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Toward a "Well-balanced" Design: A Robotic Case Study
— How should Control and Body Dynamics be Coupled? —

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Abstract

Over the past decade, it has been widely recognized that the emergence of intelligence is strongly influenced by not only control systems but also their embodiments, that is the physical properties of robots' structure. This implies that the control dynamics and its body dynamics cannot be designed separately due to their tight interdependency, which is significantly different from the traditional design approach on a "hardware first, software last" basis. Now a question arises: how should these two dynamics be coupled?; what sort of phenomena will emerge under the so-called "well-balanced" design? In spite of its importance, to our knowledge, still very few studies have explicitly investigated this mutual interaction. In light of these facts, this study is intended to deal with the interaction dynamics between control and mechanical systems, and to analytically and synthetically discuss "relationship as it should be" between the two dynamics. To this end, a decentralized control for a multi-legged robot is employed as a practical example. The result derived indicates that the convergence of decentralized gait control can be significantly ameliorated by modifying its interaction dynamics between the control and mechanical systems to be implemented.

1. Introduction

In robotics, traditionally, a so-called *hardware first, software last* based design approach has been employed, which seems to be still dominant. Recently, however, it has been widely accepted that the emergence of intelligence is strongly influenced by not only control systems but also their embodiments, that is the physical properties of a robots' body[1]. In other words, the intelligence emerges through the interaction dynamics among the control systems(*i.e.* brain-nervous systems), the embodiments(*i.e.* musculo-skeletal systems), and their environment(*i.e.* ecological niche). In sum, control dynamics and its body(*i.e.* mechanical) dynamics cannot be designed separately due to their tight interdependency. This leads to the following conclusions: (1) there should be a "*best combination*" or a "*well-balanced coupling*" between control and body dynamics, and (2) one can expect that quite an interesting phenomenon will emerge under such well-balanced coupling.

On the other hand, since the seminal works of Sims[2][3], so far various methods have been intensively investigated in the field of Evolutionary Robotics by exploiting concepts such as *co-evolution*, in the hope that they allow us to simultaneously design control and body systems[4][5]. Most of them, however, have mainly focused on automatically creating both control and body systems, and thus have paid less attention to gain an understanding of well-balanced coupling between the two dynamics. To our knowledge, still very few studies have explicitly investigated this point(*i.e.* appropriate coupling)[1].

In light of these facts, this study is indended to deal with the interaction dynamics between control and body systems, and to analytically and synthetically discuss a well-balanced relationship between the dynamics of these two systems. More specifically, the aim of this study is to clearly answer the following questions:

- how should these two dynamics be coupled?
- what sort of phenomena will emerge under the well-balanced coupling?

[1]Pfeifer introduced several useful design principles for constructing autonomous agents[1]. Among them "*the principle of ecological balance*" does closely relate to this point, which states that control systems, body systems and their material to be implemented should be balanced. However, there still remains much to be understood about how these systems should be coupled.

Since there are virtually no studies in existence which discuss what the well-balanced coupling is, it is of great worth to accumulate various case studies at present. Based on this consideration, a decentralized control of a multi-legged robot consisting of several body segments is employed as a practical example. The derived result indicates that the convergence of decentralized gait control can be significantly ameliorated by modifying both control dynamics(*e.g.* information pathways among the body segments) and body dynamics(*e.g.* stiffness of the spine) to be implemented.

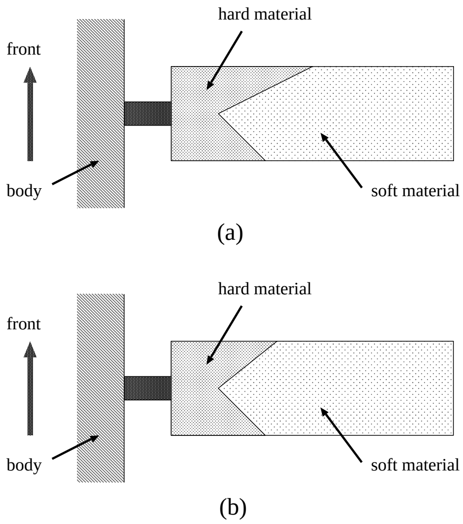


Figure 1: Material configuration in insects' wings.

