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Design of the Mechanism for Emergent Perceptibility of Autonomous Agents

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Preface

The environment contains enormous amount of information in wide divergent forms. We are somehow behave appropriately in the environment with the limited number and sort of sensors, such as eyes, ear, and so on. Animals also behave appropriately in the environment with the limited sensors different from that of the ours. " Do we perceiving the world as quite the same thing?" This question leads me to consider the another: " Do we have the quite same perception with the others when facing with the same environment?" I would like to say "No" to the both questions.

Within our human community, we can talk to each other on what we are perceiving by means of the symbols. This lead us a confusion: do we have the same perception or what we see is the same. What we mean by symbols, however, is only the surface of our complex inner system. Those symbols might be grounded differently, person by person. The perceptual model, if there exist some kinds, of each person would be different.

I then come across the next question when designing an autonomous agent that is expected to behave like us: " Should the agent have the same perception with us?" I could now decide my answer more quickly "No". However, those agent based on the Cartesian System seems to me that they have designed by the designers whose answer to the question is "Yes". The recent studies on the autonomous agents seems supporting this way of thinking. Because those agents designed to have the same, (but symbolic), perception with that of designers' are come across the several problems such as the Frame Problem, the Symbol Grounding Problem, the Lack of

Situatedness, and the Embodiment Problems. Namely, the activity space of those agent are often restricted to the designed space, so-called " Toy-World".

"How could we design the perception mechanism as a non-Cartesian System?" This is the question this thesis should answer to, throughout the thesis. For this purpose, I should ground the thoughts on some reliable ones. Fortunately, Theory of Affordance provide me of the basis of perception. With inspired by the theory, this thesis is decided to design the perception mechanism as to be able to acquire the self-measurement of the environment with respect to the behaviors of the agent.

Namely, the perception mechanism that would emerge its own view of the environment with respect to the behavior is aimed in this thesis. For this aim, the perceptual model is assumed as an inner representation system of the agent so that the agent is able to have its own inner representation of the environment. However, the representation within the system should be intrinsic to the agent itself. It means that the agent should somehow acquire the representation of the environment with respect to the behaviors. What to be learned is not the use of the representation but the representation itself. The representation together with the behavior would be considered as the perception of the agent and it is called the mechanism to achieve the representation as the Mechanism for Emergent Perceptibility in this thesis.

This will provide the autonomous agent to have its activity space to be much larger and more complex than that of the agent based on the Cartesian System. Therefore, it is expected that the agent with proposed mechanism will break through the walls around the Toy World.

For this purpose, the thesis consist of the following six chapters:

In Chapter 1, discussions the background of the thesis is made. Then, discussions on the Cartesian System on which the most agents stand is made. In Chapter 3, the theory of Affordance is introduced as a theory of

perception that has the other viewpoint than that of the Cartesian System, namely, of non-Cartesian System. Two mechanisms those are able to be regarded as the Mechanism for Emergent Perceptibility in some respects ares introduced in Chapter 4. Chapter 5 is assigned for the experiments to confirm the proposed mechanisms achieving the emergent perceptibility.

CHAPTER 1

Backgrounds of Thesis

1.1 Arts of Today

We are surrounded by the enormous amounts of information in every respect of our life. We utilize these enormous information to survive, and to execute a wide variety and levels of activities for survive. How do we utilize the information? Do we make attention to every available information? What kind of information we are perceiving? How do we capture the environment? What makes us able to behave adaptively to the environment? What makes us able to achieve intelligence? At a moment, a lot of questions are appeared in our brain when thinking of the relation among the information, our behavior, and our ability to survive. There have been enormous number of studies those will give us a lot of knowledge in the field of engineering, philosophy, psychology, cognitive science, and so on. However there is no theory that provide us an explanation on the whole mechanism of our organ to make enable us to answer to the above questions.

The same question have been coming across to us when trying to design the autonomous agents those are able to behave appropriately in the complex and dynamic environment, i.e., in the real world. Throughout the thesis, the design of the autonomous agent of this kind is aimed. At the same time, the answer from the engineering point view is made by designing the mechanism that emerges the perceptibility of those useful information for the autonomous agents.

Then, what is the autonomous agents, and what is required to the autonomous agents? To achieve the autonomy, this thesis introduces the three measurement listed bellow:

Independency

The agent should be independent of the interference from the outside the agents such as human and the other agents. This means that the autonomous agent should making decision on every respect that it is facing with. No direct intention to the decision making process is available. Namely, once the agent is beginning to work, it is independent of interference on its decision process unless the interference is made as indirect one such as persuasion or commission and so on. Even in the case of indirect interference, the decision whether it should be taking into account or not is up to the agent itself. Therefore, the agent should have some mechanism that it can understand the environment including the interaction with the others.

