Decentralized Autonomous Control of a Quadruped Locomotion Robot using Oscillators

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Abstract

This paper deals with the design of a control system for a quadruped locomotion robot. The proposed control system is composed of a leg motion controller and a gait pattern controller describing a hierarchical architecture. The leg motion controller drives the actuators at the joints of the legs using high-gain local feedback control. It receives the commanded signal from the gait pattern controller. The gait pattern controller, on the other hand, involves nonlinear oscillators. These oscillators interact with each other through the signals from the touch sensors located at the tips of the legs. Various gait patterns emerge through the mutual entrainment of these oscillators. As a result, the system walks stably in a wider velocity range by changing its gait patterns and holding the increase of energy consumption of actuators. The performance of the proposed control system is verified by numerical simulations.

1 Introduction

Locomotion is one of the basic functions of a mobile robot. Using legs is one of the strategies for accomplishing locomotion. Although simpler forms of locomotion such as wheels can be easier to design and control, using legs for locomotion allows the robot to move on rough terrain, and therefore improves access to many locations. Therefore, a considerable amount of research has been done on motion control of legged locomotion robots. This paper deals with the motion control of a quadruped locomotion robot.

Several gait patterns can be considered for quadruped locomotion robots. The gait pattern in which any combinations of three legs of the robot support the main body at any instant during locomotion is called walk pattern. For low velocities in which the inertia effect is small enough, the walk pattern is statically stable in terms of the dynamics of the robot mechanism. However, if the velocity of locomotion increases, the locomotion of the robot becomes unstable. On the other hand, the gait patterns in which two legs of the robot support the main body at any instant during locomotion are called trot or pace patterns. These patterns are statically unstable, and it is difficult for the robot to sustain a stable locomotion at low velocities. However, at higher velocities, the robot can sustain stable locomotion with the trot pattern by using its inertia effectively. Designing a control system for realizing stable locomotion by changing the gait pattern to adapt to the desired velocity or to the properties of the environment is a subject of the research in motion control of the quadruped locomotion robot.

There are two ways to design the control system of the robot, top down approach and bottom up approach. The top down approach to design the control system is based on control theory. The design of the trajectories of the legs and the gait patterns are implemented through optimization based on the inverse model of the robot. By eliminating nonlinear dynamics such as Coriolis forces with the computed torque method and the nonlinear feedback method, etc[1,2], the motion controllers are designed based on the linearized model. The control system designed by the top down approach is the model-based control system and then is not always robust against the change of the dynamic states of the system or the physical properties of the environment. On the other hand, the bottom up approach to design the control system is based on the animal behavioral sciences [3~6]. The animal behavioral science teaches us that animals make the legs repeat a forward and backward motion periodically if the legs have no mechanical interaction with the ground and that animals have touch sensors at the tips of the legs and motions of the legs interact with each other through the input signals from the touch sensors. These interactions modify the phase relations of periodic motions of the legs appropriately. As a result, a gait pattern that can satisfy the requirements of the locomotion velocity or the properties of the environment emerges. The bottom up approach design is performed in the following way: First, we introduce nonlinear oscillators in the leg motion controllers and determine the periodic motion of the legs as functions of the phase of the oscillators. Next, we design the local feedback controllers of the legs that use the nominal motions of the legs as reference signals. On the other hand, we determine the dynamic interactions among the nonlinear oscillators so that they interact with each other through the input signals from the touch sensors at the tips of the legs. The phase differences among the nonlinear oscillators emerge through the mutual entrainments of the oscillators. As a result, the proposed control system is expected to generate adequate and stable gait patterns corresponding to the dynamic states of the system or to the physical properties of the environment.

Control systems based on the bottom up approach design have already been applied to the locomotion of hexapod robots in some research. In such research, it has been shown that the control system can adaptively generate the adequate gait patterns corresponding to the system states or to the variations of the environment. The efficiency of the control system was also verified by hardware experiments[7]. On the other hand, there is only a small amount of research based on the bottom up approach that deals with the control system of a quadruped locomotion robot[8].