2. Lessons from Biological Findings

Before explaining our approach, it is highly worthwhile to look at some biological findings. Beautiful instantiations of well-balanced couplings between nervous and body systems can be found particularly in insects. In what follows, let us briefly illustrate some of these instantiations.

Compound eyes of some insects such as houseflies show special *facet* (*i.e.* vision segment) distributions; the facets are densely spaced toward the front whilst widely on the side. Franceschini *et. al.* demonstrated with a real physical robot[2] that this non-uniform layout significantly contributes to detect easily and precisely the movement of an object without increasing the complexity of neural circuitry[6].

Another elegant instantiation can be observed in insects' wing design[9][10]. As shown in Fig.1(a), very roughly speaking, insects' wings are composed of hard and soft materials. It should be noted that the hard material is distributed asymmetrically along the moving direction. Due to this material configuration, insects' wings show complicated behavior during each stroke cycle, *i.e.*, twist and oscillation. This allows them to create useful aerodynamic force, and thus they can realize agile flying. If they had symmetrical material configuration as shown in Fig.1(b), the complexity of neural circuitry responsible for flapping control would be significantly increased.

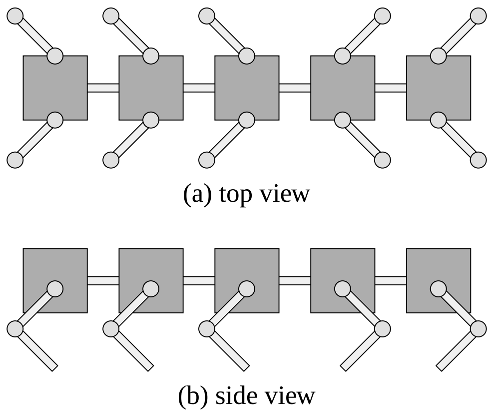


Figure 2: Structure of the multi-legged robot.

3. The Model

In order to investigate *well-balanced coupling as it should be* between control and body systems, a decentralized control of a multi-legged robot is taken as a case study. Figure 2 schematically illustrates the structure of the multi-legged robot. As shown in the figure, this robot consists of several identical body segments, each of which has two legs, *i.e.*, right and left legs. For simplicity, the right and left legs of each body segment are allowed to move in phase, and the duty factor and trajectory of all the legs are assumed to be identical, which have to be prespecified before actually moving the robot. For convenience, hereafter the phase of the leg movement of the ith body segment is denoted as θ_i ($i = 1, 2, \cdots, n$). Thus, the control parameters in this model end up to be the set of the phases $\theta_1, \theta_2, \cdots, \theta_n$.

The task of this robot is to realize rapid gait convergence which leads to a gait with minimum energy consumption rate from arbitrary initial relative-phase conditions. Note that each body segment controls the phase of its own legs in a decentralized manner, which will be explained in more detail in the following section.

[2] Another interesting robot can be found in [7][8].

4. Proposed Method

4.1. Analysis of the gait convergence

Based on the above arrangements, this section analytically discusses how the control and body dynamics influence the gait convergence. Let P be the total energy consumption rate of this robot, then P can be expressed as a function of the phases as:

$$P = P(\boldsymbol{\theta}), \quad (1)$$
$$\boldsymbol{\theta} = (\theta_1, \theta_2, \cdots, \theta_n)^T. \quad (2)$$

