Emergence of Autonomous Behaviors on Elastic Circular Robot Consisting of Modular Units
-Planning for a Task with Composite Behaviors-
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Abstract: There are many studies on hardware and software experiments to control autonomous robots. We have focused the elastic robot which has a body with multiple degrees of freedom. The elastic robot consists of homogeneous or heterogeneous simple modules. A feature of them is that their behavior is obtained by an each module movement based on local communications between connected modules. A physical simulation on the computer is carried out to achieve tasks autonomously for a virtual elastic robot. Our goal is to acquire a control system in evolution to achieve a composite task in specific circumstances with and without a obstacle.

1. INTRODUCTION

We focus on a virtual elastic robot which is capable of changing its shape and adapting to the surrounding environment. This elastic robot behaves autonomously to achieve tasks. Therefore, the purpose of this paper is to acquire their adaptive behaviors that achieve tasks. This task achievement problem is regarded as a learning problem for autonomous robots and has been studied actively in areas such as evolutionary robotics and artificial life. Recently, the designing must take consideration in interaction between robots and their surrounding environment.

There are many studies to acquire autonomous behaviors for them by computer simulations [1–3]. K. Sims [1] proposed a method for creating a virtual creature. In this methodology, the geometric morphology for a body structure and a neural system for controlling a creature are both generated automatically using the genetic programming (GP). Therefore, it is expected that the creature adapts to the surrounding environment by the use of the physical simulation. Similarly, in the area of artificial life, behavior emergence and evolution of the artificial creature on a computer are a significant problem. This is to acquire a suitable shape for an accomplishing a task. H. Lipson, J. B. Pollack et al. [2,3] proposed the evolved robot which constructed from some bars connected to each other so as to form truss structures. They show how to design body shape and acquire locomotion in a physical simulation using evolutionary computation (EC). Furthermore, they demonstrated a potential to construct a real robot using the evolved robot. Optimizing a body, sensors and a control system its studied not only to adapt to the surrounding environment but also to construct its real robot.

There are many studies about modular robots which aim to achieve tasks by changing their body structure [4–7]. A modular robot consists of simple modules, and its behavior is obtained by each module movement based on local communications between connected modules. In many studies, it is attracted how to control each module autonomously and emerge its self-reconfigurable property which is changing their module structure by ducking and separation. These studies aim to develop real robots, and many original robots are proposed [5, 7]. However, it is not shown how to determine the optimum body structure to adapt to the surrounding environment, like challenges found in research of K. Sims [1]. M. Yim et al. [4] presented some challenges about the controlling and designing of a modular robot. There are rooms how to control a robot consists of a number of modules, to determine the optimum shape for a given task and environment, to obtain locomotion with and without obstacles and so on.

In these background, we have focused on an elastic robot which has a body with multiple degrees of freedom and aimed to acquire behaviors to achieve some tasks [8]. This elastic robot can flexibly behave such as an amoeba and a snake. Especially, the robot is constructed by connecting flexible spring joints. Then a controller to manipulate elastic movements of spring actuators is acquired by using EC. The body has a circular structure to transmit a elastic motion efficiently (Fig. 1). In this paper, a movement to move toward a light source is break down to two basic behaviors such as:

1. A light tracking behavior to approach a light source.  
2. A light searching behavior when obstacles interrupt light information.

This paper focuses to acquire not only a locomotive behavior but also a light searching behavior when the robot cannot perceive a light source by obstacles. Attainment of basic behaviors allow to achieve tasks with composite behaviors with and without obstacles. The rest of this paper is composed as follows. Section 2 introduces some related works. Section 3 proposes an elastic circular robot consisting of modular units. Section 4 describes a learning experiment to acquire a light tracking behavior and shows some experimental results. Section 5 also describes learning experiments to acquire a light searching behavior and shows results. Section 6 discusses about attainment of composite behavior which is combined basic behaviors and Section 7 concludes this study with some remarks and gives some directions toward the future work.
2. RELATED WORKS

A primary challenge to a modular robot is to observe a control method to allow it behave autonomously. Controlling the modular robot is generally studied by the use of a rule-based control which is described by the specific behavior rule for each module [5, 6]. However the rule-based controlling approach has only allowed robots to behave simple motion. Furthermore, it is also difficult to control a robot with scalability based on the rule-based approach. Then, an evolutionary heuristic approach is used instead of a traditional rule-base approach to control a modular robot [9]. A. Kamimura et al. [9] develop a self-reconfigurable modular robot "M-TRAN" which consists of lattice type module units. This robot can change its module structure to diverse structures byducking and separation such as a walking robot and a snake robot to adapt to several environments. However, a elastic motion is not obtained by the use of a body with multiple degrees of freedom.

