Toward Social Robotics

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Abstract

This paper describes conception of social robot system as self-organizing system. Distributed autonomous robot system is not autonomous as a group, if the system totally depends on the external intervention to maintain its fundamental function. We discuss the meaning of autonomy for group robot system and a concept of collective autonomy as a fundamental framework for design of the social robotic system. It is firstly discussed the difference between cooperative and self-organizing behavior. After brief review of the classical self-organizing system theory, we present the self-referential coupling of self-organizing systems as a design framework of the collective autonomous system. Through primitive simulation model, we also discuss relation between redundancy and optimality in the system structure.

Introduction

Group robot system is expected to take an important role for tasks which require massive labor powers, capabilities of various structure formations, and functional and structural flexibility. For these advanced feature, the self-organizing properties will be essential. Also, since cooperation among robots is the most basic issue, much work has focused on the topic, such as cooperation architecture, learning schema, including self-organization. Hence, it should be noticed the difference between the cooperative and the self-organizing robot system. In a cooperative robot system, multiple robots "intentionally" work together for a common goal. In most cases, the content of task is commonly shared and recognized by each robot. The problem in cooperative robot is focused on the efficient implementation of the given task with communication, negotiation. Sometimes a behavior-based approach is taken, but its aim is identical. However, intentional cooperation becomes difficult as the number of robot increases such as in a group robot system. The self-organization is a process of the spontaneous order emergence through the local interactions, and is not produced by individual intentional behavior in general. It means that the cooperative phenomena cannot be explained directly as a result of architecture or learning and optimization of individual behavior. Self-organization occurs by non-trivial effect of the dynamics of interactions among agents and also with the environment. To realize the group behavior, various approaches have been attempted. Cellular robotic system (CEBOT) is aiming at realization of dynamical structure reconfiguration of robots according to the environmental changes[6]. Principle of group formation and structure organization with a large number of robot is explored[7]. Self-organizing temporal behavior is applied to the group level coordination[5]. Several types of group behavior are realized based on selection of the basis behavior of robot[9]. It is also reported that diversity of strategy selection tends to stabilize chaotic behaviors[10]. However, no standard framework for designing group robot system is proposed so far. Also, not only stabilization or realizing pattern in the group behavior, we would like to find more constructive meaning for the self-organizing behavior. Because, the meaning of the self-organizing pattern is found only in the relation with components or the other systems and the environment. Otherwise, the produced pattern has no functional meaning itself. Most of the conventional works on group behavior have devoted efforts to realize a pattern formation without much discussion of its functional aspect. The work for understanding and realizing group behavior should be respected. But, this paper insists that the group robot system should be treated as a functional organization network system, i.e., a kind of social system. Actually, the social animals /insects like ants and bees, organize an amazing society based on the various labor differentiation and maintain themselves through self-organizing group behaviors, coping with a dynamical environment. The fundamental purpose of this work is to peruse the design framework of organization network of group robot system. The key concept is a collective autonomy, and self-producing properties which will be obtained through self-referential coupling of the self-organizing process. In the following sections, we firstly discuss the matter of cooperation and competition as a local coordination, and we proceed the issue of self-organization where we outlook of classical theory of self-organization. Then, the notion of collective autonomy and a general structure of self-organizing process focusing on relation between the system and environment is presented. In the discussion, we point out the problem to overcome for realizing self-producing properties and propose a framework for the organization network. Finaly we show rather primitive simulation work where robot can select how much they depend on environmental condition internaly.

From Cooperation to Coordination

In general, we consider that the system is cooperative when its condition seems to be coordinated or balanced through the interaction between agents. In order for the system to evolve to the coordinated states or maintain harmonious condition, there seems to be different types of cooperation; *intentional cooperation* and *nonintentional (implicit) cooperation*. In the following, we describe the difference between these cooperative systems in terms of design methodology.