This paper deals with the design method of the control system of a quadruped locomotion robot based on the bottom up approach. The proposed control system has a hierarchical architecture. It is composed of the leg motion controller and the gait pattern controller. The leg motion controller drives the actuators of the legs by using local feedback control. The gait pattern controller involves non linear oscillators. Various gait patterns emerge through the mutual entrainment of these oscillators. The performance of the proposed control system is verified by numerical simulations.

2 Equations of Motion

Consider the quadruped locomotion robot shown in Fig. 1, which has four legs and a main body. Each leg is composed of two links which are connected to each other through a one degree of freedom (DOF) rotational joint. Each leg is connected to the main body through a one DOF rotational joint. The inertial and main body fixed coordinate systems are defined as $[\boldsymbol{a}^{(-1)}] = [\boldsymbol{a}_1^{(-1)},\ \boldsymbol{a}_2^{(-1)},\ \boldsymbol{a}_3^{(-1)}]$ and $[\boldsymbol{a}^{(0)}] = [\boldsymbol{a}_1^{(0)},\ \boldsymbol{a}_2^{(0)},\ \boldsymbol{a}_3^{(0)}]$, respectively. $\boldsymbol{a}_1^{(-1)}$ and $\boldsymbol{a}_3^{(-1)}$ coincide with the nominal direction of locomotion and vertically upward direction, respectively. Legs are enumerated from leg 1 to 4, as shown in Fig. 1. The joints of each leg are numbered as joint 1 and 2 from the main body toward the tip of the leg. The position vector from the origin of $[\boldsymbol{a}^{(-1)}]$ to the origin of $[\boldsymbol{a}^{(0)}]$ is denoted by $\boldsymbol{r}^{(0)} = [\boldsymbol{a}^{(-1)}]r^{(0)}$. The angular velocity vector of $[\boldsymbol{a}^{(0)}]$ to $[\boldsymbol{a}^{(-1)}]$ is denoted by $\boldsymbol{\omega}^{(0)} = [\boldsymbol{a}^{(0)}]\omega^{(0)}$. We define $\theta_i^{(0)}$ $(i = 1,\ 2,\ 3)$ as the components of 1-2-3 Euler angle from $[\boldsymbol{a}^{(-1)}]$ to $[\boldsymbol{a}^{(0)}]$. We also define $\theta_j^{(i)}$

as the joint angle of link j of leg i. The rotational axis of joint j of leg i is parallel to the $\boldsymbol{a}_2^{(0)}$ axis.

The state variable is defined as follows;

$$q^T = \left[\begin{array}{ccc} r_k^{(0)} & \theta_k^{(0)} & \theta_j^{(i)} \end{array} \right] \tag{1}$$

$$(i = 1, \cdots, 4, \quad j = 1, 2, \quad k = 1, 2, 3)$$

Equations of motion for state variable q are derived using Lagrangian formulation as follows;

$$M\ddot{q} + H(q,\ \dot{q}) = G + \sum(\tau_j^{(i)}) + \Lambda \tag{2}$$

where M is the generalized mass matrix and the term $M\ddot{q}$ expresses the inertia. $H(q,\ \dot{q})$ is the nonlinear term which includes Coriolis forces and centrifugal forces. G is the gravity term. $\sum(\tau_j^{(i)})$ is the input torque of the actuator at joint j of leg i. Λ is the reaction force from the ground at the point where the tip of the leg makes contact. We assume that there is no slip between the tips of the legs and the ground.

3 Locomotion control

The architecture of the proposed control system is shown in Fig. 2. The control system is composed of leg motion controllers and a gait pattern controller. The leg motion controllers drive all the joint actuators of the legs so as to realize the desired motions that are generated by the gait pattern controller. The gait pattern controller involves 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 mutual entrainment of the oscillators with the feedback signals of the touch sensors. The generated gait pattern is given to the leg motion controller as the commanded signal.

