# A principle of design of an autonomous mobile robot

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## Abstract

In this paper, it is proposed that a principle of design of an autonomous mobile robot, i.e., a walking robot carrying out a task in the real world from dynamic systems perspective. The control system is composed of the modules, each of which has its own function, cognition, planning and motion control. The modules are realized in terms of a dual dynamic system. A dual dynamic system is composed of a rule dynamics and an element dynamics; An element dynamics processes input signals under the control of the rule dynamics. The outputs of the modules are combined and realize a task specific motion of the robot.

## 1 Introduction

Research on a walking robot is proceeding actively[1]. A walking robot is a mechanical system with legs composed of links. The control of a walking robot is to make the robot walk stably and efficiently to a target. Currently, the study on the control of a walking robot is done under the condition that a desired motion of the robot is given. At that time, the difficulty of the control of a walking robot is to control the motions of a lot of elements with nonlinear interactions. The motion control of a walking robot has been achieved by a model based control[2]; The inverse kinematics and the inverse dynamics of the robot are preprogrammed and when the desired motion is given, the motion of each link is controlled on the basis of the inverse models. In the future, it is required that a walking robot which can carry out tasks in the real world, where the geometric and kinematic conditions of the environment are not specially structured. In such an environment, first, the robot has to extract the parameters characterizing the environment from sensor signals and compose a desired motion carrying out the tasks and then, control motions of the links realizing the desired motion. The difficulty of the control of a walking robot carrying out a task in the real world is not only the difficulty to control the motions of a lot of elements with nonlinear interactions, but also the difficulty to form a task specific pattern of the motion of a lot of elements.

Now, mechanisms of motion of animals have been studied in ethology[3]. From the view point of behaviorism, the motion of an animal has been modeled as a series of actions caused by the environment. Then, by ethologists, each one of the actions has been revealed to be developed from a set of simple, stereotyped movements of muscle activities. A body of an animal is composed of a lot of joints and muscles. During a motion, a lot of elements are organized into a collective unit to be controlled as if it had fewer degrees of freedom and yet to retain the necessary flexibility for changing internal and external contexts. The motion of an animal seems to offer solutions to the problem to control a lot of elements and the problem to form a task specific pattern[4]. Recently, a motion of an animal have been studied from the dynamic systems perspective. The dynamic model of the behavior of a single celled animal has been proposed by Oosawa[5]; A single cell is modeled as a particle with internal variables where the state of the animal is determined by internal variables and the internal variables vary according to the input signals. The action of the animal to the input signals is determined not by the input signals directly but by the state of the animal and then, the motion of the animal realizes a context-conditioned variability. Kelso[6] has investigated the motion of an animal from the viewpoint of Synergetics; The motion of an animal results from the processes of self-organization and a task specific motion appears when a certain control parameter is scaled to some critical magnitude.

On the other hand, based on the latest achievements of neurobiology and ethology, a new approach to robotics has been developed. Brooks[7] has proposed the subsumption architecture as principle of design of an autonomous mobile robot which can carry out a task in the real world; The control system is composed of behavior-generating units. Each of units responds to the changes in the environment and generates a stereotyped action. Responses from all the units compensate each other and one of which determines the action of the robot. Using the subsumption architecture, Brooks[8] developed a six-legged robot, Genghis to walk over a rough terrain. Through the trajectory of the body is not specified, the robot successfully navigates a rough terrain. When the geometric and kinematic conditions of the environment are complicated, it is required that the motions of the robot become to be complex and a lot of behavior-generating units are needed. At that time, a mechanism to manage a lot of units may be necessary. In this paper, we will propose a principle of design of a walking robot carrying out a task in the real world from a dynamic systems perspective.

## 2 Design Principle

In this chapter, a design principle of control system of a walking robot is proposed. In order to make the issues clear, a quadruped locomotion robot is picked up as an example of this kind of robot (Fig. 2.1).

