A Study on Proportion Regulation Model for Multi-Robot System

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Division of labor performed by social insects is one of the most advanced functions that they have evolved. For effective performance, the groups exhibit proportional regulation of population, which implies the proportion of each group is regulated against external disturbances without aid from a special individual. This paper addresses a variable probability model fot the proportion regulation of population in a homogenous multi-robot system, in which the state transition rate is combined with the external materials produced by corresponding task execution. Performance of the proposed model is confirmed by numerical simulations and experiments of simple multi-robot system.

1 Introduction

Cooperative multi-robot system is one of the most attractive topics in robotics, and many researchers have investigated multi-robot systems[1]. Some of them were inspired by biological systems and analyzed their performance using real robot systems[2, 3, 4, 5]. Actually, animals living in groups often show advanced functions or performances which exceed the simple sum of individual abilities. Especially, social insects like ants, bees, and termites exhibit some remarkable behaviors, such as colony formation, age polyethism, group foraging, etc[6, 7, 8]. The important point of their behavior is that their collective behaviors do not require a special individual which controls the behavior of the entire group. In spite of the lack of the special, behavior of the group is adaptable, flexible and robust against environmental disturbances. In their groups, hereditarily homogeneous individuals achieve these collective behaviors by interacting with each other through direct visual informations or chemical materials, such as pheromones.

Our interest in their characteristics is division of labor and proportion regulation of population. In their society, division of labor plays an important role, and it is known that proportion regulation of population are observed in division of labor for effective working. Fig.1 is a schematic figure of the "division of labor" and "proportion regulation of population" in the homogeneous multi-robot system that is treated here.

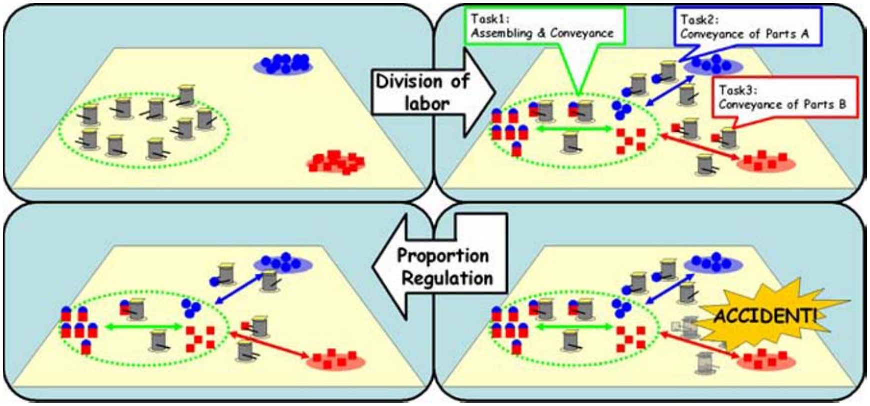

Fig. 1. A schematic figure of "division of labor" and "proportion regulation of population" in homogeneous multi-robot system.

Division of labor is also one of the most attractive topics in the study of multi-robot system[9, 10]. It will be important to consider division of labor and proportion regulation when the system needs to execute complex tasks autonomously and cooperatively. This paper addresses simple model of the proportion regulation of population in a homogenous multi-robot system, in which the state transition rate is combined with the external materials produced by corresponding task execution.

2 Model for division of labor and proportion regulation

As described above, division of labor can be widely observed in social insects. Many researchers, including biologists and theoretical scientists, have been interested in this phenomenon, and several mathematical models have been investigated.

Response threshold model
Bonabeau et al.[11] have developed a simple mathematical model based on response threshold. In this model, each individual has a response threshold for every task. They engage in a task when the internal stimuli exceeds the threshold of the task.

Based on this model, some experimental studies have been reported[4], in which the homogeneous group of robots divide into foraging robots and inactive robots effectively. This model functions well, if the threshold is scattered depending on the individual differences. However, it may cause "oscillatory" phenomena, when the scatter is small.