3.1 Design of gait

Oscillator i is assigned on leg i. The state of the oscillator i is expressed as follows;

$$z^{(i)} = \exp(j\ \phi^{(i)}) \tag{3}$$

where $z^{(i)}$ is a complex number representing the state of the oscillator, $\phi^{(i)}$ is the phase of the oscillator and j is the imaginary unit.

(i) Design of the leg motions

We design the nominal trajectories of the tips of the legs: First, We define the position of the tip of the leg where the transition from the swinging stage to the supporting stage and the position where the transition from the supporting stage to the swinging stage as the anterior extreme position (AEP) and the posterior extreme position (PEP), respectively. Then, we set the nominal PEP, $\hat{r}_{eP}^{(i)}$ and the nominal AEP, $\hat{r}_{eA}^{(i)}$

in the coordinate system $[\boldsymbol{a}^{(0)}]$ where the index $\hat{*}$ indicates the nominal value. The nominal trajectory for the swinging stage, $\hat{r}^{(i)}_{eF}$ is a closed curve which involves the points $\hat{r}^{(i)}_{eA}$ and $\hat{r}^{(i)}_{eP}$. On the other hand, the nominal trajectory for the supporting stage, $\hat{r}^{(i)}_{eS}$ is a straight line which also involves the points $\hat{r}^{(i)}_{eA}$ and $\hat{r}^{(i)}_{eP}$. These trajectories are given as functions of the phase of the corresponding oscillator. The nominal phase dynamics of the oscillator is defined as follows;

$$\dot{\hat{\phi}}^{(i)} = \omega \tag{4}$$

The nominal phases at AEP and PEP are determined as follows;

$$\hat{\phi}^{(i)} = \hat{\phi}^{(i)}_A \quad \text{at AEP}, \quad \hat{\phi}^{(i)} = \hat{0} \quad \text{at PEP} \tag{5}$$

The nominal trajectories $\hat{r}^{(i)}_{eF}$ and $\hat{r}^{(i)}_{eS}$ are given as functions of the phase $\hat{\phi}^{(i)}$ of the oscillator.

$$\hat{r}^{(i)}_{eF} = \hat{r}^{(i)}_{eF}(\hat{\phi}^{(i)}) \tag{6}$$

$$\hat{r}^{(i)}_{eS} = \hat{r}^{(i)}_{eS}(\hat{\phi}^{(i)}) \tag{7}$$

We use one of these two trajectories alternatively at every step of AEP and PEP to generate the nominal trajectory of the tip of the leg $\hat{r}^{(i)}_e(\hat{\phi}^{(i)})$ as follows(Fig. 3);

$$\hat{r}^{(i)}_e(\hat{\phi}^{(i)}) = \begin{cases} \hat{r}^{(i)}_{eF}(\hat{\phi}^{(i)}) & 0 \le \hat{\phi}^{(i)} < \hat{\phi}^{(i)}_A \\ \hat{r}^{(i)}_{eS}(\hat{\phi}^{(i)}) & \hat{\phi}^{(i)}_A \le \hat{\phi}^{(i)} < 2\pi \end{cases} \tag{8}$$

The nominal duty ratio $\hat{\beta}^{(i)}$ for leg i is defined to represent the ratio between the nominal time for the supporting stage and the period of one cycle of the nominal locomotion.

$$\hat{\beta}^{(i)} = 1 - \frac{\hat{\phi}_A^{(i)}}{2\pi} \tag{9}$$

The nominal stride$\hat{S}^{(i)}$ of leg i and the nominal locomotion velocity $\hat{v}$ are given as follows;

$$\hat{S}^{(i)} = \hat{r}_{eA}^{(i)} - \hat{r}_{eP}^{(i)} \ , \qquad \hat{v} = \frac{\hat{S}^{(i)}}{\hat{\beta}^{(i)}\hat{T}} \tag{10}$$

where, $\hat{T}$ is the nominal time period for a locomotion cycle.