There are studied to acquire an amoebic motion by the use of a body with multiple degrees of freedom [10,11]. A. Ishiguro et al. [10] proposed an amoeboid robot which is connected by springs joints in a circular structure. This robot behaves based on a mathematically-modeled protoplasmic streaming motion which is specific to an amoeba. Though it can behave to move toward a light source, it has not been obtained composite behaviors. D. M. Kriesel et al. [11] proposed a beanbag robot with swarm robots. This robot can behave autonomously by using collective behavior of miniature robots. However, a whole motion of this robot is overly complicated as its behavior is a swarm behavior. This paper focuses on an elastic motion by the use of a body with multiple degrees of freedom and aims to allow to construct a virtual elastic robot which has a simple structure and to acquire composite behaviors.

3. ELASTIC CIRCULAR ROBOT

3.1 Body System

An intended elastic robot is modeled by connecting rectangular modules with spring joints (Fig. 1). It behaves by maintaining an initial state topology since the robot does not change its topology. Each module is connected to neighboring four modules by four springs. It can move by pushing and pulling forces of springs and also using the friction force between the modules and ground. The behavior of the robot is controlled by manipulating elastic velocities of each spring actuator. Accordingly, all modules of this robot move by propagating spring forces to the whole modules efficiently.

This robot is constructed from 32 modules and has a symmetric structure. The density of each module is 2,700[kg/m³]. The coefficient of restitution of each module is 0.3. The coefficient of dynamic friction between the modules and the ground is 0.4. The coefficient of static friction between the modules and the ground is 0.6. The natural length of each spring actuator is 0.2[m]. The natural length of each spring joint is 0.4[m]. All spring length are able to range from 0.25-fold to 2.0-fold in length. The spring constant is 500[N/m].

3.2 Sensor System

This robot aims to achieve an easy task that the robot mainly moves toward a light source. Then, the light sensor is defined to perceive the peripheral information. The light sensor is installed on each module. The light sensor of the i-th module is capable of perceiving a light intensity \( L_i(t) \) at time \( t \). \( L_i(t) \) is defined by Eq. (1) which decays exponentially on distance \( d_i \) measured from the i-th module to the light source.

\[
L_i(t) = \begin{cases} 
  e^{-\alpha d_i} & \text{if the -th module receives the light} \\
  0 & \text{otherwise} 
\end{cases} 
\]  

where, \( \alpha \) is a constant. However, if the i-th module does not receive a light, it cannot perceive the goal (Fig. 2). In general, the light intensity is inversely proportional to the square of the distance measured from the light source. In this paper, Eq. (1) is defined as the light intensity function which takes 1.0 to the maximum value and decays in inverse ratio to the distance measured from the light source.

3.3 Control System

Expansion and a compression of springs make mainly this module move. Each spring actuator generates an elastic force calculated by Eq. (2) for this movement.

\[
f_i(t + \Delta t) = A_i(t) \sin(\omega_i(t)\Delta t + \theta_i(t)) 
\]  

where \( f_i(t) \) is the elastic force of the i-th spring actuator at time \( t \), \( A_i(t) \) is the amplitude, \( \omega_i(t) \) is the angular velocity, \( \theta_i(t) \) is the accumulated phase (\( \theta_i(0) = 0 \), \( \theta_i(t + \Delta t) = \theta_i(t) + \omega_i(t)\Delta t \)). If \( v_i(t) > 0 \), the spring is expanded, if \( v_i(t) < 0 \), it is compressed. Thus, the behavior of the whole body is controlled by manipulating \( A_i(t) \) and \( \omega_i(t) \) for the i-th spring actuator. The spring actuator is controlled by neural controllers equipped with spring ac-
4. Acquisition of a Light Tracking Behavior