Adaptability

The autonomous agents should make their own decision according to the environmental situation observed by the innate sensors. This means it should somehow change its perception and the process of decision making with learning. Without this characteristics, the

autonomous agents are not expected to behave appropriately and intelligently in the real environment.

Obedience

They should also be obedient for the user of them in the basis. In other words, the agent should adapt to the diversity of tasks it is asked by the user. The agent is expected to have abilities to somehow understand its tasks, divide the task into some sub-tasks by itself, and plans its behaviors. As McFarland pointed out, the agent will be an self-sufficient one. The self-sufficient agent is make much of the self preservation. Therefore, it is not expected to achieve the task in case of it should gain energy resource, or avoiding danger.

These three factors, i.e., independency, adaptability, and obedience, are the necessary conditions for the agents to be autonomous. To satisfy the three factors, the autonomous agents should have the emergent perceptibility that organized in such a way that an outside agent cannot obtain sufficient knowledge to control the autonomous agents.

Most of the autonomous agents proposed by now are considered to be based on the same view of the world, i.e., Cartesian System. From Cartesian point of view, the agents should have the cognitive mechanism based on the images on the human retina. This forces the agents to possess the objective and physical measurements to capture the environment such as feature space and symbolic representation of the world. These measurements are given by the designer and often are fixed as previously defined. Therefore, intelligent process or problem solving realized by the agents is limited their valid space of activities.

Furthermore, the world for the agents should be consisted of the Cartesian product of the measurements as formulated in Section 1.7. The agents based on this view of the world are able to act plausibly only in the

world that could be represented by means of those measurement. Who can prepare the set of measurement that is able to represent the complex and dynamic real world?

We are now time to explore a new view of the world that might allow us being free from the restraint by Descartes. In other words, the agents based on Non-Cartesian System, such as Affordance, should be developed to enable the agents to act in the more various spaces of their activities. The real world we are facing with requires almost infinite variety of the agent's space of activities. We will not be able to achieve the autonomous agent that behaves like us unless trying to explore the other view of the world than Cartesian System.

1.2 Landscape of the Field

The purpose of this thesis is to make the agent behave autonomously in the real world with enormous amount of information, dynamic, and complex environment. For this purpose, the several study area should be considered from the perspective of the realization of the aim.

This section is assigned to depict the fields concerned with the thesis. Fig. 1.1 depicts the place of the autonomous agents based on the proposed mechanism of this thesis will cover from the perspective of the view of the world. As shown in the figure, proposed mechanism will still also in the Cartesian World even though it should be in the non-Cartesian World in this context. It is because each methodology constituting my mechanism have arisen from the Cartesian World. However, it will not harm the purpose of the mechanism.

To depict the desired knowledge flow with study areas of this thesis, Fig. 1.2 is given. The pen-width of the arrow in the figure depict my wish