(ii) Design of the gait pattern

We design the gait patterns, which are the relationships between motions of the legs. There are three gait patterns in which two legs support the main body at any instant during locomotion: In the trot pattern, legs 1 and 3 form one pair and legs 2 and 4 form the other pair, in the pace pattern, legs 1 and 2 form one pair and legs 3 and 4 form the other pair, finally in the bounce pattern, legs 1 and 4 form one pair and legs 2 and 3 form the other pair. In such patterns, the phase difference of oscillators in a pair is zero, and the phase difference between the pairs is π.

On the other hand, there are two gait patterns in which tree legs support the main body at any instant during locomotion; One is transverse walk in which the legs 1,3,2 and 4 touch on the ground in this order and the other is rotary walk in which legs 1,2,3 and 4 touch on the ground in this order. Figure 4 shows the gait pattern diagrams of trot and transverse walk where the thick solid lines represent supporting stages.

Each pattern is represented by a matrix of phase differences $\Gamma_{ij}^{(m)}$ as follows;

$$\phi^{(j)} = \phi^{(i)} + \Gamma_{ij}^{(m)} \tag{11}$$

where, $m = 1, 2$ represent transverse walk pattern and rotary walk pattern, respectively. $m = 3, 4, 5$ represent trot pattern, pace pattern and bounce pattern, respectively.

3.2 Control of gait

(i) Leg motion controller

The angle $\hat{\theta}_j^{(i)}$ of joint j of leg i is derived from the geometrical relationship between the trajectory $\hat{r}_e^{(i)}(\hat{\phi}^{(i)})$ and is written as a function of phase $\hat{\phi}^{(i)}$ as follows;

$$\hat{\theta}_j^{(i)} = \hat{\theta}_j^{(i)}(\hat{\phi}^{(i)}) \tag{12}$$

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

$$\tau_j^{(i)} = K_{Pj}(\hat{\theta}_j^{(i)} - \theta_j^{(i)}) + K_{Dj}(\dot{\hat{\theta}}_j^{(i)} - \dot{\theta}_j^{(i)}) \tag{13}$$

$$(i = 1, \cdots, 4, j = 1, 2)$$

where $\tau_j^{(i)}$ is the actuator torque at joint j of leg i, and K_{Pj}, K_{Dj} are the feedback gains, the values of which are common to all joints in all legs.

(ii) Gait pattern controller

We design the phase dynamics of oscillator i as follows;

$$\dot{\phi}^{(i)} = \omega + g_1^{(i)} + g_2^{(2)} \qquad (i = 1,\ \cdots,\ 4) \tag{14}$$

where $g_1^{(i)}$ is the term which is derived from the nominal gait pattern and $g_2^{(i)}$ is the term caused by the feedback signal of the touch sensors of the legs.

Function $g_1^{(i)}$ is designed in the following way: We define the following potential function.

$$V(\phi^{(i)},\ \Gamma^{(m)}) = \frac{1}{2} K \sum_i \left(\phi^{(i)} - \phi^{(j)} - \Gamma_{ij}^{(m)} \right)^2 \tag{15}$$

where matrix of phase differences $\Gamma_{ij}^{(m)}$ represents the commanded gait pattern defined in Eq.(11). Then, function $g_1^{(i)}$ is derived from the potential function V as follows;

$$g_1^{(i)} = -K \left(\phi^{(i)} - \phi^{(j)} - \Gamma_{ij}^{(m)} \right) \tag{16}$$

Function $g_2^{(i)}$ is designed in the following way: Suppose that $\phi_A^{(i)}$ is the phase of leg i at the instant when leg i touches on the ground. Similarly, $r_{eA}^{(i)}$ is the position of leg i at that instance. When leg i touches the ground, the following procedure is undertaken.

1. Change the phase of the oscillator for leg i from $\phi_A^{(i)}$ to $\hat{\phi}_A^{(i)}$.

2. Alter the nominal trajectory of the tip of leg i from the swinging trajectory $\hat{r}_{eF}^{(i)}$ to the supporting trajectory $\hat{r}_{eS}^{(i)}$.

