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Purposive Locomotion of Insect in Indefinite Environment

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Abstract

There are many scientific and technological problems that we cannot deal with today. Our current scientific methodology cannot be applied to what is called the real world problem. Because the real world is unpredictably and dynamically changing, it is impossible to objectify it in advance and to apply the traditional methodology to it. This real world problem especially arises in information processing systems such as the recognition and the control systems coping with the real world. The current information systems request in advance the complete information to deal with.

In the case of robot in the real world, to attain the purpose a robot is usually required to solve the inverse problem adjusting the changes of the real world. It is always an ill-posed problem. When the robot autonomously solves the ill-posed problem, some proper constraints should be self-organized in the robot. In addition to the self-organization of the constraints, the robot is required to satisfy the constraints in real time. Here we propose a new real-time control mechanism for the purposive movements of a robot under the unpredictably changing environment.

1. Introduction

The real world is by far more complicated than what we up until today have been able to clarify fully through the natural sciences. It contains many phenomena that the methodology of the separation of self and other cannot be applied to.When one isolates something, there is always something left. Therefore, there are always intrinsic problems remaining in the parts left over. There are many problems that we cannot deal with today. Since the real world is unpredictably and dynamically changing, it is impossible to objectify it in advance and to apply the traditional methodology to it. Especially this real world problem is crucial in information processing systems, that is, the recognition and the control systems coping with the real world. Since the current information systems could only deal with explicit and complete information, all problems should be defined and formalized in advance. That is, our current methodology could be applied only to a limited problem, which is rigorously objectified in advance, but the real world is not the case.

This difficulty is arisen from the uncertainties of the real world. There are two kinds of uncertainties in the world. One is a definite uncertainty and the other is an indefinite uncertainty. The former is related to the stochastic problem. When the stochastic phase space can be defined but it is enormous large, it is possible to find the solution in principle, but actually impossible to find the solution from its very large phase space. In this sense, it is a definite uncertainty. On the contrary, the real world is essentially indefinite, because it is unpredictably and dynamically changing. So it is impossible to prepare the complete information in advance, indicating an indefinite uncertainty. In the cases of indefinite uncertainty, these are always ill-posed problems. It means that the information processing systems coping with the real world should have the ability to self-emerge the information needed for. I will point out the requirements that the emergent systems should satisfy. The system should be indefinite, which is well known as the law of requisite variety proposed by Ashby. It means that the information system interacting with the complex environment should have more complexity than that of environment. Second, the system should be self-referential, because the necessary information could not be added externally. Finally, the emergence of information might be abduction process. The deductive and the inductive logic can be applicable only for the definite problems.

In order to change the ill-posed problem to the well-posed one, it is necessary some appropriate constraints to make up the incompleteness of the information of the problem. In the traditional methodology, it is possible to add some appropriate constraints externally, if we can objectify the problem in advance. If the pre-assumed world is stationary, this methodology will be powerful and useful. For example, in the case of locomotion, the trajectories are usually determined in advance and then the robot walks along the trajectory by feedback control. Or the locomotive patterns are determined kinematically in advance, one of which is selected depending on the condition of the locomotion. On the contrary, in the real world the system itself should incessantly emerge the necessary constraints in a self-referential way in response to the ever-changing environment and satisfy them at every moment. Here we propose a new paradigm for the purposive locomotion in the real world.

2. Motion control system

Characteristics of animal walking

The motion control systems of animals seem to autonomously create appropriate information depending on the purposes self-organized in the system under the unpredictably changing environment. The motor systems of the animals are generally controlled through three sub-regions in a hierarchical way, the brain, the central pattern generator (CPG) and the effector organs. The flexibility of the movements is generated by the neural network as a control system, indicating that they can organize dynamically their gait patterns quickly in response to the changes of the environment. To coordinate the movements of the muscles in response to the unpredictably changing environments, the control system should be indefinite. Indefinite system means that the properties of the elements of the system and the relationship of them are not specified in advance. If the control system is definite, it is impossible to adapt to the unpredictably changing environment.