of amount of knowledge. It is of cause deeply connected with engineering, and is tries to utilize the knowledge from the other study area, remarkably from the cognitive psychology.
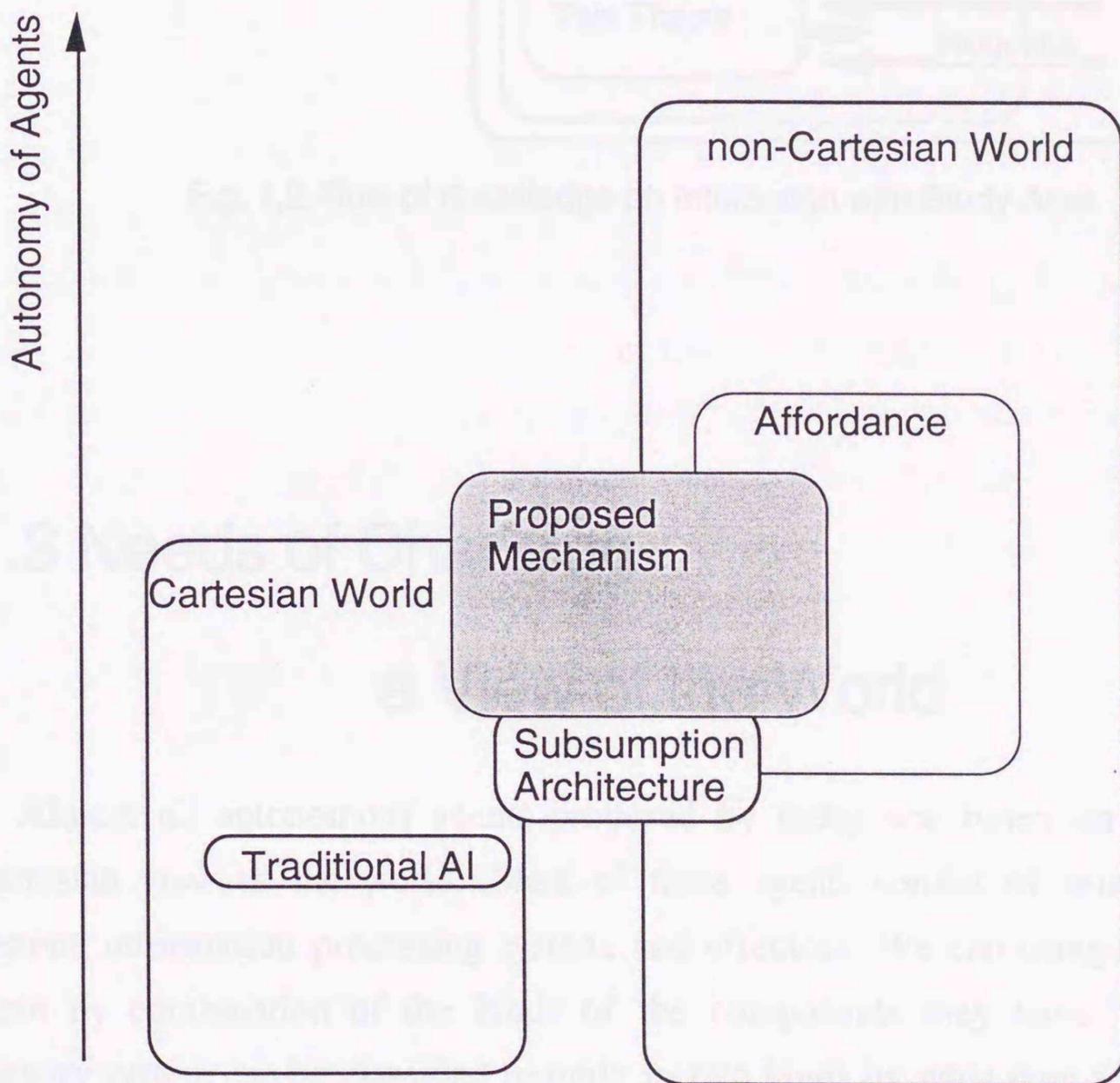
Fig. 1.1 Map from Perspective of View of World
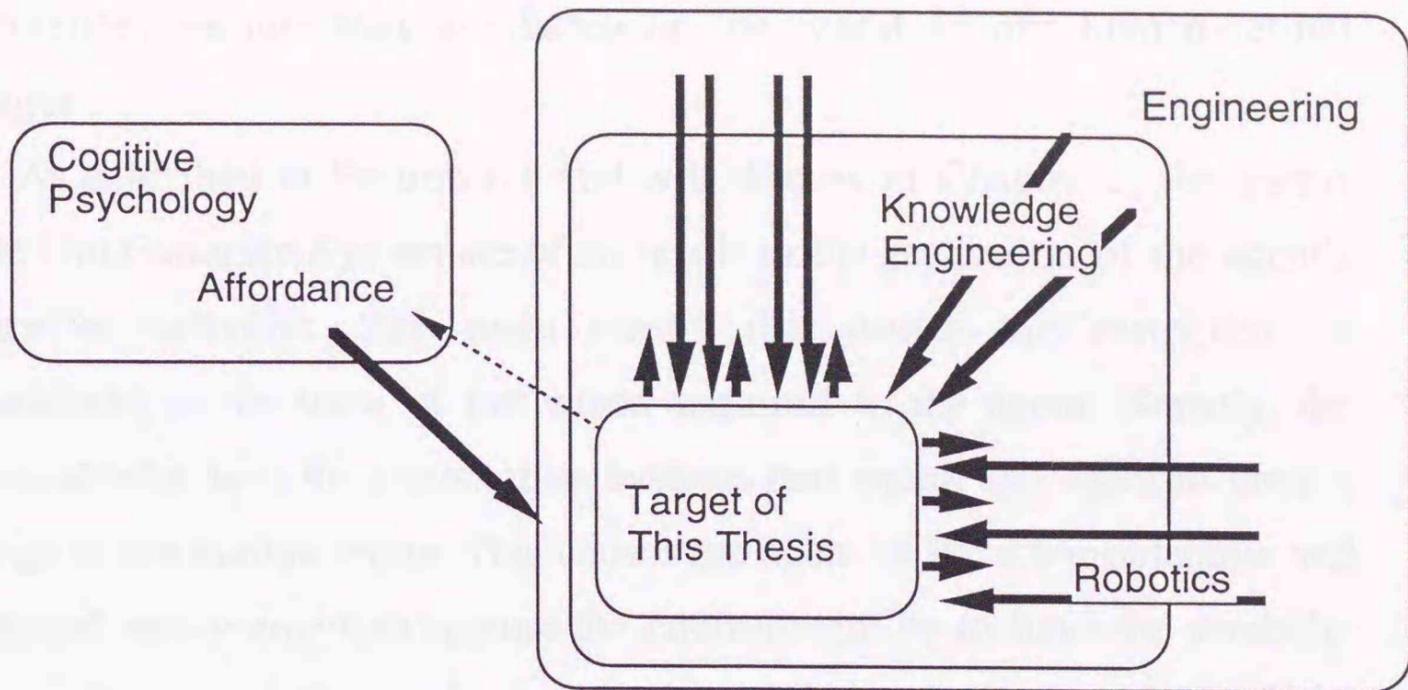
Fig. 1.2 Flow of Knowledge on Interaction with Study Area