3. Replace parameter $\hat{r}_{eA}^{(i)}$, that is one of the parameters of the nominal trajectory $\hat{r}_{eS}^{(i)}$, with $r_{eA}^{(i)}$.

Function $g_2^{(i)}$ is given as follows:

$$g_2^{(i)} = \hat{\phi}_A^{(i)} - \phi_A^{(i)} \quad \text{at the instant leg } i \text{ touches the ground} \tag{17}$$

The oscillators form a dynamic system that affect each other through two types of interactions. One is continuous interactions derived from the potential function V which depends on the nominal gait pattern. The other is the pulse-like interactions caused by the feedback signals from the touch sensor. Through these interactions, the oscillators generate gait patterns that satisfy the requirements of the environment.

4 Stability of locomotion

The steady locomotion of the quadruped locomotion robot is periodic and is characterized by a limit cycle in the state space.

The stability of the limit cycle is examined in the following way: First, four variables are selected as state variables.

$$X \in R^4, \quad X = \begin{bmatrix} \theta_1^{(0)} & \theta_2^{(0)} & \dot{\theta}_1^{(0)} & \dot{\theta}_2^{(0)} \end{bmatrix} \tag{18}$$

The variables $\theta_1^{(0)}$, $\theta_2^{(0)}$ are roll and pitch angles of the main body. When the robot starts the locomotion under a certain initial condition, the variable set X moves on a certain trajectory in the four-dimensional state space. If we choose a Poincaré section using the timing when the tip of one leg touches the ground, the first intersection of the trajectory of X with the Poincaré section is mapped as X_0, and for every intersection, the corresponding values of X lead to a sequence of iterates in the state space.

$$X_1 \quad X_2 \quad \cdots \quad X_n \quad \cdots$$

The Poincaré map from X_n to X_{n+1} is expressed as follows;

$$X_{n+1} = F(X_n) \tag{19}$$

The fixed point $\bar{X}$ is defined such that $\bar{X}$ satisfies the following equation on the Poincaré section and expresses a limit cycle.

$$\bar{X} = F(\bar{X}) \tag{20}$$

This Poincaré map is approximated by use of linearization around the fixed point.

$$X_{n+1} - \bar{X} = M(X_n - \bar{X}) \tag{21}$$

Stability of the sequence of points $\{X_n\}$ is examined by checking the eigen values λ_k $(k = 1, \cdots, 4)$ of matrix M.

5 Numerical Analysis

Table 1 shows the physical parameters of the robot which are used in the numerical analysis.

Numerical simulations are carried out under the condition that the nominal stride $\hat{S}$ is set to be 0.10 [m] and the commanded gait patterns $\Gamma^{(m)}$ are fixed to be $\Gamma^{(1)}$, transverse walk and $\Gamma^{(3)}$, trot. The nominal time period of the swinging stage is chosen as 0.20 [sec]. The nominal duty ratio $\hat{\beta}$ is selected as a parameter.

The frequency band width of joints 1, 2 are given as 5.5 [Hz] and 9.5 [Hz] for feedback gains of the joints, respectively.

We investigated the performance of the model-based control system through numerical simulation as a comparison with the performance of our system. The model-based control system is designed in the following way: The trajectories of the legs are given as functions of time corresponding to the commanded gait pattern. The actuators of the joints are controlled by using feedback control with the desired joint angles as the reference signals.

First, we investigated stability of the proposed control system, selecting duty ratio $\hat{\beta}$ as a parameter. Figure 5 shows the stability of the period-one gait, the largest eigenvalue modulus of matrix M, Eq.(21) associated with the fixed point of the Poincaré map, Eq. (20). CASE 1 and 2 indicate the model based control system and the proposed control system, respectively. In the figures, region "period-one gait" is the region where the walking solution with period-one gait exists. One the other hand, region "other gaits" is the region where the robot walks with other periodic or non periodic gaits and region "tumble" is the region where the robot can not walk and falls down. From these figures, we can find that the proposed control system established stable locomotion of the robot with a wide parameter variance for duty ratio $\hat{\beta}$.