Higher centers

Since the decision-making mechanism is far complicated and not clarified sufficiently yet, it is assumed that the instruction of behavior is generated in the higher center of cerebrum. So the higher center of cerebrum can be regarded as the highest constraint generator for motor control. The organized program and instructions in the higher center are the sequence of the purposive direction and the velocity. Although the detail of the mechanism of the higher center is not clarified yet, some physiological experiments indicate that the higher center can be considered as coordinating organ between the purposive movement and posture control. There are parallel pathways from the brain stems to the motoneurons, one of which is directly pathway to motoneurons and the other is the descending to the thoracic ganglion known as the CPG. The former might be thought to adjust the muscle tone to maintain its posture and the latter to contribute the coordination of the muscle movements to attain the purposive behavior. To coordinate the functions between the higher center and the thoracic ganglion, neurotmodulators play profound effects on the organization of the behavioral states by switching a neural network from one operating mode to another. The walking patterns are quickly changed depending on the walking velocities and load [1-6]. In the case of stick insect, at high speed the front leg and the hind move simultaneously and the middle antiphasic to the others, forming a tripod to support their body. On the contrary, when they walk slowly, the three legs of each side move metachronally. A pair of legs of the same segment step alternately. As increasing the walking velocity, the insect changes the patterns critically depending on their velocity, resembled to a phase transition. The walking patterns also vary with the load [1,5,6]. In the case of horse, energy consumption during walking does not depend on the walking distance, but almost on the distance.

Central pattern generator

The thoracic ganglions, as central pattern generators, are an indefinite control system to coordinate between the purposive movements and the unpredictably changing environment, which is well known as the polymorphic circuits or multifunctional circuit [7]. Recently, we have demonstrated that the polymorphic circuits can generate various spatio-temporal patterns using a hardwired model [8]. But the indefinite control system is only one of necessary conditions. To attain the purpose, the proper constraints should be self-organized and fulfilled by the system itself in response to the changes of the purpose and the current environment. These motor control organizations are summarized in Fig. 1.

One of the aims of biological motion is to reach its destination. If more complex purpose such as reaching a destination with a required velocity is imposed on the system, the arrival to the destination takes the priority over all other purposes. The

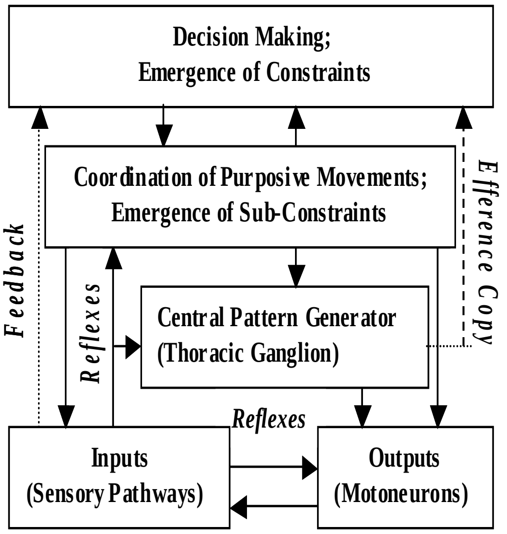

Figure 1: Hierarchical organization of motor control.

velocity of stance phase of right and left side legs is tuned proportional to the angle between the axis of the body and the direction of the destination, which is feed backed until the second time derivative of the angle becomes zero. The velocities of the two sides are given by

$$V_{leg.req} = V_{body} \pm k_1 \theta \pm k_2 \ddot{\theta}. \qquad (1)$$

Insects walk usually at an optimal stride, indicating that they have an optimal anterior and posterior extreme point. From the viewpoint of the balancing constraints, the frequencies of the two sides should be the same. At lower walking velocity, the frequency of the leg motion is almost constant but minimal, showing that its stride increases with the velocity up to the extreme points. Beyond the velocity determined by the minimal frequency and the maximal stride, they quicken the pace to attain the required velocity. In the turning motion at higher velocity, the frequencies of the two sides tend to be different, but the balancing constraint requires the same frequencies of the two sides. In this case we assume that the lower velocity side increase its frequency to its posture, decreasing the stance duration. The tuning of the frequency of the lower velocity side is given by

$$\begin{aligned} \frac{dD_{opt}}{dt} &= D_{max} - (D_{opt} + k_b), && (2) \\ \Delta k_b &= +k_1 && \textit{in unbalanced state}, \\ \Delta k_b &= \begin{cases} -k_2 & k_b \geq 0 \\ 0 & k_b < 0 \end{cases} && \textit{in balanced state}, \end{aligned}$$

This quantity is feedbacked to the rhythmic neuron as follows;

$$\Delta D_R = k_b (D_{opt} - D_{stance}). \qquad (3)$$

So the higher center of brain sends velocities and the frequencies of the two sides to the CPG as the constraints of the purposive movement and posture control.