1.3 Needs of Changing
a View of the World

Almost all autonomous agents proposed by today are based on the Cartesian view of the world. Most of these agents consist of sensory system, information processing system, and effectors. We can categorize them by combination of the kinds of the components they have. The sensory system can be classified roughly in two kinds by what they sense: physical stimulus and the symbols representing the environment interpreted by the designer. We have so many candidates for the information processing mechanisms. For example, some are based on Logic, some are based on Connectionist Approach, some are able to learn while some are not, and so on. However, the activity space of the agents with the above combination are considered to exhibit not so much

differences because they are based on the world of our human retinal images.

As described in Section 1.1 and will discuss in Chapter 2, the agents based on Cartesian System are often result in the restriction of the agent's space of activities. The main reason that causes the restriction is considered as the view of the world required to the agent. Namely, the agent should have the observation systems that enable the agent to have a image of the human retina. This causes the agent to have the objective and physical measurement to capture the environment or to have the symbolic representation of the environment given by the designer. Most of the measurement and symbolic representation are fixed, and therefore, the valid space of the activities of the agent is limited. In the case of the agent with symbolic representation of the environment, the agent's adaptability to the environment is considered to be pessimistic, the independency is all right within the assumed limited problem space, and the Obedience will be excellent in that it obeys perfectly given single task but pessimistic when applied in the environment with diverse tasks.

In the case of the agents with objective and physical measurement, the adaptability and independency of the agent is considered to be achievable, and the Obedience will be possible. However, there exist several hard problems, as described in Chapter 2, in front of us to make the agents adaptive, independent, and obedient to the level where the agents can work autonomously in the real environment. Moreover, the agents based on the Cartesian System is hard to possess its cognition at the level of " an outside agent cannot obtain sufficient knowledge to control the autonomous agent" (McFarland, 1995). McFarland discussed that an autonomous agent should have some degree of motivation and cognition, organized in such a level.

We are time to explore the other view of the world as the basis of the framework of the autonomous agents. Of course, there might exist the methodologies those are effective in the real environment. Moreover,

there might exist some artificial autonomous agents that acquires the cognition quite as same as that of ours. However, the representation achieved in the cognitive mechanisms based on Cartesian system might be quite as same as that of the designer's, even though it is acquired through the uncontrollable process such as McFarland discussed. Why should we stick to Descartes? We should explore the ideas free from the Cartesian System as a candidate for the design framework of the autonomous agents. However, this thesis is not trying to deny every each methodologies based of Cartesian System but proposing to expand the possibilities of attaining the autonomy for the agent by exploring another view of the world.

1.4 Cartesian vs. Non-Cartesian View

In this section, the differences between the Cartesian and non-Cartesian view of the world with respect to the purpose of the thesis is mainly discussed. We are accustomed to the Cartesian view of the world because our science, especially concerning with engineering, by now have been deeply dependent on it. The Cartesian View of the world requires us to simplify and subdivide the complex world to enable us to explain our world in the finite set of symbols so that the entire world would be expressible as the Cartesian product of specific representations, e.g., features. To the contrary, the non-Cartesian view requires us no such processes but seems to utilize the information directly and therefore it does not make much of the specific representation of the world. In this section, discussion on the both view of the world respectively is made, at

first. Then, brief discussion on what is the basic difference between them from the perspective of the design of autonomous agents is made.

1.4.1 Cartesian View of the world

To explain the mechanism of our human cognition, Descartes introduced the architecture so called "mind". The role of the mind is explained as the information processing to unify the stimulus from the sensors, analyze them, make inference, and to generate meanings of them. There seems no subjectivity lie between the process. Therefore, the result of the process will be a objective explanation of the physical world.

The accuracy of the explanation depends heavily on the qualities and number of the sensors. The sensors to the agents on the Cartesian System are equivalent to the world itself to the agents. In other words, Cartesian System requires the designer of the simplification and subdivision process of the world to prepare the suitable sensors for certain problems that assigned to the agent. Therefore, the agent's ability to represent the environment is fixed in most cases by the sensors given by the designer. Further discussion on this will be done in Chapter 2 and 3.