Intentional Cooperation
Intentional cooperation is characterized by a metaphor, such as teamwork or collaboration, where agents work together for the *shared purpose* or a *common goal*. Therefore, the form of cooperation in this type is task-dependent. Tasks often considered are object handling, luggage transportation, resource sharing, cooperative navigation, environment exploration, and map building etc. Related issues are deadlock avoidance and resolution, negotiation protocol, prediction, planning and scheduling etc. Learning abilities are also essential. These issues cover large part of domain in multiple robot system. However, most of the work are case-dependent and a general methodology has not been established. This indicates that cooperative behavior is pre-programmed in which task information is often explicitly incorporated to behavior strategy. In real world, cooperation form is rather situation-dependent. The same task may require a different cooperation form according to the change of environment. Therefore carefully pre-programmed cooperation strategy is not effective for dynamical task environment. Evolutionary approaches are under explored in recent years. The scheme of intentional cooperation, which can deal with local and closed up problems in MAS, depends on the function and ability of individual agent in terms of hardware structure and intelligence level. In this sense, more rigorous research should be performed for realizing intelligent agent. Particularly, for more complicated tasks, task interpretation of other robots should be pursued for higher level collaboration. Also, cooperation between heterogeneous functional agents should be more discussed. Where, different kind of sensory information is utilized. Distributed sensing becomes the fundamental technique for advanced cooperation strategy for such problem.

Emergence of Cooperative Behavior
Since the abilities of individual agent, in terms of perception and information capacity, are limited, it is difficult to consider that agents can share the common information in a large scale system. So, without knowing the global information, is it possible to realize the global coordination ? Typical successful examples can be seen in the biological system, i.e., societies of ants and bees etc. It is hardly assumed that the ants or bees recognize their purpose of behavior or any leaders exist to coordinate numerous autonomous agents. What is meant by implicit cooperation is thus the spontaneous emergence of coordinated or coherent states due to the self-organizing effects of a large group of interactions, which cannot be explained directly in the level of intentional behaviors. The paradigm of group intelligence or collective behavior has been attracting research interest from the view point of behavior science, as well as engineering applications. It is truly inter-disciplinary field of nonlinear physics, chemistry, biology, social science, robotics and the other engineering fields, etc. Self-organizing robot system (SORS) is a multi-ARS which exhibits emergence feature to coordinate its global behaviors. Research targets include realization of pattern formation in the group behavior which is explored by real multiple robots as well as simulation work, collective learning and evolution based on the biologically inspired approaches, and also philosophical consideration from the view point of system science. We believe that SORS has a great potential for realizing advanced flexible system. However, since theoretical foundation for design principle is still the stage of under explored, it will take time to reach the level of the use for engineering applications and to prove its powerfulness, except very limited cases. In research for the group robotics, we can have two types of possible view for robot. One is conventional view; a machine for executing the given task. In other words, that is application-oriented viewpoint which regards much on the aspect that how efficiency is improved by introducing the robot system. Another is principle-oriented viewpoint where the ARS is considered to be a testbed for the study of complex group behavior. For this research, the purpose is to understand and explore the mechanism of the cooperative behavior, where a hypothetical model is addressed and verified through construction using *programmable* agent; robot. Both of viewpoints are essential, but it should be careful that misunderstanding of these research approach can cause meaningless criticisms each other.

Role of Competition
One thing we have to add to consider the cooperative behavior is importance of *competition*. In conventional research, conflicts between agents are believed to be excluded from the system. Numerous methods have been proposed to avoid and resolve competitions in various situations. However, it is interesting enough to observe that even the competition takes an essential role for global harmony in natural world. In large scale systems, we can raise many examples that some local conflicts and competitions often bring an important effect to global coordination. Relation between pray and predator is a fundamental for maintaining ecosystem, where the local competition is indispensable. One of the fundamental process in self-organization is a balance of positive-

feedback and negative-feedback. The former implies to facilitate the growth of some factors, and the latter indicates reflection for the growth. Also, internally caused fluctuation becomes the trigger for the system to develop. In this sense, the role of cooperative behavior is considered to be positive-feedback and competition is regarded as a negative-feedback or fluctuation. In particular, fluctuation is a cause of disorder, but it also give diversity to the system, that is, the chance of evolution. In designing self-organizing cooperative behavior, we must understand the relation of these processes in contrast with actual behavior and interaction rules. The role of competition is, thus, as important as that of cooperation for the global coordination in the MAS.