3. Central Pattern Generator Model

In our model we focus on the walking of insect, so we discuss the control of the motor system after the decision-making, that is, selection of the behavior. The higher center of brain sends the velocities of the both sides of the limbs and their muscle tones as the instructions to CPG after coordinating the purposive movements and the standing posture. In this model the neural network of the control system composed of the higher center of brain and CPG is shown in Fig.2. The CPG send motor outputs to control leg muscles and receive the external afferents as to position, load and force of each muscle. We have already demonstrated in the case of insect walking that the well coordinated motion among the legs is organized not only by the neural system composed of the three ganglion, connected through the inter-segmental connectives, but by the mechanical interaction through the movements of legs. Central pattern generators (CPG) are networks of neurons to control the motor system generating spatio-temporal pattern of neural activities. In this paper, we also construct a coupled nonlinear-oscillator system as the polymorphic network, which can produce various walking pattern by modulating the properties of the composing neurons.

The walking of the insect is controlled by the three thoracic ganglions, prothoracic, mesothoracic and methathoracic ganglions [9]. These ganglions send motor outputs to control leg muscles and receive the external afferents as to position, load and force of each muscle. These ganglions are internally connected each other through a pair of thoracic connectives. It has been clarified that the well coordinated motion among the legs is organized not only by the neural system composed of the three ganglion, connected through the inter-segmental connectives, but by the mechanical interaction through the movements of legs. Central pattern generators (CPGs) are networks of neurons to control the motor system generating spatio-temporal pattern of neu-

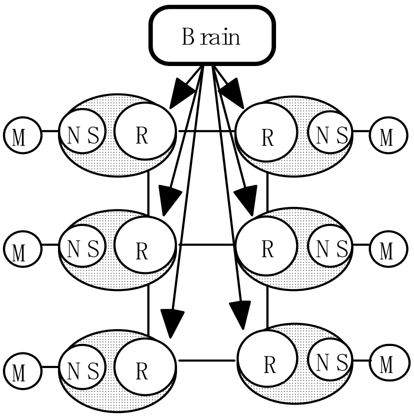

Figure 2: Inter-segmental connection among CPGs.

ral activities. In this paper, we construct a coupled nonlinear-oscillator system as the polymorphic network, which can produce various walking pattern by modulating the properties of the composing neurons.

Inter-segmental inter-neurons in a thoracic ganglion of locust have been extensively investigated by Laurent and Burrows [10,11]. We adopt fundamentally their results as schematically shown in Fig.1.In thoracic ganglion, this signal is transformed into rhythmic wave by rhythmic neuron corresponding to a spiking inter-neuron in the ganglion. The rhythmic neuron makes direct synaptic connection with nonspiking inter-neuron (NS neuron), which is great important to integrate the information on the states of muscles and inter-segmental pathway. NS neuron transforms the output of the rhythmic neurons to send the motor neuron. We adopt fundamentally their results as schematically shown in Fig.2. In thoracic ganglion, this signal is transformed into rhythmic wave by rhythmic neuron corresponding to a spiking inter-neuron in the CPG.