The another point of Cartesian System is that it distinguishes the self from the environment as "nature and a human that controls the nature". Namely, there are two categories of the world: a self and the others. However, the self observing the others are not more than a part of the others as quantum theory suggests.

1.4.2 Non-Cartesian View of the World

We might have so many view of the world that is not based on Cartesian System because any view of the world other than the Cartesian System may considered as non-Cartesian System. The perception mechanism based on the non-Cartesian View of the world may have the possibilities to be very different from that of based on the Cartesian System. It is because the perception realized in the Cartesian System is only the single solution to the problem: "How we are perceiving the world?". The Cartesian world might be, so to say, a local solution to the problem. There must be the other solutions to the question.

Affordance Theory (Gibson 79) would be an another solution to the problem. It differs from the Cartesian System in mainly that it makes much of the information in the environment as it is, while the Cartesian perception considers the existence of the human to have the information. More concrete, the Affordance theory pays attention to the functional properties of the environment, while the Cartesian pays attention to the physical properties (only observable ones). From these points, the Affordance is able to be considered as the object of perception needless to analyze every detail of the environment, but is perceived as a whole of the environment. In other words, the measurement of the environment in the Affordance theory would be acquired through experience of the agent in bottom-up processes, while that of the Cartesian system is given in the top-down processes.

The perception aimed here tries to beyond the Cartesian viewpoint for achieving the adaptivity, independency, and obedience, i.e., autonomy of the agents. For the purpose, this thesis is paying attention to the Affordance as to be providing us the new viewpoint of the world.

1.4.3 Differences between Cartesian and non-Cartesian View of World

From the above descriptions on the both views of the world, the differences between them are roughly described as follows:

1. The values of perception for the Cartesian view is detecting certain specific pre-defined features, while that of non-Cartesian view is just accept the environmental information.

2. The objects of perception for the Cartesian view is the physical and objective property of the environment, while that of non-Cartesian view is the functional and subjective property of the environment.

3. The Cartesian view requires the analysis process of what have been perceived and how is the environment. While, the non-Cartesian view does not require such processes.

4. Therefore, the measurement to know the environment for the Cartesian view should be prepared in the top-down process and is definite one that detects the specific features of the environment. While the measurement of the non-Cartesian view is acquired through experience of itself in the bottom-up process and will be successive one deeply related to the behavior of the agent (Fig. 1.3).

Note that only the Affordance theory is considered as the non-Cartesian view of the world in this thesis. However, it is considered that the other ideas not being based on the Cartesian view would not require the subdivision of the environment to capture it as the Cartesian product of the subdivided component of the environment such as features.
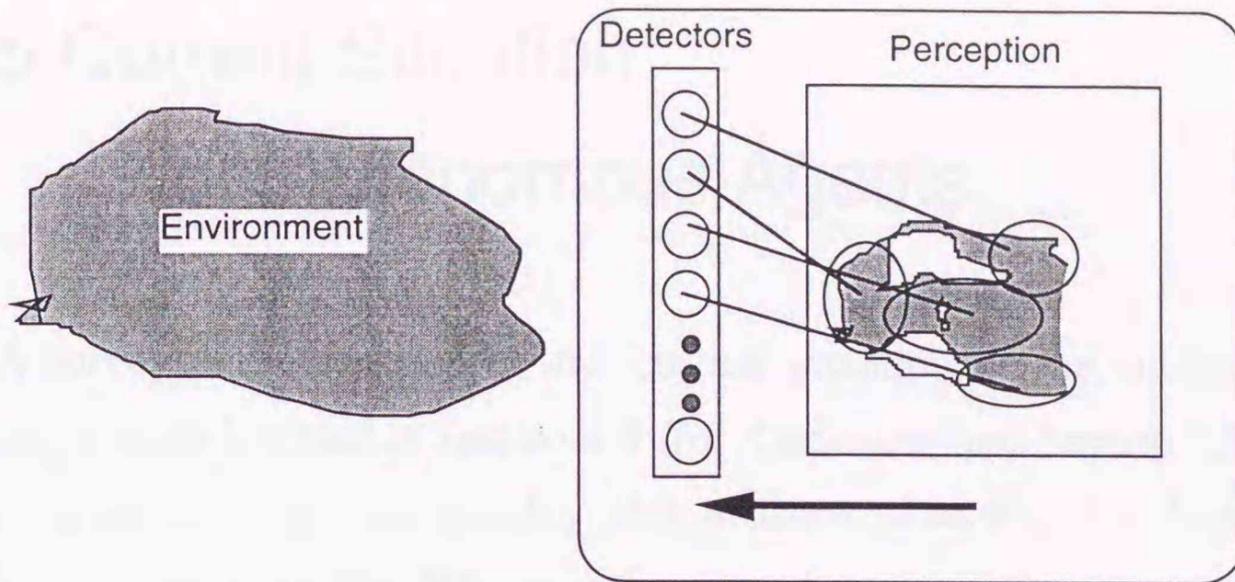
Fig. 1.3a   Cartesian View of the World