Self-organizing Cooperative Behavior

Group behavior exhibited by self-organizing effects is not explicit intentional behavior of individual agents. The reason why we investigate this kind of behavior is following; robot society, which is composed of a large number of robotic agents with flexible structure and emergence capability, is prime goal of this research. Based on the local interactions which include information exchanges, intentional cooperation and some degree of competitions, emergent socially intelligent behavior is expected to coordinatie the large scale system[2,3,6,7,8]. In the living system of nature, such a example is abundant. This fact of the universality of complex behavior observed in interdisciplinary fields, gathers much interest and many results have been obtained in nonlinear science. In the follwing, we discuss what features of self-organization should be provided to design the MAS.

Forward and Inverse Problem in Self-Organizing System

There are two basic stances for the research on collective behavior. From the viewpoint of scientific attitude, we are interested in why simple rules and mutual interactions can cause the coordinated group behavior. What kinds of relations and mechanisms should exist behind it. This can be called a forward problem for understanding processes of the self-organization. On the other hand, the inverse problem is fundamental from the viewpoint of engineering applications, where the self-organizing behavior must be designed to satisfy specific purpose expected to the system. What particular behavior and interaction rule should be imbedded to each agent for the purposive group behavior ? For this inverse problem, two approaches are considered. One is that the designer investigates the forward problem and attempt to utilize obtained principle to establish the system[8]. Another is to let the system solve it. This is what the living systems actually implement. For the moment, let us consider the former approach. In order to solve the inverse problem, the forward problem must be revealed. Unfortunately, the most of the research works on group behavior do not attempt to analyze and reveal the behind principle of emerging behavior, although some kinds of interesting behaviors are presented. They are often explained as a result of the learning or adaptation of each agent to the environment. But this does not give the fundamental answer, because what should be explained is a relation of processes for evolution. Hence, it should be noted that our knowledge is not yet enough to establish satisfactory group robot system for actual applications. Therefore, constructive approach is taken, where a conjecture model is constructed and tested repeatedly.

Outlook of Self-Organizing System

Designing self-organizing system starts from understanding its basic mechanism. But, so called *self-organization* is discussed in so wide ranging contexts and different meaning. There are several classes in self-organizing system. The aim of discussion in this section is, therefore, to give an outlook of the level and features of self-organizing system and consider which level of theory and concept is applicable to social robotic. The self-organizing system often discussed can be categorized as follows;

Level 1: Physical / Chemical System
Level 2: Biological System
Level 3: Social System

Common features among them are that 1) the system is collective system and 2) it exhibits spontaneous structure emergence. Let us discuss respective class in more detail.

1) Physical / Chemical System

This class of self-organization is extensively investigated. Many mathematical theories and models are presented for complex pattern formation and chaotic behavior due to collective interactions. The component unit of this system is atom or molecular. But the molecular is not deserved to be called as a *agent*, because it is not considered as autonomous. It dose not recognize environment, and just follows the physical and chemical laws of the nature. Physical and chemical system is not living system by itself. However, obtained results are often useful to understand a partial process of the activity of biological or social system when the system is analyzed from the macroscopic viewpoint, where individual characters of the agent are averaged and the dynamics of the system are often reduced to low dimensional dynamics for simplicity to the mathematical treatment. It is often pointed out that this treatment may erase fundamental properties to understand more complex behavior. Bifurcation and chaos, dissipative structure, synergetics, catastrophe theory etc. are well known theoretical framework. However, the self-organizing system in this class is not autonomous because the self-organized structure depends on boundary condition and which must be sustained by exterior of the system. See fig.1. What is mostly required to the living system is the characteristic of self-regulation of self-organization.