Variance of energy consumption of actuators E_c is investigated, selecting duty ratio $\hat{\beta}$ as a parameter. Energy consumption of actuators E_c is defined as follows;

$$E_c = \frac{< \sum_{i,j} \tau_j^{(i)} \theta_j^{(i)} >}{< v >} \tag{22}$$

where, $< * >$ expresses the time averaged value of $*$. The results are shown in Fig. 6. From Fig. 6, we can see that the values of E_c of the proposed control system are smaller than those of the model-based control system. The increase of E_c is held with repeat to the variance of duty ratio β.

In order to clarify how the proposed control system adapts to the change of the environment, we investigated variance of the gait patterns, selecting duty ratio $\hat{\beta}$ as a parameter. We investigated the variance of the gait pattern according to duty ratio in the following way: The states of leg i are represented by introducing the variable $\zeta^{(i)}$ as follows;

$$\zeta^{(i)} = \begin{cases} \dfrac{1}{1-\beta} & \text{Swinging stage} \\ -\dfrac{1}{\beta} & \text{Supporting stage} \end{cases} \tag{23}$$

Correlation between the swinging or supporting states of leg i and those of leg j is defined as follows;

$$W_{ij} = < \zeta^{(i)} \zeta^{(j)} > \tag{24}$$

Each gait pattern is characterized by correlation matrix W. Matrices $\hat{W}^{(m)}$ and W are the correlation matrices according to the nominal gait pattern $\Gamma^{(m)}$ and the actually obtained gait pattern, respectively. The similarity between these two gait patterns is defined as follows;

$$D^{(m)} = \frac{1}{4} trace(\hat{W}^{(m)T} W) \qquad (25)$$

Figure 7 shows the similarity of gait patterns $D^{(m)}$ with respect to duty ratio $\hat{\beta}$. From Fig. 7 (a), we can find that although trot pattern is given as the nominal gait pattern, similarity between the obtained gait pattern and transverse walk pattern $D^{(1)}$ increases as duty ratio $\hat{\beta}$ increases. To the contrary, from Fig. 7 (b), we can see that the gait pattern does not change from the given gait pattern when we use a model-based control system.

Gait pattern diagrams for $\hat{\beta} = 0.5$ and $\hat{\beta} = 0.75$ are shown in Fig. 8.

From these results, it is clear that the robot using the proposed control system adapts to variance of duty ratio $\hat{\beta}$ by changing the gait patterns, keeps the stability of locomotion in a wide parameter area, and holds the increase of energy consumption of the actuator.

6 Conclusions

We proposed a control system for a walking robot with a hierarchical architecture which is 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 high-gain local feedback based on the commanded signal from the gait pattern controller. Whereas the gait pattern controller alternates the motion primitives by synchronizing with the signals from the touch sensors at the tips of the legs, and stabilizes the phase differences among the motions of the legs adaptively. In this paper, the nominal gait pattern is given as the command. In the future, we are planning to design the control system in which the nominal gait pattern is selected or generated according to the state of the robot. Using such a control system, it is expected that adaptability of the robot to variations of the environment will be highly improved.

Acknowledgments

The authors were funded by grants from the The Japan Society for the Promotion of Science (JSPS) as the Research for the Future program (RFTF) and from the Japan Science and Technology Corporation (JST) as the Core Research for Evolutional Science and Technology program (CREST).