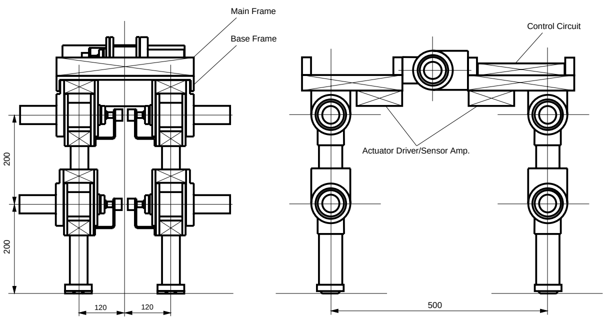


Fig. 2.1 Quadruped locomotion machine

This model has two joints on each leg and two joints on the main body. At each joint, motors are equipped as actuators. This model has three kinds of sensor; visual sensors, reaction force sensors equipped at the end of legs and angle sensors at the motors. The task to the robot is to walk safely and efficiently to a target; The role of the control system is to recognize the environments by the sensor signals and to generate a gait pattern adapted to the environments and to output the control command to the motors which realize the gait pattern. That is to say, the function of the control system is the optimization, i.e., to generate the optimal gait pattern on real-time under the geometric and dynamic constraints of the environments. In order to design a control system as an effective optimization system, three principles are adopted. The first principle is to divide the optimization problem considered into some small problems. In this case, it is divided into following three problems (modules); cognition module, planning module and motion control module. The cognition module derives the model of the environments by using the input signals, i.e., to extract the parameters characterizing the environments; The shape and the inclinations of the paths are estimated by using the input signal of the visual sensor and dynamic state of the system is estimated by using the input signal of the reaction force sensors and the angle sensors. The planning module constructs a desired pattern of motion from the given task, that is, to generate a gait pattern of the robot. The motion control module calculate the control command to the actuators from the desired motion. The control command is composed of the feed-forward command based on the desired pattern of motion and the feedback command based on the sensor signals. The processes in these modules are not necessarily executed successively. The second principle is the inner model principle. That is, each optimization module has its own inner model. The inner model is used to construct or to restrict the search space of the optimization. In the cognition module, the models of the passageways are derived by using the input signals of the visual sensors. This derivation is executed based on the Bayes estimation using a priori informations of the environment, where a priori informations of the environment play a role of the inner model. On the other hand, in the motion control module the control command to the actuators are calculated by using the desired motion. This calculation is established by using the inverse kinematics model and the inverse dynamics model of the system where these inverse models play roles of the inner models. These inner models are not static. They will change slowly through the comparison of the results of the behavior with the given tasks. The last principle is that of distributed parallel processing. The optimization processes are considered as to select or to construct the best assumption in a set of the elements of assumptions under some constraints. In order to make it in terms of the distributed parallel processing, following strategies are adopted; The elemental assumptions are coded into the dynamic elements which has own dynamics. Then, the interactions between the elements are embedded corresponding to the constraints(inner model). The dynamic system constructed in this way can construct the best assumption through their own dynamics as the saptio-temporal pattern on the elements. For example, the model of the environment is derived in the cognition module from the signal of CCD camera. The dynamic elements of the cognition module are assigned to the pixels of the CCD camera and the interactions between the elements are embedded according to the inner model as the priori informations. When the outputs of the CCD cameras are input to the elements, the elements extract the parameters of the environments through their dynamics. Figure 2.2 shows the control system proposed.

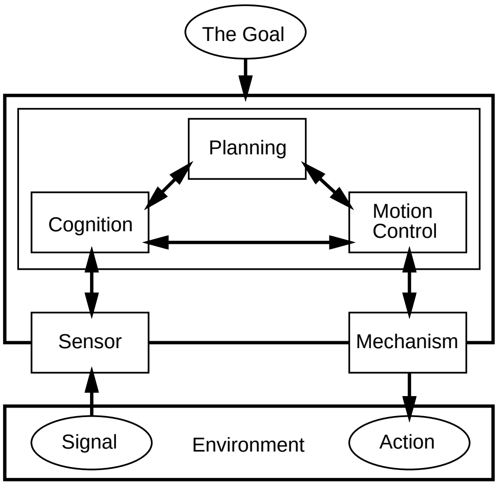


Fig. 2.2 Control system

## 3 Design method

The control system proposed is composed of modules and each module is the dynamic system composed of dynamic elements. This dynamic system is two time scaled system with the fast variables and the slow ones. The slow variables express the inner model and change slowly through the evaluation of the behavior from the given tasks. The fast variables deal with the external inputs or the inputs from the other modules under the control of the slow variables. The spatio-temporal pattern emerges on the fast variables. The typical example of this class of dynamic system is an artificial neural network model with plastic synapses. Here, a design method of each module proposed based on the dual dynamic system is mentioned[9]. The dual dynamic system is composed of the fast dynamics (element dynamics) of the fast variables and the slow dynamics (rule dynamics) of the slow variables. The fast variables change their values under the constraints of the slow variables. The constraint to the first dynamics is given as a positive function of the fast variables $u_i$ as $H^{(m)}(u_i,\ v_j)$, $\quad m = 1, \cdots, M$, where $v_j$ are the external inputs or the inputs from the other modules. The outputs of the fast dynamics are the spatio-temporal patterns emerged on variables $u_i$. Here, suppose that the required outputs are static spatial patterns. It is required that each module has the various spatial patterns as possible under the given constraints in order to make the system adaptive to the environments. This means that when we design the first dynamic system with a stochastic differential equation, it makes various equilibrium solutions as possible under the given constraint $H^{(m)}(u_i,\ v_j)$ $m = 1, \cdots, M$. ,that is, the absolute entropy $S = \int p(u_i|v_j) \ln p(u_i|v_j) du_i$ defined with probability density $p(u_i|v_j)$ at the equilibrium states becomes maximum. According to the maximal entropy principle, probability density $p(u_i|v_j)$ is expressed by using constraint $H^{(m)}(u_i,\ v_j)$ as follows;