2) Biological System

Biological system is obviously a living system. The component of system is *cell* which can be considered as autonomous agent. Neural network and immune network in creature are self-organizing system which is well investigated. Biological system is a network system composed of heterogeneous functional organization. Cell is also heterogeneous, but the interesting fact is that the characters of cell depends on its location in the system, in other words, it depends upon the characters of the other cells around itself. Biological system is thus, a *self-referential system* in that each cell affects characteristic of neighbor cells and vice versa . It follows not only natural law, but also the genetic rules which are acquired in the evolutional process. The largest difference between living system and nonliving system is ability of self-producing of the rules, to which the components obey. Although these are observable fact, its fundamental mechanisms are still open problems in life science. Many of the theoretical basis are given from physical / chemical nonlinear science. But also, philosophical issues are often discussed. Autopoiesis has been presented for the definition of biological autonomy, and its concept is innovative, but it does not cover all of the features of biological activity.

3) Social System
The social organization is also a living system and the most complex system in this classification of the self-organizing system. There are several advanced considerations for the social system, but mathematical formulation seems to be very difficult. Some attempts have been made to grasp a fragmented aspect of social phenomena by chaos and nonlinear dynamics. But there is much argument for the way of treatment which ignores diversity of characteristics of the agents. Compared with the biological system, role of symbolic information of language, political balance, and self-organization of information network become more explicit.

Collective Autonomy
Based on the consideration, it can be suggested that the common feature in self-organizing system as a living system is the ability of internal regulation of rules which define organization and disorganization of the system structures. Hence, the system structure indicates the rule structure as well as the physical structure. According to social science, the *social structure* denotes relation of the rules, such as social laws, custom, regulations etc. Based on the rule structure, the physical structure; spatial pattern and distribution of agents etc., will evolve. Also, the rule structure is reorganized through negotiative process among the agents, which is dependent on the physical structure. This coupling self-organizing processes enable consecutive evolution in the context of the environment. Fig.2 depicts this conception. Self-organization of rule structure and physical structure are coupled as self-referential system. Now, let us consider how this conception can be applied to robotic system. Component unit of the social system does not have to be a biological agent. There can be a social

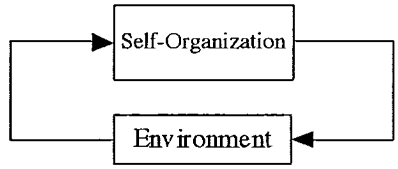


Fig.1 General Form of Self-Organization

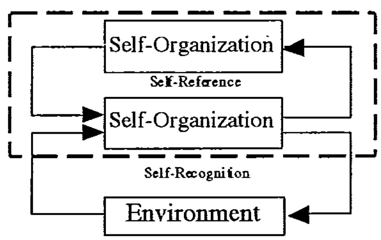


Fig. 2 Self-referential coupling of self-organizing systems

system composed of artificial autonomous agents, that is a robot society. In the distributed autonomous robot system (DARS), robots are designed to be autonomous. Therefore, the DARS is interpreted as an autonomous system, because it is composed of autonomous agents. However, if the system is merely aggregation of the robot and its group behavior totally depends on given constraints or control from outside of the system, the system cannot be considered as an autonomous system. As long as the system depends on environmental changes and has no capability for maintaining a peculiar structure or function as an organization of the group system, it is not collectively autonomous even if the system indicates the self-organizing properties. Hence, if the group system composes network structure as a functional organization, internal relation of network can generate diversity and flexibility augmentation. We call this group level autonomy as the collective autonomy, distinguishing from autonomy of individual robot. The most important and fundamental difference between individual and collective autonomy is that, the former is inherently autonomous, but the latter is emerged feature through the structural organization of the functional network.

Design of Organization Network

Basic model description
We are going to discuss an example of the collective autonomy. Let us consider a minimum level organization network of resource mining task, as shown in fig.3-(a). The model represents the relation of functional processes of robot society, that is, resource mining, resource and energy transportation, and parts assembling task. The symbols used in fig.3 are defined in table 1. In this model, energy is supplied from environment to the site ET, and the energy is distributed to site P and R through path T1 and T3 respectively by the robots. At site R, robots execute resource mining task. The resource is transported to and consumed at site P or RC for the parts assembling and

energy conversion. The converted energy at RC can be carried to ET for energy supplement. Environmental constraints to the system are twofold; constant energy supply from site ET and request of part production at site P. Parts are constantly removed from P. If too many robots work for parts production, the labor power to energy supply and resource mining decrease and this deteriorates coordinated balance of total system function. This system depends on energy supply to ET from outside of the system. What we are going to see is how distribution of the population can be organized according to change of energy support.