The objects of perception determines what should be
perceived.Namely the measurement applied to capture the
environment is determined in top-down process.
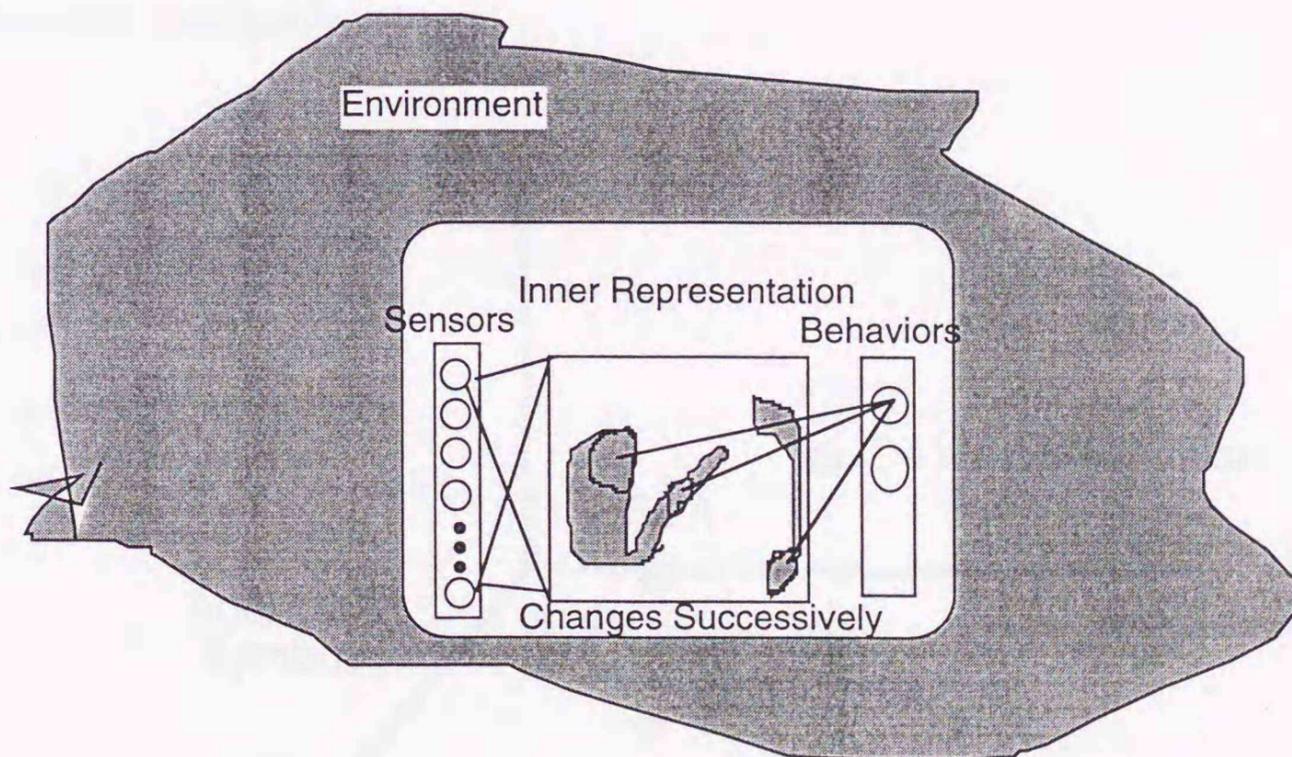
Fig. 1.3b Non-Cartesian View of the World

The Perception realized in this view is achieved by as available
behavior. The measurement for the environment will be organized
as the patterns in the inner representation through trial and error,
and therefore it is considered that it is acquired in the bottom-up
process.

1.5 Current Situation
on Autonomous Agents

A survey and discussion on the current situation of the autonomous agents is made in detail in Section 2.3 (for Cartesian) and Section 3.3 (for non-Cartesian). They are roughly able to depicted as Fig. 1.4 from the perspective of autonomy defined in Section 1.1.