4.1 Experimental Description

A simulation experiment is carried out to achieve a task for a given robot described in previous section. The purpose of this task is to acquire behavior which moves toward a light source on a flat ground (Fig. 4). In the initial condition, the light source is around 3.0[m] far from the center of gravity of the robot. In Fig. 4, gray graduation indicates amount of light intensity. The white area indicates a higher light intensity than the black area.

Actuators determine the robot behavior. Each actuator has a controller implemented with ANN. Therefore, an acquisition of an adapted behavior is to optimize the synaptic weights assigned to ANN of all spring actuators. We set that all ANN has the same synaptic weights to allow a decentralized autonomous control system to be scalable. Then the real-coded genetic algorithm (RCGA) is adopted to optimize the synaptic weights assigned to one ANN.

Obtained behaviors are evaluated by Eq. (3)

\[ E = \sum_{t=0}^{N_s} \sum_{i=1}^{N_m} L_i(t) \]  

where, \( N_s \) is the number of steps in a simulation, and \( N_m \) is the number of modules of which a modular robot consists. Eq. (3) plays a role of a fitness function in GA and it evaluates how much all modules receive accumulated intensities during one simulation. A photo-tactic behavior is evaluated by Eq. (3). Finally results that GA optimizes so as to maximize Eq. (3) become obtained behaviors. It is expected to acquire behaviors that the robot moves toward its goal faster and faster, and stays close to its goal as long as possible. Experimental conditions for GA and simulation are shown in Table 1. This experiment uses these conditions.

4.2 Physical Simulation

The computer simulation environment is implemented to allow the robot to accomplish a task. This simulation environment is constructed by the use of a physics computing library PhysX [12]. PhysX [12] is able to numerically calculate a position and a velocity of the object in considerations of a gravity, a friction and collision detections.

4.3 Experimental Results

Fig. 5 shows snapshots of behaviors for the best trial obtained by use of RCGA in this experiment. In Fig. 5, motions at 1,000, 3,000, 5,000 and 7,000 steps are drawn. It is confirmed that the robot can arrive at a light source along the elapsed time (Fig. 5(b)). In particular, it is confirmed that three movements, such as start, move and
Table 1: Experimental condition

<table>
<thead>
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<th>Type</th>
<th>Value</th>
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<tr>
<td><strong>ANN</strong></td>
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<tr>
<td>number of neurons on input layer</td>
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</tr>
<tr>
<td>number of neurons on hidden layer</td>
<td>15</td>
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<tr>
<td>number of neurons on output layer</td>
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<td><strong>GA</strong></td>
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<td>number of individuals</td>
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<td>number of generations</td>
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<td>probability of crossover [%]</td>
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<tr>
<td>probability of mutation [%]</td>
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<tr>
<td><strong>Simulation</strong></td>
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<td>weighting coeff. $\alpha$ in Eq. (1)</td>
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<tr>
<td>time-delay step $t_d$</td>
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<tr>
<td>step time [sec] $\Delta t$</td>
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<tr>
<td>number of steps in simulation</td>
<td>7,200</td>
</tr>
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</table>

Fig. 5: Obtained behaviors of tracking locomotion at the 300th generation

Fig. 6: A length change in each simulation step for tracking locomotion task

stop, emerged for the obtained behavior.

Moreover, Fig. 6 shows a diagram showing the spring length change of the behavior along the vertical axis and the number of simulation steps along the horizontal axis for the best trial. In Fig. 6, the head, side and tail actuators conform corresponding actuators in Fig. 5(a). It is observed that each actuator generates a locomotion creating a phase difference. Fig. 7 shows a diagram showing the distance between the robot and the light source along the vertical axis and the number of simulation steps along the horizontal axis for same trial. In Fig. 7, the obtained behaviors at the 10th, 50th and 300th generations in GA are shown. As the GA generation is elapsed, it is confirmed that behaviors are obtained such as moving toward its goal faster and faster, and staying close to its goal as long as possible. From this experiment, it is seen that behaviors are capable of achieving the tracking locomotion task.