Multi-layer Network Expression

Pattern of labor distribution is only meaningful in the relation to the other information, namely distribution of energy and resource flow. Hence, observation of the system is a projection with respect to particular viewpoint and criteria. If we focus on labor distribution of the system, network structure depicted in fig.3-(b) is obtained. In our model, fig.3-(b), (c), and (d) represent energy flow network (EFN), population flow network (PFN), and resource flow network(RFN), as a projection of the structure fig.3-(a) which is the total social network. Since robots transport energy and resource from site to site, energy and resource flow is caused by population flow network (PFN:3-(b)). Also labor distribution is reorganized dependent on pattern of energy and resource flow network. Thus, these spatial patterns in the network are closely coupled. Figure 4 represents the conception of this relation. In short words, changes of one pattern is caused by state of the other patterns. Self-organizing patterns continuously evolve such that it satisfies the environmental condition.

Nonequilibrium and Purpose generation

How is population flow network self-organized is following; Behavior of the robot is determined purely based on the internal observation in the society, not based on the evaluation defined outside of the system. Therefore the task and purpose for each robot are determined in a relative context and location. So, the fundamental principle to which every robot should obey is defined to reduce the difference between the current state and the one to be realized. The difference between the sites which is obtained by eq.(1), (nonequilibrium condition of the site) is a driving force of purpose generation. Robots recognize energy and resource amount of neighboring sites, and decide next task type with eq.(2). In other words, robot recognizes the nonequilibrium condition between the location site and neighboring site (eq.1). Then task selection is performed based on the ratio of concerning nonequilibrium conditions(eq.2). Task kind is defined in tab. 2. For example, if robot is located in the site P, and recognized shortage of the resource for parts assembling despite energy amount is satisfied, it heads to the site R via route T4 to supply resource to the site P.

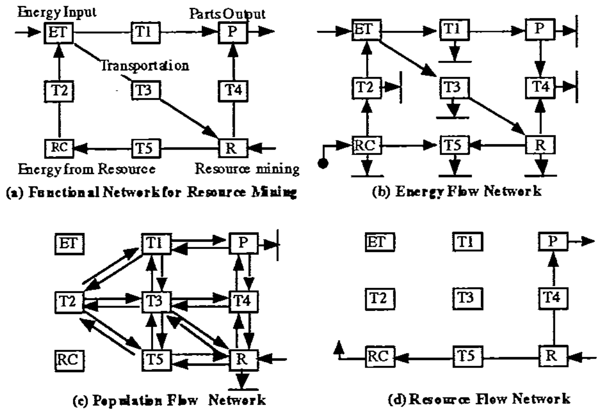


Fig.3 Organization network structure for respective information currency

Table 1 Role of the site

ET	Energy Tank site
P	Parts assembling site
R	Resource mining site
RC	Resource to energy conversion site
Tx	Transportation paths (x=1 to 5)

Table 2 Task type of robot
((*) denotes energy consumption for a behavior. cf. tab.3)

1	Resource mining (m)	5	Energy explore (e)
2	Resource supply (e)	6	Assemble parts (b)
3	Resource explore (e)	7	Doing nothing (0)
4	Energy supply (e)		

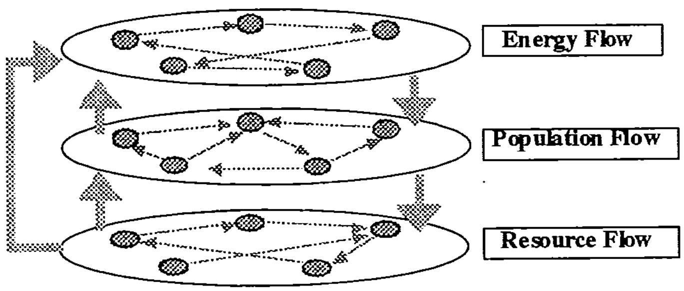


Fig.4 Interdependence of network structure

Table 3 Simulation setup value
([*] denotes unit of amount.)