Here, for purposes of simplified analysis, a simple learning scheme based on a *steepest descent method* is employed. It is denoted by

$$\Delta\boldsymbol{\theta}^{(k)} = -\boldsymbol{\eta}\frac{\partial P(\boldsymbol{\theta})}{\partial\boldsymbol{\theta}}\bigg|_{\boldsymbol{\theta}^{(k)}}, \quad (3)$$

where $\Delta\boldsymbol{\theta}^{(k)}$ is the phase modification at time step k, $\boldsymbol{\eta}$ is an $n\times n$ matrix which specifies how a body segment will exploit the information about phase modification done in other body segments in its determination of the phase modification. Based on Equation (3), the set of the phases at time step k is expressed in the following form:

$$\boldsymbol{\theta}^{(k+1)} = \boldsymbol{\theta}^{(k)} + \Delta\boldsymbol{\theta}^{(k)} = \boldsymbol{\theta}^{(k)} - \boldsymbol{\eta}\frac{\partial P(\boldsymbol{\theta})}{\partial\boldsymbol{\theta}}\bigg|_{\boldsymbol{\theta}^{(k)}}. \quad (4)$$

Let $\boldsymbol{\theta}^{(\infty)}$ be a set of converged phases. By performing the Taylor series expansion around $\boldsymbol{\theta}^{(\infty)}$, the partial differentiation of $P(\boldsymbol{\theta})$ with respect to $\boldsymbol{\theta}$ is:

$$\frac{\partial P(\boldsymbol{\theta})}{\partial\boldsymbol{\theta}} \simeq \boldsymbol{C}(\boldsymbol{\theta} - \boldsymbol{\theta}^{(\infty)}), \quad (5)$$
$$\boldsymbol{C} = \frac{\partial^2 P(\boldsymbol{\theta})}{\partial\boldsymbol{\theta}\partial\boldsymbol{\theta}}\bigg|_{\boldsymbol{\theta}^{(\infty)}}, \quad (6)$$

where $\boldsymbol{C}$ is an $n \times n$ *Hesse* matrix. Hence, the substitution of Equation (5) into Equation (4) yields:

$$\boldsymbol{\theta}^{(k+1)} = \boldsymbol{\theta}^{(k)} - \boldsymbol{\eta}\boldsymbol{C}(\boldsymbol{\theta}^{(k)} - \boldsymbol{\theta}^{(\infty)}). \quad (7)$$

For the sake of the following discussion, a *residual vector* $\boldsymbol{e}^{(k)}$ is introduced, which is equivalent to $\boldsymbol{\theta}^{(k)} - \boldsymbol{\theta}^{(\infty)}$. Then, Equation (7) can be rewriten as:

$$\boldsymbol{e}^{(k+1)} = \boldsymbol{A}\boldsymbol{e}^{(k)}, \quad (8)$$
$$\boldsymbol{A} = \boldsymbol{I} - \boldsymbol{\eta}\boldsymbol{C}, \quad (9)$$

where $\boldsymbol{I}$ is an $n \times n$ unit matrix.

4.2. Physical meaning of η and C

$\boldsymbol{A}$ in Equation (8) is a matrix which characterizes the property of gait convergence. This will automatically lead to the following fact: for rapid convergence, the matrix $\boldsymbol{A}$ has to be a *strictly diagonally dominant matrix* which ensures its spectral radius being less than 1.0. The definition of a strictly diagonally dominat matrix can be found in the appendix listed below.

What should be stressed here is the fact that as shown in Equation (9) the matrix $\boldsymbol{A}$ is composed of the two matrices: $\boldsymbol{\eta}$ and $\boldsymbol{C}$. As has been already explained, the matrix $\boldsymbol{\eta}$ specifies the information pathways (or neuronal/axonal interconnectivity) among the body segments, which will be used to calculate the phase modification. This implies that the matrix $\boldsymbol{\eta}$ does relate to the design of the control dynamics.

On the other hand, obviously from the definition(see Equation (6)), $\boldsymbol{C}$ is a matrix whose nondiagonal elements will be salient as the *long-distance interaction* among the body segments through the physical connections(*i.e.* the spine of the robot) becomes significant. This strongly suggests that the property of this matrix is highly influenced by the design of the body dynamics.