Next, we verify that the obtained controller is possible to behave tracking a light source when the position of a light source is changed. Fig. 8 shows snapshots of behaviors indicating a verification result. In these snapshots, the position of a light source is changed to the other place after the elapse of 10,000 simulation steps (Fig. 8(b)). From this verification result, it is observed that this robot is able to track a light source.

5. Acquisition of a Light Searching Behavior

5.1 Experimental Description

The experiment in previous section aims to acquire a locomotion which behaves to track a light source. However, the previous experiment is not supposed to accomplish a task in environment with obstacles. In this section, it is conduct the experiment which is supposed to set a obstacle to interrupt a light source. 2 behaviors are given as behaviors in the case of interrupting a light source information.

1. A searching behavior when a light source is interrupted completely.
2. A locomotive behavior when a light source is interrupted partially.
In the former case, a wander behavior is required to search a light source such as a random walk. However, an acquisition of a random walk need to evaluate a stochastic behavior. Therefore, it is difficult to acquire the requirement behavior in evolution. This experiment aims to achieve a task supposing the latter case.

The purpose of this task is to acquire behavior which moves toward a light source on a flat ground with obstacle (Fig. 9). In Fig. 9, a shaded area is interrupted a light. The robot has to move to a light detectable area, and move toward to a light source. Experimental conditions for GA and simulation use a set of values likewise the previous experiment (Table 1). Obtained behaviors are also evaluated by Eq. (3).

5.2 Experimental Results

Fig. 10 shows snapshots of the obtained behaviors with a obstacle. It is confirmed that the robot can get around a obstacle to arrive at a light source along the elapsed time.

Next, Fig. 11 shows a diagram showing the spring length change of the behavior along the vertical axis and the number of simulation steps along the horizontal axis for the best trial. It is observed that the head, side and tail actuators generate a locomotion creating a phase difference. Fig. 12 shows a diagram showing the distance between the robot and the light source along the vertical axis and the number of simulation steps along the horizontal axis for same trial. In Fig. 12, the obtained behaviors of the robot at the 10th, 50th and 300th generations in GA are shown. As the GA generation is elapsed, it is confirmed that behaviors are obtained to moving toward its goal getting around a obstacle. Then, in this experiment, it is seen that behaviors are capable of achieving the searching locomotion task.

6. ATTAINMENT OF A COMPOSITE TASK

Experiments in section 4 and 5 show that the robot acquires behaviors to achieve locomotion tasks in the environment with and without a obstacle. It is expected that attainment of composite behaviors which is combined these acquired behaviors as basic behaviors to achieve complicated tasks. A simulation experiment is carried out to verify the effectiveness of composite behaviors by the use of basic behaviors. The task of this experiment is to move toward a light source passing through the gate constructed from obstacles. When more that 80 % of modules can perceive the light source, the robot behaves using a light tracking controller. Otherwise, it behaves using a light searching controller.

Fig. 13 shows snapshots of a composite behavior by use of basic behaviors. Fig. 14 shows a diagram showing the distance between the robot and the light source along the vertical axis and the number of simulation steps along the horizontal axis. From this experimental result, the robot behaves using the searching controller until it reaches to the gate. When many modules can perceive a light source, it behaves using the tracking controller. How-
ever, in more complicated situation, it is not expected to achieve a task by use of a threshold-based composite controller. To address this, we need to adopt new approach to use effectively basic behaviors.

7. CONCLUSIONS AND FUTURE WORKS

We have focused on an elastic robot and its physical simulation. Emergence of behaviors for the virtual elastic robot in simulation can be regarded as a learning problem how the robot acquires the adapted behavior. Evolutionary computation is a successful approach to this learning problem. The followings are this paper conclusions.

1. Analyzing a motion mechanism that the robot generates a locomotion through time.
2. Investigating a robust property of the robot on disturbances.
3. Proposing a new composite controller to use effectively basic behaviors in more complicated situation.

REFERENCES