The characters to be appeared in the following chapters might be able to arranged as in the figure. The disadvantage of the proposed mechanism with respect to the autonomy will be the decrease of the obedience. However, it would achieve the increase of independency and adaptability as shown in the figure.
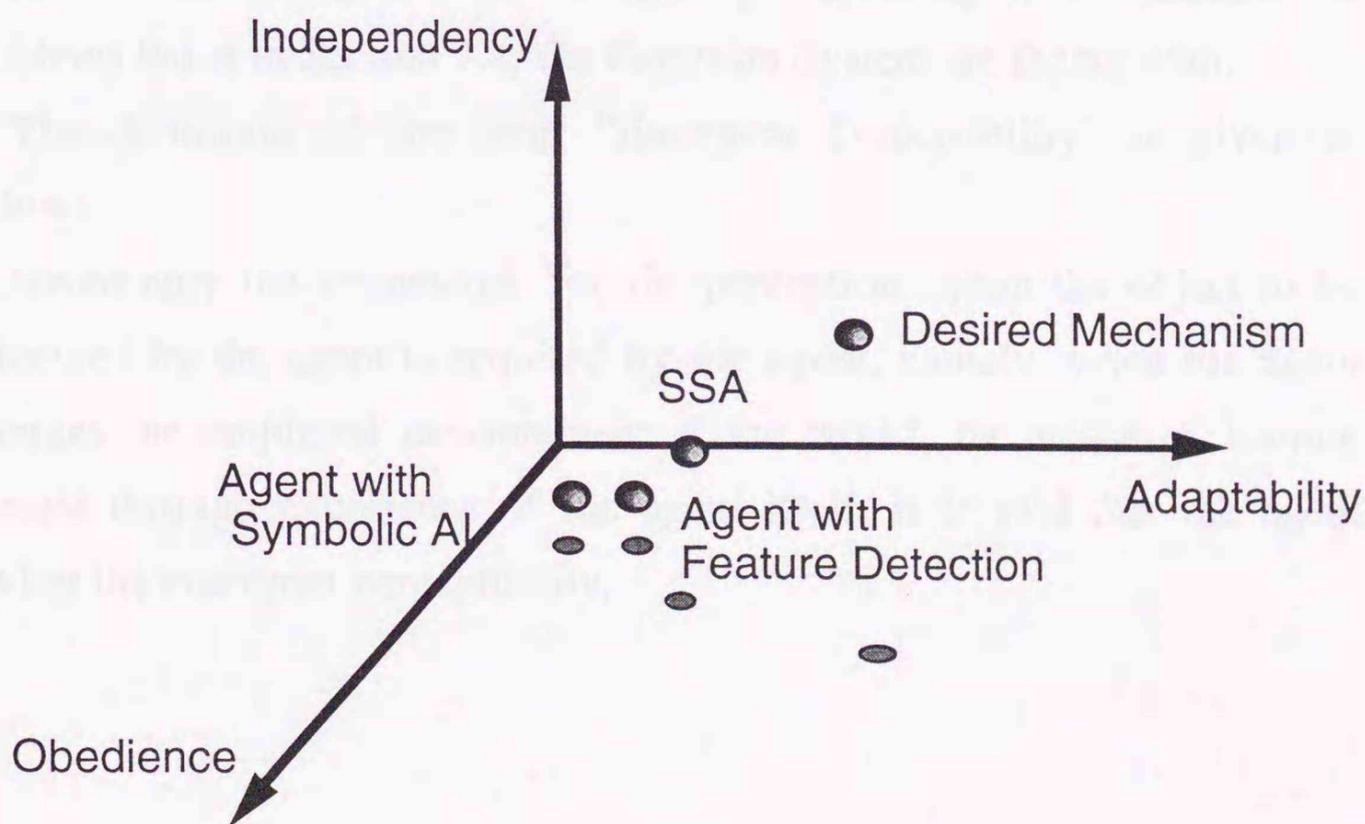
Fig. 1.4   Autonomy of Agents with Several Mechanisms

1.6 Emergent Perceptibility

In this section, the definition of the word "Emergent Perceptibility" used in this thesis is made. The agent based on the Cartesian System are designed not only the ability to perceive but also the objects to perceive and ways to perceive. Namely, the perceptual world of the agent is given framework of the perception and the perceiving measurement, and therefore, object of perception. To the contrary, however, the agent with proposed mechanism is expected to learn the object and the measurement of the perception given the framework for the perception.

Acquired perception of the both agent, therefore, will be quite different in each other. The perception acquired by the Cartesian Agent is interpretable by the designer, to say more, human. To the contrary, the perception acquired by the proposed mechanism will be unable to be interpret by the others but only the agent itself.

As a result the agent with emergent perceptibility will overcome the problems listed in Section 2.4: the Cartesian System are facing with.

The definition of the term "Emergent Perceptibility" is given as follows:

Given only the framework for the perception, when the object to be perceived by the agent is acquired by the agent, namely, when the agent emerges the empirical measurement of the world, by means of leaning process through experience of the agent itself, it is said that the agent having the emergent perceptibility.