$$p(u_i|v_j) = Z^{-1} \exp\left(-\sum \lambda_m H^{(m)}(u_i,\ v_j)\right) \qquad (1)$$

where, $Z$ is a partition function and $\lambda_m$ is Lagrangian multiplier corresponding to constraint $H^{(m)}(u_i,\ v_j)$. Lagrangian multipliers $\lambda_m$ are adopted as the slow variables in the dual dynamic system. The stochastic differential equation which realizes probability density (1) is given as a Langevin equation which satisfies the detail balance conditions. One of the simple forms is given as follows;

$$\dot{u}_i = -\sum_m \lambda_m \frac{\partial H^{(m)}(u_j,\ v_l)}{\partial u_i} + w_i \qquad (i = 1, \cdots, N) \qquad (2)$$

where, $w_i$ is the white Gaussian noise. The performances of the system are evaluated based on the given tasks. Here, suppose that the performances are evaluated in each module and also suppose that the slow variables $\lambda_m$ have effects on the performances of the modules through function $g^{(m)}(u_i)$. The desired value of function $g^{(m)}(u_i)$ is given as probability density $\hat{p}^{(m)}\left[g^{(m)}(u_i)\right]$. By using probability density $p^{(m)}\left[g^{(m)}(u_i)|\lambda_m\right]$ calculated from Eq.(refeq:eq2). Relative entropy $K^{(m)}(\lambda_m)$ of probability density $\hat{p}^{(m)}\left[g^{(m)}(u_i)\right]$ in terms of $p^{(m)}\left[g^{(m)}(u)_i|\lambda_m\right]$ is defined as

$$K^{(m)}(\lambda_m) = \int \hat{p}^{(m)}\left[g^{(m)}(u_i)\right] \times \ln\left\{\hat{p}^{(m)}(g^{(m)}(u_i))/p^{(m)}\left[g^{(m)}(u_i)|\lambda_m\right]\right\}$$

The slow variable $\lambda_m$ is designed so that relative entropy $K^{(m)}(\lambda_m)$ decreases.

$$\dot{\lambda}_m = -\frac{1}{\tau_m}\frac{\partial K^{(m)}(\lambda_m)}{\partial \lambda_m} \qquad (3)$$

where, $\tau_m$ is designed so that the dynamics of variable $\lambda_m$ is slow enough compared with that of variable $u_i$. When each module is designed based on the dual dynamic system, each module is composed of the two dynamic systems; One is the element dynamics and the other is the rule dynamics. These dynamic systems have complimentary properties; In the element dynamics, the absolute entropy increases with time while in the rule dynamics, the relative entropy decreases with time ,that is, the former is a Markov process while the latter is a Bayes process. These properties may make the system robust against and adaptive to the changes in the environment.

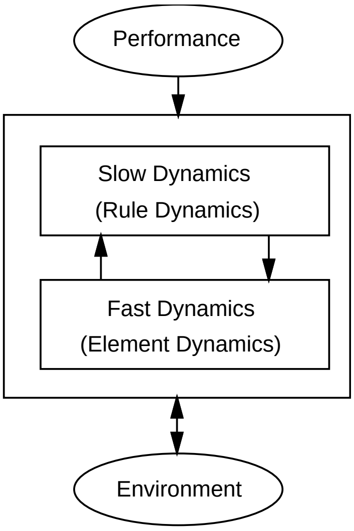

Fig.3.1 Dual dynamic system

## 4 Summary

This paper has proposed a principle of design of a walking robot carrying out a task in the real world from dynamic systems perspective. The control system proposed is composed of three modules, each of which has its own function, cognition, planning and motion control. The modules are realized in terms of a dual dynamic system. The dual dynamic system is composed of a rule dynamics and an element dynamics where the element dynamics processes the input signals under the control of the rule dynamics. Outputs of the modules determine the task specific behavior of the robot. Hereafter, a hardware mode will be developed based on the principle of design proposed.

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