1) total robot number N:	100
2) transportation step t [T]:	10.00
3) energy carrying/robot e [*l*]:	3.00
4) resource transportation r [*k*]:	1.00
5) energy consumption d [*l*]:	0.50
6) resource mining cost m [*l*]:	1.00
7) parts assembling cost b [*l*]:	2.00
8) resource exchange rate c [*l*/*k*]:	(8.0)
9) energy supply/time E [*l*/T]:	(3.00)
10) parts demand/time P [*p*]:	2.00

$$\mu_i = \begin{cases} (x_i - x_c)^2 \\ 0 & iff \quad x_i > x_c \end{cases} \qquad (1)$$

$$\Delta\mu_{ST} = \begin{cases} \mu_S - \mu_T \\ 0 & iff \quad \mu_S > \mu_T \end{cases} \qquad (2)$$

where μ_i denotes shortage from critical value x_c of energy or resource at each site. Also, $\Delta\mu_{ST}$ represents gradient of the nonequilibrium potential between the sites.
The decision of robot becomes different dependent on its location. Every condition and task selections is situation dependent. Also, since energy and resource transportation are carried out by the robots, structure of EFN and RFN is organized based on the spatial pattern (structure) of PFN which denotes labor distribution on the network. In this meaning, pattern of PFN is a constraint condition of EFN and RFN organizing processes. On the other hand, since the labor distribution is reformed to facilitate solution of the nonequilibrium state, the structure of EFN and RFN are constraints conditions of reorganization of PFN structure as well. These networks are impossible to divide each other and have meaning only in the context of inter-relation of the other network structures.

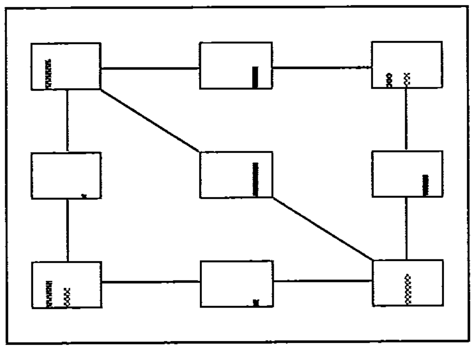
Simulation of Network Behavior

Structure organization

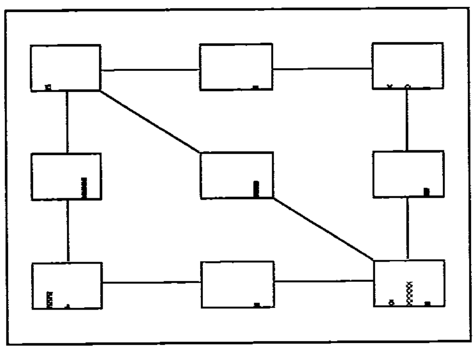
This section examines a relation of structure reorganization due to dynamical labor distribution. Time average labor distribution (PFN) characterizes behavior of the network system. If the energy supply is sufficient, the robot can fully work without considering energy amount. They work to produce the parts as many amounts as required, and PFN is organized as such. On the other hand, if the energy supply is not enough, some parts of robots should be distributed for the task related to producing energy from the resource. This simulation is performed to examine that network robot system performs as expected according to the energy supply. Population of the robot is 100. The other simulation setup values are shown in tab.3. Figure 5 depicts the time average network structure of labor distribution, where bar graph at respective site represents energy, resource stock, and population from left to right order. As shown in fig.5-(a), in case that sufficient amount of energy is supplied, most of the robots are allowed to engage in the task which is related to the parts assembling job. However, in the case of the lack of energy supply, since every behavior of robot requires certain amount of energy, a large part of labor power must be devoted to energy producing task. That is, many parts of resource obtained at site R are carried to site RC in order to convert it to energy, and transported to site ET. The self-complimentary structure for energy shortage ET-R-RC is organized with internal regulation as shown in fig.5-(b).