Non-linear dynamical model
A non-linear dynamical model[12] was proposed, especially focusing on the cell differentiation of Dictyostelium slug, in which all cells are divided into two types of cells, prestalk and prespore cells. The differentiation is flexible and it is known the ratio between them is almost constant. In this model, each element has two internal variables, - activator and inhibitor -, and they are coupled globally using their average quantities. The population "differentiates" into two states, and the system maintains the ratio against large disturbances by changing the state of the individuals.

Dynamic potential model
In a colony of social insects, we can observe "*age polyethism*," a division of labor based on individual age. In an insect colony, it is known that individuals change their tasks depending on their age. A dynamic potential model[13] consists of N indentical individuals, M tasks, M external materials and one-dimensional internal reference potential with m valleys. Each individual has an internal variable whose dynamics obey the effective potential. In this model, each individual detects the concentration of the external materials, and changes its internal variable depending on the effective potential derived from the concentration of the materials and the reference potential. Here, the proportion of population in each task can be controlled by the depth of the valleys in the potential. Since the reference potential is expressed by the valleys of the one-dimensional function, each individual changes its task sequentially. Hence, this model is suitable for expressing age polyethism.

Proposal
In this paper, we propose a variable probability model. Let us assume all the robots are homogeneous and each robot has some states and corresponding tasks. For simplicity, this paper treats the case that the robots have three states and three corresponding tasks. For the proportion regulation of population, each robot needs to determine its state appropriately. The simplest method to determine the proportion of the number of robots in state 1, 2, and 3 is to control the transition rates among them. Here the proportion can be expressed by the relative ratio of the transition rates. Let's denote the transition rates between the states as α_1, α_2, and α_3(Fig2(a)). If we set α_1, α_2, and α_3 as $0.1, 0.2$, and 0.3, respectively, the proportion of the number of robots in each state becomes $1 : 2 : 3$.

It should be mentioned that the proportion depends on the relative ratio at the equilibrium state and that the time to reach the equilibrium state depends on the transition rate itself. For example, if we compare the transition rate set $(\alpha_1, \alpha_2, \alpha_3) = (0.1, 0.2, 0.3)$ and $= (0.01, 0.02, 0.03)$, the proportion of population becomes 1:2:3 in both cases at the equilibrium state, but the balancing time of the former set is ten times faster than the latter one. It means that the balancing time can be independently controlled by w_j when we describe the transition rate as α_j/w_j instead of α_j. Fig.2(b) shows the schematic of the proposed model.

We also mentioned that we can generalize this model as shown in fig.2(c). It enables us to make an asymmetric transition flow,by describing the transition rate asymmetrically. It means that this model can also treat one-way transition such as age polyethism.

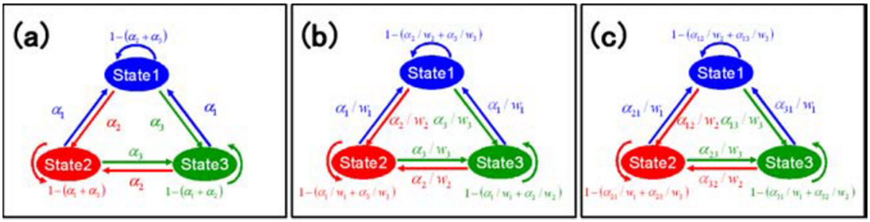

Fig. 2. State transition diagram. (a) Simple probability model. (b) Extended probability model. (c) Generalized transition model.

Next, we describe how to control the balancing time. When the system reaches the desired proportion, it is preferable that each robot does not change its state. It means w_j should be relatively large. On the contrary, when the balance of the proportion becomes worse, it is desirable to raise the transition rate in order to reach the desired proportion in a short time. It means w_j should be relatively small. Hence, it is necessary to introduce a dynamics to change the value of w_j flexibly depending on the balancing condition. In this paper, we realize the dynamics by combining the transition rates and the concentration of volatile external materials. Here we call this material as "a stock material", which is inspired by the chemical signals of social insects. As known well, social insects communicate by chemical signals and establish well-ordered society.
The quantity of the stock materials P_j is assumed to obey the following equation.

$$\dot{P}_j = -\tau_j P_j + c \cdot n_j,$$

where the first term on the right hand side represents the decay of the material, and the second represents the production of the materials by n_j robots which engage in task j. τ_j is a decay time of jth stock material. Here τ_j and c

is a constant. The value w_j, which regulates the transition rate, obeys the following equation.

$$w_j = \frac{k}{1 + exp(-\beta(P_j - L \cdot \alpha_j \cdot \sum P_m))},$$

where β, k, L are constant.