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Table 1

Main body		
Width	0.182	[m]
Length	0.338	[m]
Height	0.05	[m]
Total Mass	9.67	[kg]

Legs		
Length of link 1	0.188	[m]
Length of link 2	0.193	[m]
Mass of link 1	0.918	[kg]
Mass of link 2	0.595	[kg]

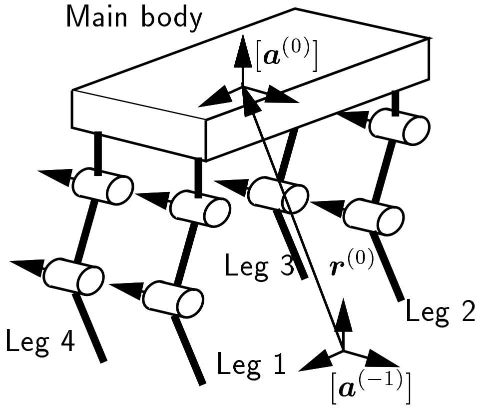


Figure 1: Schematic model of a quadruped locomotion robot

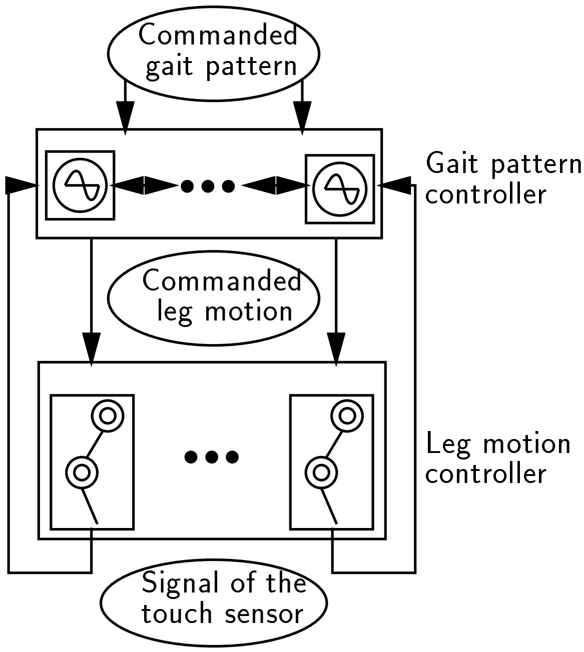


Figure 2: Architecture of the proposed controller

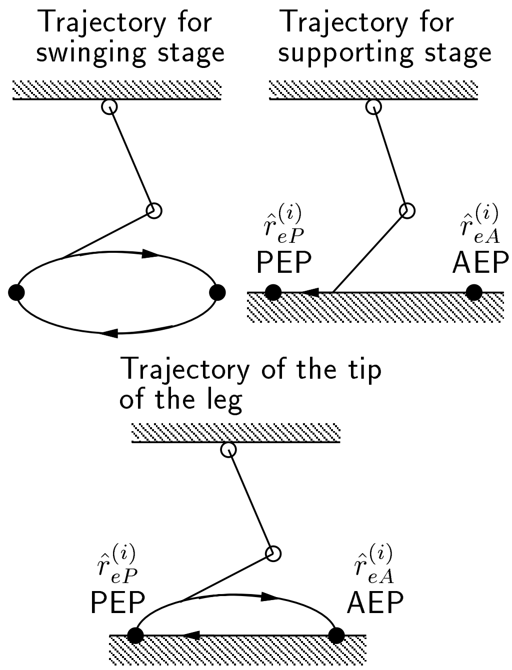


Figure 3: Nominal trajectory of the tip of the leg

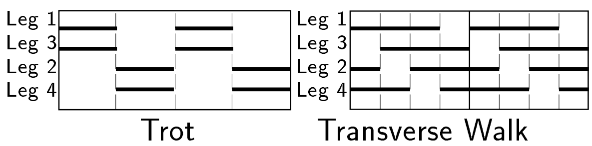
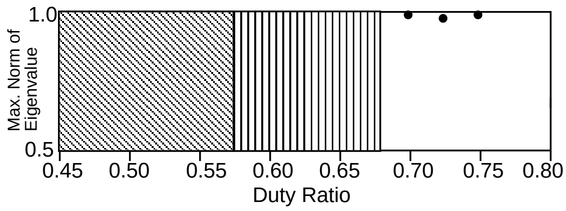
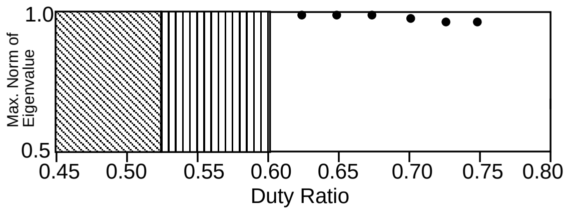