The rhythmic neuron makes direct synaptic connection with non-spiking inter-neuron (NS neuron), which is great important to integrate the information on the states of muscles and inter-segmental pathway. NS neuron transforms the output of the rhythmic neurons to send the motor neuron. Inter-segmental connections between rhythmic neurons in the CPG are inhibitive, which produce asynchronous oscillation between neighboring rhythmic neurons. The frequency of the rhythmic neuron determines the temporal patterns of walking, which inhibits each other to appear any phase relationship among the movement of legs. In this sense, the rhythmic neuron is a kind of command neuron that receives the information of walking velocity, that is, purpose of the animal created in the brain. The spatio-temporal patterns of the movement of legs are emerged by integration of the dynamical information of the effector organs in the NS neurons under the constraint driven from the purpose. Under unpredictably changing environment, the system requires some rule to satisfy the constraints, and then walking patterns of the animals should be emerged as the results of the coordination of the movements of the leg muscles. The constraints on the robot should be contented by optimally integrating each objective function of the elements through competition and cooperation among them. The objective function is derived from the energetics of muscle contraction, in which muscle has an optimal shortening velocity to provide the highest efficiency of the energy conversion. So we introduce "the least dissatisfaction for the greatest number of the elements" rule to generate the walking patterns. This rule is quite similar to the Pareto optimum in the economics and brings forth the cooperation and/or competition among leg movements, resulting in emerging the most efficient walking pattern [12,13].

The equations of rhythmic neuron model are given by

$$\begin{aligned}\frac{dx_{Ri}}{dt} &= -y_{Ri} - f_R(x_{Ri}) - \sum_j \alpha_{Rij}(x_{Rj} - x_{Ri}) \\ &\quad +\beta_{NSi}x_{NSi}, \\ \frac{dy_{Ri}}{dt} &= g_R(x_{Ri}) + D_{Ri}, \\ f_R(x) &= (A_{R1}x^2 + B_{R1}x + C_{R1})x, \\ g_R(x) &= (A_{R2}x^2 + B_{R2}x + C_{R2})x, \qquad (4)\end{aligned}$$

where x denotes voltage of neuron and D_R is the input to the rhythmic neuron, which determines the frequency of the oscillation.

The NS neurons is given by

$$\begin{aligned}\frac{dx_{NSi}}{dt} &= -y_{NSi} - f_{NS}(x_{NSi}) + \beta_{Ri}x_{Ri}, \\ \frac{dy_{NSi}}{dt} &= g_{NS}(x_{NSi}) + D_{NSi}, \\ f_{NS}(x) &= (A_{NS1}x^2 + B_{NS1}x + C_{NS1})x, \\ g_{NS}(x) &= (A_{NS2}x^2 + B_{NS2}x + C_{NS2})x, \quad (5)\end{aligned}$$

where D_{NS} is the input to the rhythmic neuron, which controls the phase relationship among the movement of legs. And the motoneuron is governed by the following equation,

$$
\begin{aligned}
x_{mi}(t) &= sigmoid[G_i^{th}(t)H(x_{NSi}) \\
&\quad +G_i^{ag}(t)\overline{F}_{FRF}], \\
G_i^{th}(t) &= k_i^{th}(V_{body.req} - V_{body}), \\
G_i^{ag}(t) &= k_i^{ag}(\theta_{offset} - \theta_i),
\end{aligned}
\tag{6}
$$

where x_{mi} and $\overline{F}_{FRF}$ are the activity of the motoneuron, which determines the motive force of the leg, and the average repulsive force against the floor, respectively. Each motoneuron is connected to the each corresponding muscle. The outputs of non-spiking neuron are transformed to the excitation with the strength of 1 when above a threshold, otherwise 0. Then they are sent to the corresponding motoneurons.

In order to self-organize the walking pattern according to the circumstance, it is necessary to obtain the information on the surroundings and the state of the legs. At the beginning of the stance phase, only the posterior muscle shortens, but at the end of the stance phase the position sensor of the posterior muscle should strongly inhibit the motoneuron of it, activating the motoneuron of the anterior muscle. In the case of the swing phase, the interaction between the pair of muscles should be reversed. These interactions can be presented by the direct synaptic connection of the position sensor of each muscle with the motoneurons and by the feedback to the connectives between the nonspiking neuron and the motoneuron as shown in Fig. 1. The hind leg moves antiphasic to the middle, which also moves antiphasic to the front leg, although there is no strong coupling between the hind and the front legs. So, the information required to optimize the efficiency of energy conversion is given as follows;

$$
\Delta G_{mi} = k_\eta \left(\frac{\partial \eta_i}{\partial f_i} - \frac{\sum_{j \neq i} f_j \frac{\partial \eta_j}{\partial f_j}}{\sum_i f_i} \right). \tag{7}
$$