3 Simulation

In this section, we discuss the performance of the proposed model by numerical simulation. The simulation condition is as follows:
$n = 500, \alpha_1 = 0.5, \alpha_2 = 0.3, \alpha_3 = 0.2, \tau = 40.0, k = 20.0, L = 0.8$ and $\beta = 10.0$,
where the desirable ratio of the states 1, 2, and 3 is 5:3:2. As an initial condition, all the robots are assigned state 1 and the stock materials $w_j|_{t=0}$ are all set as zero.

Fig.3 shows a typical example of the time evolution of the simple probability model(a) and that of the proposed model(b). Responses to the disturbance applied to the proposed model are also shown in this figure, in which all robots in state 3 are forced to be state 1 (Fig.3(c)) and all robots in state 3 are removed (Fig.3(d)) at $t = 30000$.

Fig.3(a)(b) shows the average ratio between state 1, 2 and 3 is almost maintained as we designed in both models, but the fluctuation observed in the simple probability model is larger than that of the proposed model. Fig.4 shows the histogram of the number of robots in each state for a constant duration. As shown here, the variance of the proposed model is smaller than that of simple probability model.

In division of labor, it is desirable that the robot engages in the same task as long as possible. It is because task change often leads to the loss of cost, time, and so on. Adam Smith (1776) claimed that one of the most important points of the division of labor is "better organization of work, which saves time in changing task." Fig.5 shows the time evolution of the state in 100 robots which are selected randomly.

As shown here, the robots based on simple probability model change the task frequently, but the robots based on the proposed model tend to engage in the same task longer. Fig.6(a) is the time evolution of the total amount of task changes, and fig.6(b) is the frequency how long each robot engages We measured how often the robots changes the tasks and how long each robot engages in the same task (Fig.6).

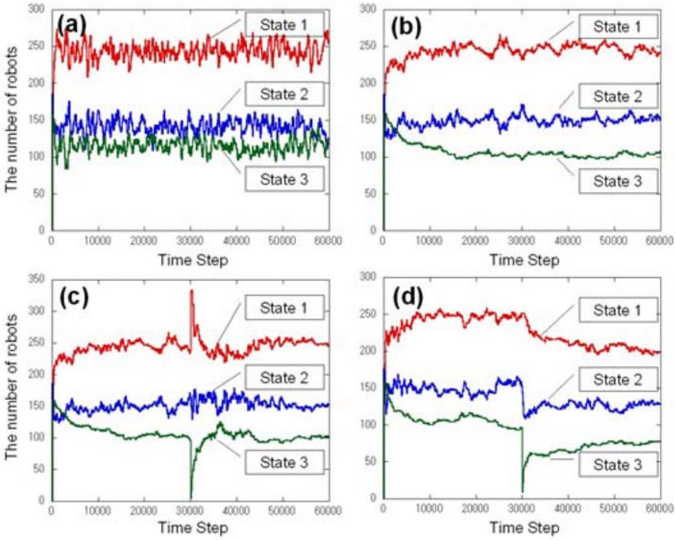

Fig. 3. The time evolution of the number of robots in each state. (a) Simple probability model. (b) Proposed model. (c) Response to the disturbance that all robots in state 3 is forced to be state 1. (d) Response to the disturbance that all robots in state 3 is removed.

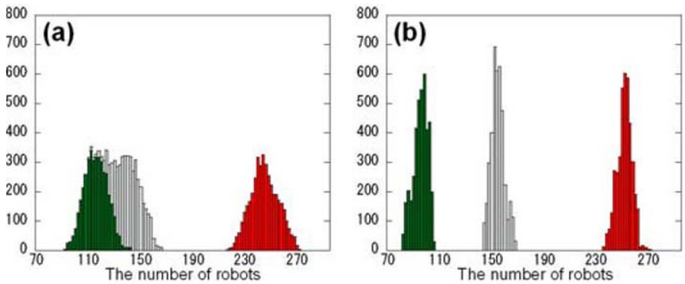

Fig. 4. Histogram of the number of robots in each state for constant duration. (a)Simple Probability Model. (b)Proposed model.