4.3. An effective design of the body dynamics

The design of the control dynamics can be easily done by tuning the elements of the matrix $\boldsymbol{\eta}$. In contrast, much attention has to be paid to the design of the body dynamics. This is simply because one cannot *directly* access the elements of the matrix $\boldsymbol{C}$ nor tune them unlike the matrix $\boldsymbol{\eta}$.

Before introducing our proposed method, let us briefly conduct a simple yet instructive thought experiment. Imagine a multi-legged robot in which its body segments are tightly connected via a *rigid* spine. In such a case, the phase modification of a certain leg will significantly affect the energy consumption rate of distant legs due to the effect of the "long-distance interaction".

As has been demonstrated in the thought experiment mentioned above, the *stiffness* of the spine poses serious influence on the property of the matrix $\boldsymbol{C}$, particularty the values of its nondiagonal elements. Therefore, it seems to be reasonable to connect the body segments via a *springy* joint. This idea is schematically illustrated in Fig. 3, in which only the two body segments are shown for clarity.

Based on the above consideration, a well-balanced design is investigated by tuning the parameters in the matrix $\boldsymbol{\eta}$ and the ones of the springs inserted among the body segments, which will lead to a reasonable gait convergence.

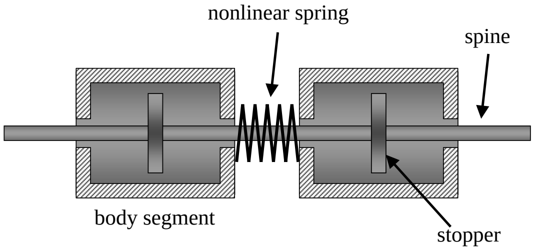


Figure 3: An effective structure for adjusting the body dynamics.

5. Result

5.1. Preliminary experiments

In order to efficiently investigate well-balanced coupling, a simulator has been developed. The following simulations have been conducted with the use of a physics-based, three-dimensional simulation environment[11]. A view of the developed simulator is shown in Fig. 4. This environment simulates both the internal and external forces acting on the agent and objects in its environment, as well as various other physical properties such as contact between the agent and the ground, and torque applied by the motors to the joints within an acceptable time limit.

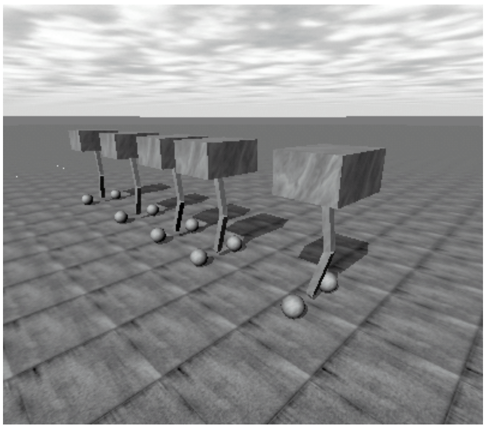


Figure 4: A view of the developed simulator.

Before carrying out a thorough search of the design parameters, a preliminary experiment has been done to understand the influence of the two dynamics on the gait convergence. In this experiment, the property of the spring inserted among the body segments is assumed to be expressed as:

$$f = -k(\Delta x)^{\alpha}, \tag{10}$$

where f is the resultant force, k is a spring constant, α controls the degree of the nonlinearity of the spring, and Δx is a displacement.