It means that the legs moved synchronously tend to share the load equivalently, where denote the efficiency curve of the energy conversion of muscle. Each leg requires working more efficiently, so the feedback to NS neuron is

$$
\Delta D_{NSi} = k_{D_{NSi}} \frac{\sum_j \frac{\int_0^T f_i \frac{\partial \eta_i}{\partial f_i} dt}{T}}{\sum_i \frac{\int_0^T f_i dt}{T}}. \tag{8}
$$

This feedback information determines the degree of the synchronization among the legs. The feedback information from leg to motoneuron is given by

$$
\Delta G_i^{th}(t) = k_\eta (V_{i.req} - V_i). \tag{9}
$$

4. Results

In case of straight walking, the required velocity is the only purpose of the robot, which is the strong constraint for our model system to attain at any required velocity and any load on the system. Our insect robot can fundamentally generate the two different walking patterns depending on the walking velocities and loads. The walking patterns are characterized by the phase relationship among the six legs, showing the walking pattern of metachronal gait. The phase relationship between the hind and the front drastically changes as the walking velocity increases. As increases the velocity, our robot shows that the front and the hind legs move simultaneously, called tripod gait as reported previously.

In this model, the structure of leg is composed of only two muscles, flexor and extensor muscles, so the movements of legs are limited to move parallel to the axis of the body. When the angle between the axis of the body and the direction of the destination is large, the walking velocity should become slower and the gait pattern is metachronal. When is small, the insect can turn at higher velocity with a tripod gait. At intermediate angle, outer side legs and inner side legs take tripod and metachronal gait, respectively, as shown in Fig.3 and 4.

5. Discussions

We have simulated an insect robot as an example that can generate appropriate walking patterns to walk efficiently. Since the walking pattern changes crucially depending on their walking velocities and loads, animals could generate a great number of diversities of walking patterns to adapt the unpredictable changes of their surroundings.

We have also showed that a new control mechanism installed in the insect robot, which can walk attaining more complex purposes of the system as possible as it can operate at higher efficiency of energy conversion under unpredictable changes of the environment. This control mechanism is derived from a metarule to determine the constraints on the motor system. In case of turning walk, the destination takes the priority over all other purposes. So the constraints are self-organized every

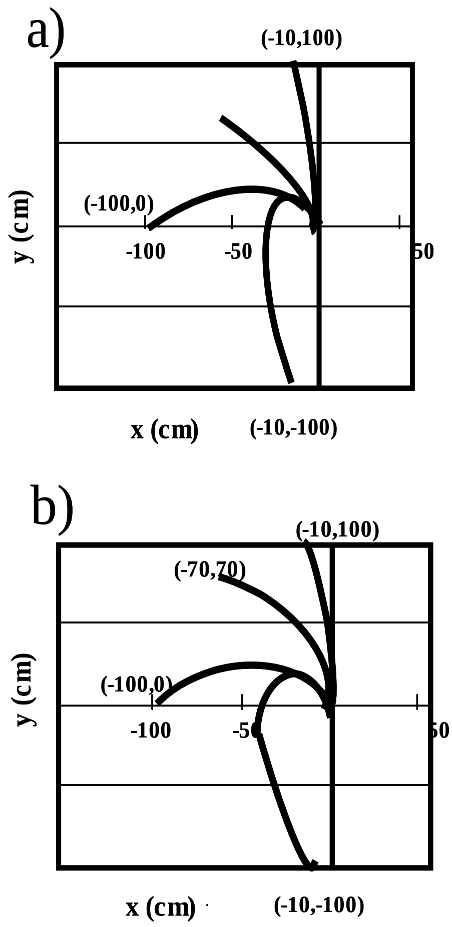

Figure 3: Trajectories of slow (a) and fast (b) walk.