As you can see, the performance of the proposed method is much better than that of the simple probability model from the viewpoint of the task changes.

We also confirmed that the system shows same equivalent performance even if the transition rate is asymmetric. We set $\alpha_{31} = 0.5, \alpha_{12} = 0.3, \alpha_{23} = 0.2$ and the others are set as zero. One typical example is shown in Fig.7.

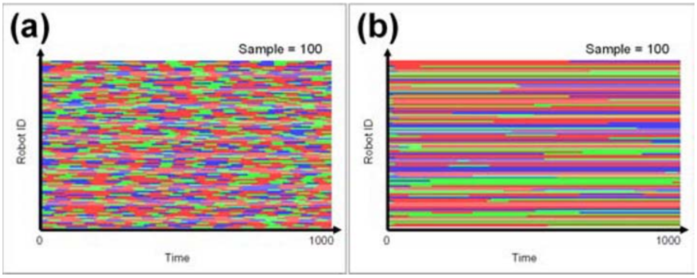

Fig. 5. Time evolution of the state in 100 robots. (a)Simple Probability Model. (b)Proposed model.

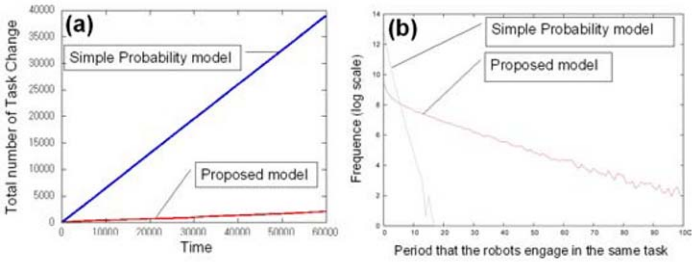

Fig. 6. (a) Total amount of the robots which change the task. (b) Frequency how long each robot engages in the same task.

In this figure, we confirmed the stability of the system. A ll robots in state 3 is forced to be in state 1 at $t = 30000$ as a large disturbance. As shown here, the system maintains the desired proportion even when large disturbance is added.

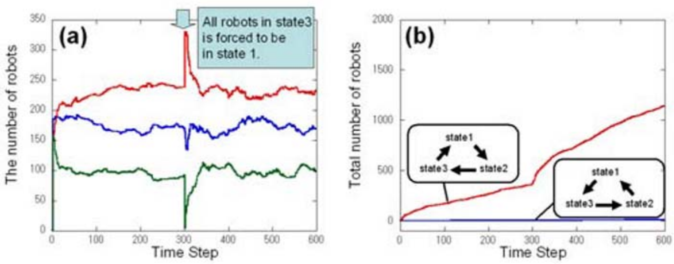

Fig. 7. Performance of the system which has an asymmetric state transition probabilities. All robots in state 3 is forced to be in state 1 at t=30000 as a large disturbance. (a) Time evolution of the number of robots in each task. (b) Total number of robots which change the task in each direction.

4 Experiment

4.1 Experimental equipment

First, we explain the overview of the experimental equipment. In the experiment, it is necessary to express volatile materials which can be detected by the robots. In this paper, we utilized "Virtual Dynamic Environment for Autonomous Robots (V-DEAR)[14]" for the robot experiment, in which the volatile materials are virtually expressed by light information (Fig.8(a)). This equipment comprises a LC projector to project the Computer Graphics, CCD camera to trace the position of the robots, and a PC to control them. Since the robots in the field have some light sensors on the top, they can measure the color and the brightness, as the field condition. Here we realize the dynamic interaction between the environment and robots.