Figure 4: Gait pattern diagram

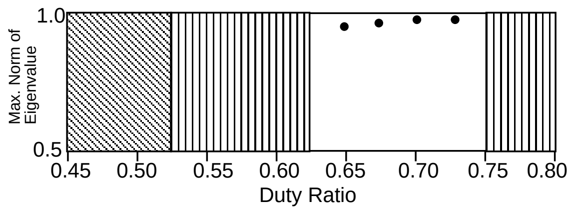


CASE 1

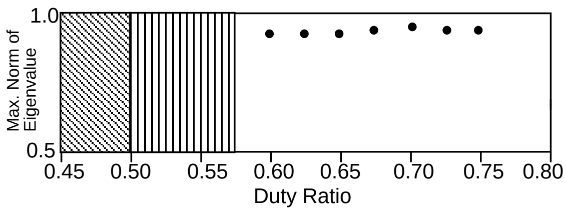


CASE 2

(a) Commanded pattern: Transverse walk



CASE 1



CASE 2

(b) Commanded pattern: Trot

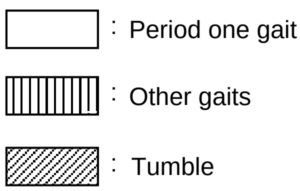


Figure 5: Stability of locomotion

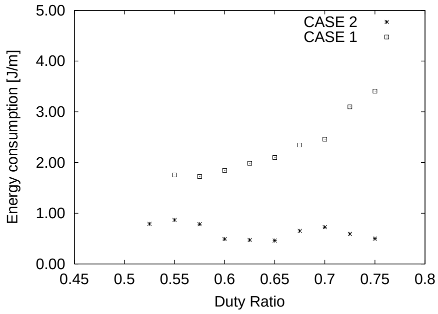
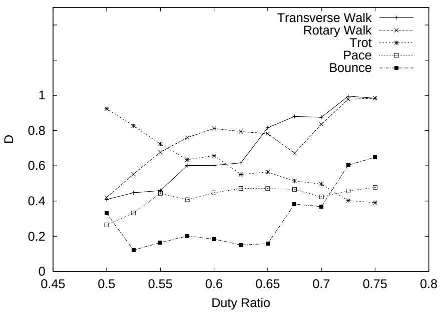
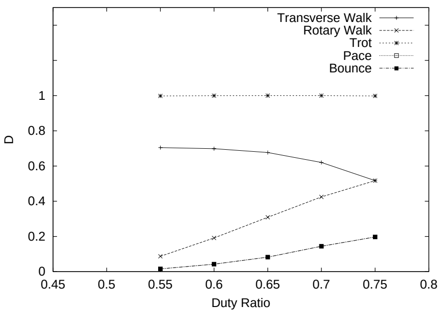


Figure 6: Energy consumption E_c

Commanded pattern: Trot



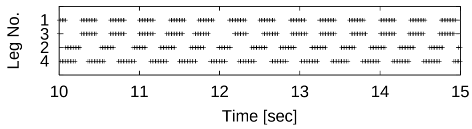
(a) CASE 2



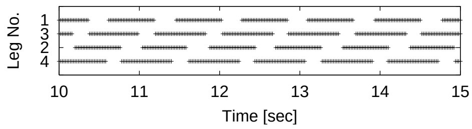
(b) CASE 1

Figure 7: Similarity of gait pattern $D^{(m)}$

Commanded pattern: Trot



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



(b) $\hat{\beta} = 0.75$

Figure 8: Gait pattern diagram (CASE 2)

Commanded pattern: Trot