Diversity, Redundancy, and Optimality

When one considers what is a good system, we will find that the answer is situation dependent. This section discusses the relation between diversity and optimality. To show this, let us consider a network structure which is disconnected to RC as shown in fig.8. Hence, let us call the network structure of fig.2(a) as type I and the one without RC site as type II. Figure 6 shows the comparison result of the total parts production output from the site P during 1000 time steps changing energy supply E. The other setup values are the same as the one as shown in table 3, except resource exchange rate c. c10, c14 indicate the value of resource exchange rate c. We discuss a relation between diversity and optimality. Let us consider a network structure which is disconnected to RC as shown in fig.6 right. Hence, we call the network structure of fig.2(a) as



(a) In case of Sufficient Energy Supply (E=10)



(b) In case of Insufficient Energy Supply (E=3)
Fig.5 Time average of Network Structure

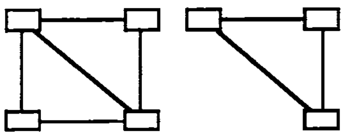


Fig. 6 Structure type of the Network

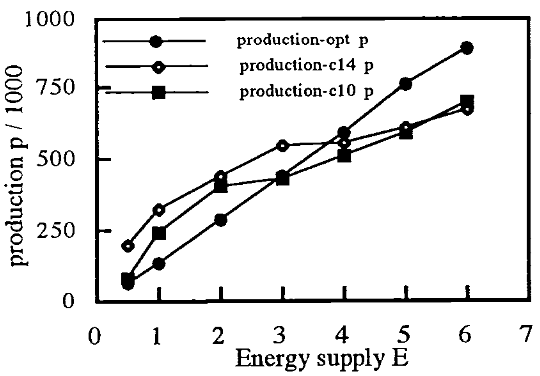


Fig.7 Total parts production during 1000 time

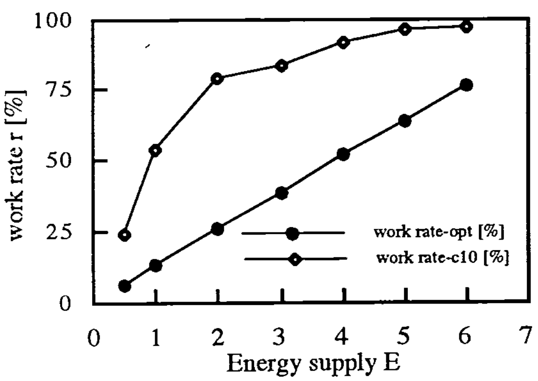


Fig.8 Average work rate of total population

type I and another without RC site as type II. Figure 7 shows the comparison result of the total parts production outputs from the site P during 1000 time steps changing energy supply E. The other setup values are the same as the one as shown in table 3, except resource exchange rate c. c10, c14 indicate the value of resource exchange rate c. In the fig. 6, production-opt denotes total output in case of the network type II, while the others are results in case of type I. Both type I and type II require energy support. When energy supply is sufficient, type II network is more efficient in terms of parts productivity, because RC (energy conversion) is a redundant part and all labor powers can be devoted to part production task in this case. However, the performance of parts production is sharply affected to the energy supply from outside. Robots work only when the working condition is satisfied by exterior support. Therefore, most of the robots cannot work in case of the energy shortage as shown in fig.8. Where, the work rate is time average ratio of the actual working robots in the total population. While, since typeI network can distribute some parts of the labor power to the energy conversion task in RC even when the energy is sufficiently supplied, type I cannot perform better than typeII in case of enough energy supply because such a labor distribution is a redundant in this case. But in the case of energy shortage, RC site of the system takes an essential role to maintain work ratio as shown in fig 8, therefore the decrease of productivity is suppressed. Productivity of typeI and typeII is reversed in this case. So, these results show that there is a trade off between the network efficiency and a potential ability of coping with dynamical changes. In engineering field, we tend to peruse optimality for the system, but it is valid only in case that the necessary condition is satisfied from outside manipulation, but it implies that the system is not autonomous by itself.

Conclusion

We described a conception of collective autonomy for social robotics. The self-referential coupling of self-organizing process is presented. The primitive example is illustrated. Currently, we are studying on a mechanism of self-regulation of self-organization, that is related to organization and disorganization of system structure base on the presented concept. It seems work.

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