In this experiment, we use a miniature robot "Khepera" (Fig.8(b)), which has a full-color LED and three color sensors on the top. Each robot indicates its condition by the LED, and acquires the light information using the sensors. The experimental field(Fig.8(c)) has three paths, which are assumed to be "task." Fig.8(d) is the schematic of the experiment. The robot in the nest measures the quantities of volatile materials, i.e. measures the color and the brightness of the light, and decides the task it should engage in. The field has three paths which represent "the tasks", and the robot passes the corresponding path. When it passes the path, the robot turns on the corresponding colored LED. V-DEAR detects the color of the LED on the top of the robot at the entrance and updates the quantity of the corresponding volatile material. Here the quantity of the materials is expressed by the brightness of the projected CG. Fig.8(e) is a snapshot during the experiment. Here the stock material 1, 2 and 3 are expressed by blue, red and green, respectively, and the quantities of the material are expressed by the brightness of each color.

4.2 Experimental result

We reveal the typical behavior of this system. Fig.9 is the time evolution of the number of robots in each state. Fig.9(a) and (b) are the time evolution of the number of robots in each state based on the simple probability model and on the proposed model. Here the desired ratio is 1:2:3. As the size of the group is small, fluctuation of the simple probability model seems to be large, but the proposed model maintains the desired ratio for long time. Fig.9(c) shows the response to large perturbation. Initial number of robots is 9, and initial population in each state is 3:3:3. Here the desired ratio is 1:1:1. We eliminated all the robots in state 1 at 120 s. As shown in this figure, the ratio converges to 1:1:1 rapidly by reallocation.

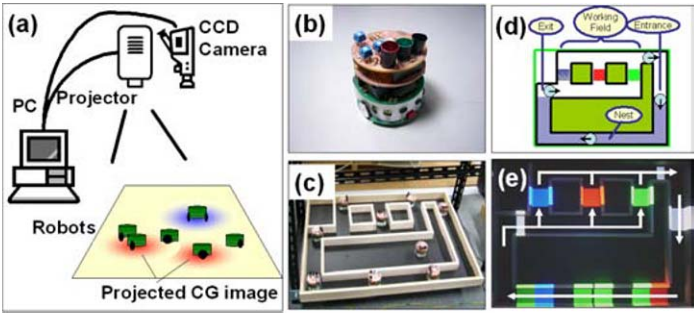

Fig. 8. (a) The schematic of V-DEAR. (b) Khepera robot for this experiment. Color sensors and a full-color LED are attached on the top. (c) The field for the experiment. (d) The schematic of the experimental field. (e) A snapshot during the experiment.

5 Conclusion

This paper addressed the proportion regulation of population in a homogenous multi-robot system. This was inspired by the task allocation of social insects. We focused on the proportion regulation of population and proposed the extended probability model. First, its performance was confirmed by numerical simulations. Second, we applied this model to a real robot system. Using V-DEAR and Khepera robots with extended sensors and indicators, we confirmed its effectiveness, especially by comparing it with the simple probability model.

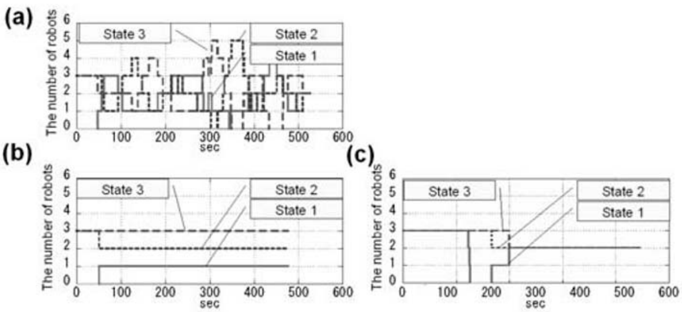

Fig. 9. Time evolution of the number of robots in each state. The total number of robots is six. The initial ratio is 0:1:1 and the target ratio is 1:2:3. (a) Simple probability model. As each robot frequently changes its task, the number of robots in each state fluctuates considerably. (b) Proposed model. The ratio rapidly converges to 1:2:3. (c) Response to large perturbation. In spite that all robots in state 1 are eliminated at 120s, the ratio converges to 1:1:1 rapidly by reallocation.

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