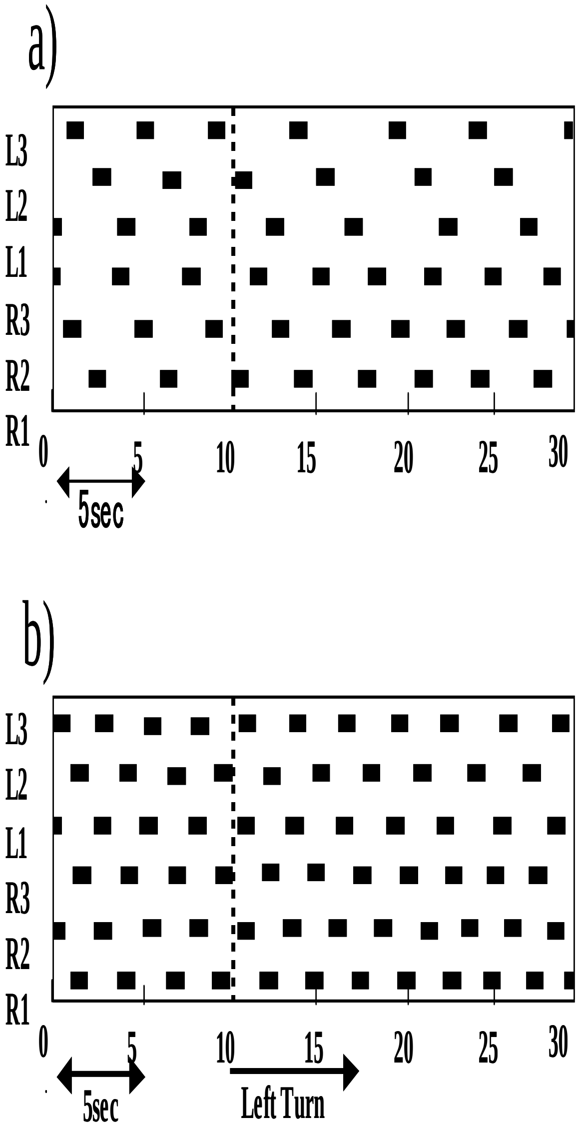

Figure 4: Gait Patterns of turning walk at slow speed (a) and high speed (b).

moment depending on the current state of the system and the environment to attain the purpose. And the constraints may be always fulfilled with more optimal efficiency. As the result the optimal trajectory and the walking patterns emerged.

References

[1] Peason, K.G., (1972). Central programming and reflex control of walking on the cockroach. J.Exp.Biol. **56**:173-193

[2] Peason, K.G, (1976). The control of walking. Sci. Am. **235**, 72-86

[3] Graham, D., (1979a). The effects of circumoesophageal lesion on he behavior of the stick insect Carausius morosus. I. Cyclic behavior patterns. Biol. Cybern. **32**:139-145

[4] Graham, D., (1979b). The effects of circumoesophageal lesion on the behavior of the stick insect Carausius morosus. II. Change in walking coordination. Biol. Cybern. **32**,147-152

[5] Foth E. and Graham D. (1983a) Influence of loading parallel to the body axis on the walking coordination of an insect. I. Ipsilateral effects. Biol. Cybern. **47**:17-23

[6] Foth E. and Graham D. (1983b) Influence of loading parallel to the body axis on the walking coordination of an insect. II.Contralateral effects. Biol. Cybern. **48**:149-157

[7] Getting PA. and Dekin MS. (1985) Tritonia swimming: a model system for integration within rhythmic motor systems. In: Selverston AI(ed) Model neural networks and behavior. Plenum Press. New York, pp 3-20

[8] Makino Y., Akiyama M. and Yano M., (2000). Emergent mechanisms in multiple pattern generations of the lobster pyloric network. Biol. Cybern. **82**C443-454

[9] Dean, J., (1989). Leg coordination in the stick insect Carausius morosus J. Exp. Biol. **145**, 103-131

[10] Laurent, G., and Burrows, M., (1989a). Distribution of intersegmental inputs to nonspiking local interneurons and motor neurons in the locust. J. Neurosci. **8**, 3019-3029

[11] Laurent, G., and Burrows, M., (1989b). Distribution of intersegmental inputs to nonspiking local interneurons and motor neurons in the locust. J. Neurosci. **8**, 3030-3039

[12] Kimura S., Yano M., and Shimizu, H., (1993). A self-organizing model of walking patterns of insects. Biol. Cybern. **69** 183-193

[13] Kimura S., Yano M., and Shimizu, H., (1994). A self-organizing model of walking patterns of insects II. The loading effect and leg amputation. Biol. Cybern. **70** 505-512