Shown in Fig. 5 are the resultant data in this experiment; the vertical axis denotes the total energy consumption rate whilst the horizontal axis depicts the number of modification of the phases conducted. Note that each graph was obtained by averaging over 10 different initial relative-phase conditions. As a rudimentary stage of the investigation, only α was varied under the following conditions: the number of the body segments was 5; duty factor 0.65; k 1.0; and $\boldsymbol{\eta}$ set to

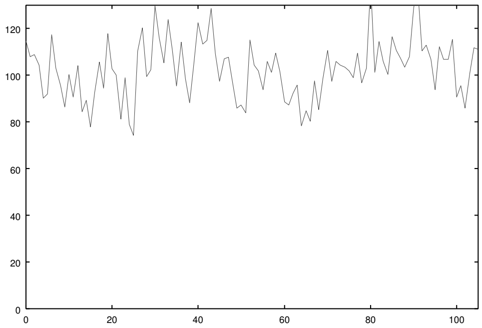
$$\begin{pmatrix} 0.005 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.005 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.005 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.005 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.005 \end{pmatrix}.$$

5.2. Discussion

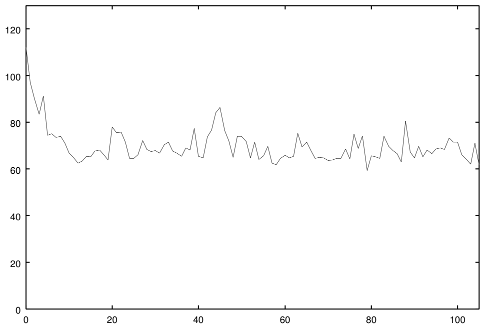
As shown in Fig. 5, the gait convergence is highly influenced by the parameter α. This is due to the fact that the long-distance interaction among the body segments depends on α, which leads to varying the property of the matrix $\boldsymbol{C}$. In spite of the simplicity, these results strongly support the conclusion that the body dynamics imposes significant influence on the gait convergence.

6. Conclusion

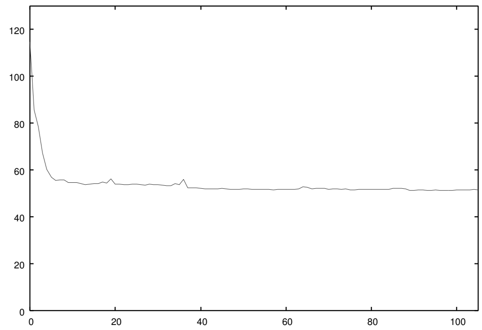
This paper investigated *well-balanced coupling as it should be* between control and body systems. For this purpose, a decentralized control of a multi-legged robot was employed as a case study. The preliminary experiments conducted in this paper support several conclusions and have clarified some interesting phenomena for further investigation, which can be summerized as: first, control and body dynamics significantly influence the gait convergence; second, well-balanced design in this case study can be analytically discussed in terms of a strictly diagonally dominant matrix; third and finally, as demonstrated in the preliminary experiments, the property of the gait convergence can be tuned by varying the dynamics experimentally, which suggests that there should be an appropriate coupling between the two systems.



(a) $\alpha = 0.25$



(b) $\alpha = 0.5$



(c) $\alpha = 3.0$

Figure 5: Preliminary simulation results.

In order to gain a deep insight into what well-balanced coupling is and should be, an intensive search of the parameters in the control and body systems is highly indispensable. For this purpose, it seems to be reasonable to implement an *evolutionary computation scheme* such as a genetic algorithm to efficiently search these parameters. This is currently under investigation.

Another important point to be stressed is closely related to the concept of *emergence*. One of the crucial aspects of intelligence is the *adaptability* under hostile and dynamically changing environments. How can such a remarkable ability be achieved under limited/finite computational resources? One and the only solution would be to exploit *emergence phenomena* created by the interaction dynamics among control, body systems, and their environment. This research is a first step to shed some light on this point in terms of balancing control systems with their body systems.

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Appendix A

If a matrix $\boldsymbol{A}$

$$\boldsymbol{A} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix}$$

satisfies with the following conditions, then this matrix will be called a strictly diagonally dominant matrix.

$$|a_{ii}| > \sum_{\substack{j=1 \\ j \neq i}}^{n} |a_{ij}| \quad (1 \leq i, j \leq n)$$

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