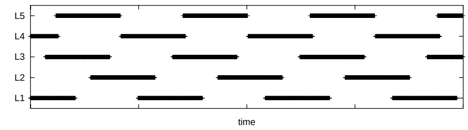


Fig. 7. Phase differences of oscillators with the oscillator of module 5



(a) $\hat{\beta} = 0.70$



(b) $\hat{\beta} = 0.50$

Fig. 8. Gait pattern (Footprint)

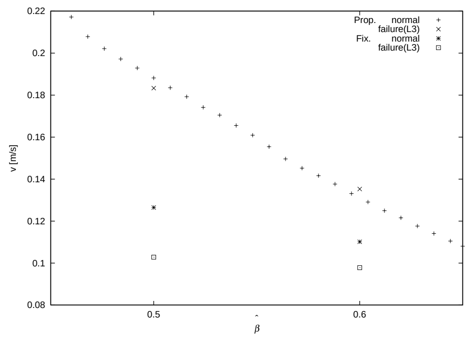


Fig. 9. Locomotion velocity (Failure mode)

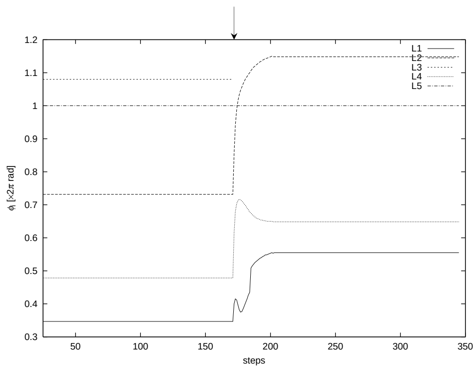


Fig. 10. Phase differences of oscillators with the oscillator of module 5 (Failure mode, $\hat{\beta} = 0.5$)