1.7   Formulation of Agent, Environment, and World

Before, go into the precise discussion, the mathematical representation of the personages of the thesis, i.e., agent, the environment, and the world. For the sake of the context of the following discussion, the agent A is defined first as follows.

$$A = \langle S, (X), Ac \rangle, \tag{1.1}$$

where, S denotes sensory system, Ac denotes actuator of the agent, and X denotes the information processing system. X is put in parenthesis, because there are some autonomous agents without explicit information processing system such as based on Sub-Sumption Architecture: SSA (e.g.,

Si: Sensory Inputs
R: Rule Set
Ir: Inner Representation
Pe: Perception Mechanism
B: Behavior
L: Learning
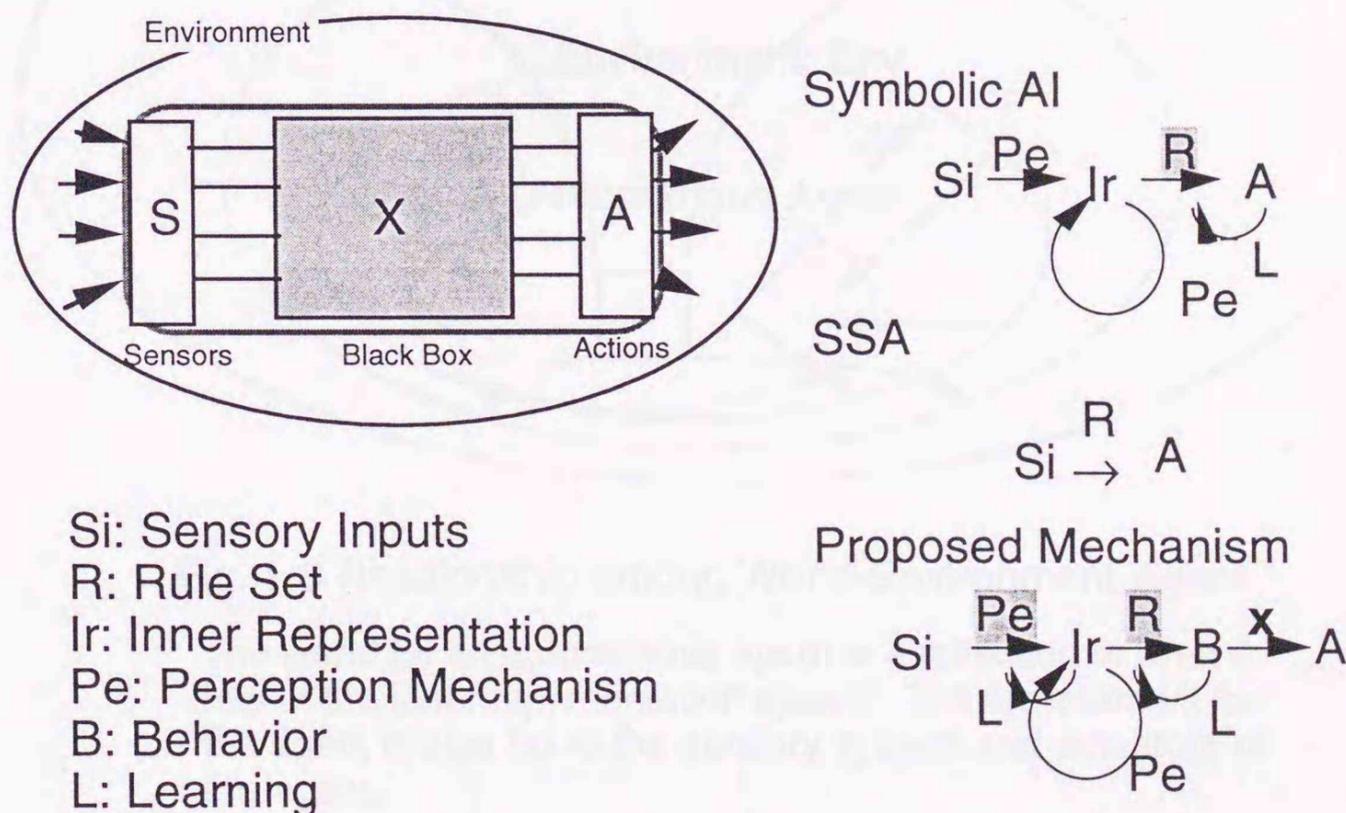
Fig. 1.5   Outline of Autonomous Agents

Brooks 89). As shown in Fig 1.5, the autonomous agents are able to classified roughly three kinds on the form of X. Details of each form of X is discussed in the following chapters.

As described in the subsequent chapters, X, S, and A of the agent determine the environment and world for the agents. Moreover, the concrete descriptions of the agents are quite different according to the view of the world they based on. This thesis distincts the entire world $\mathcal{W}$ from the world W from the perspective of the agents. It means that the agents are restricted its world by the sensory system and actuator of the agents as depicted in Fig. 1.6.
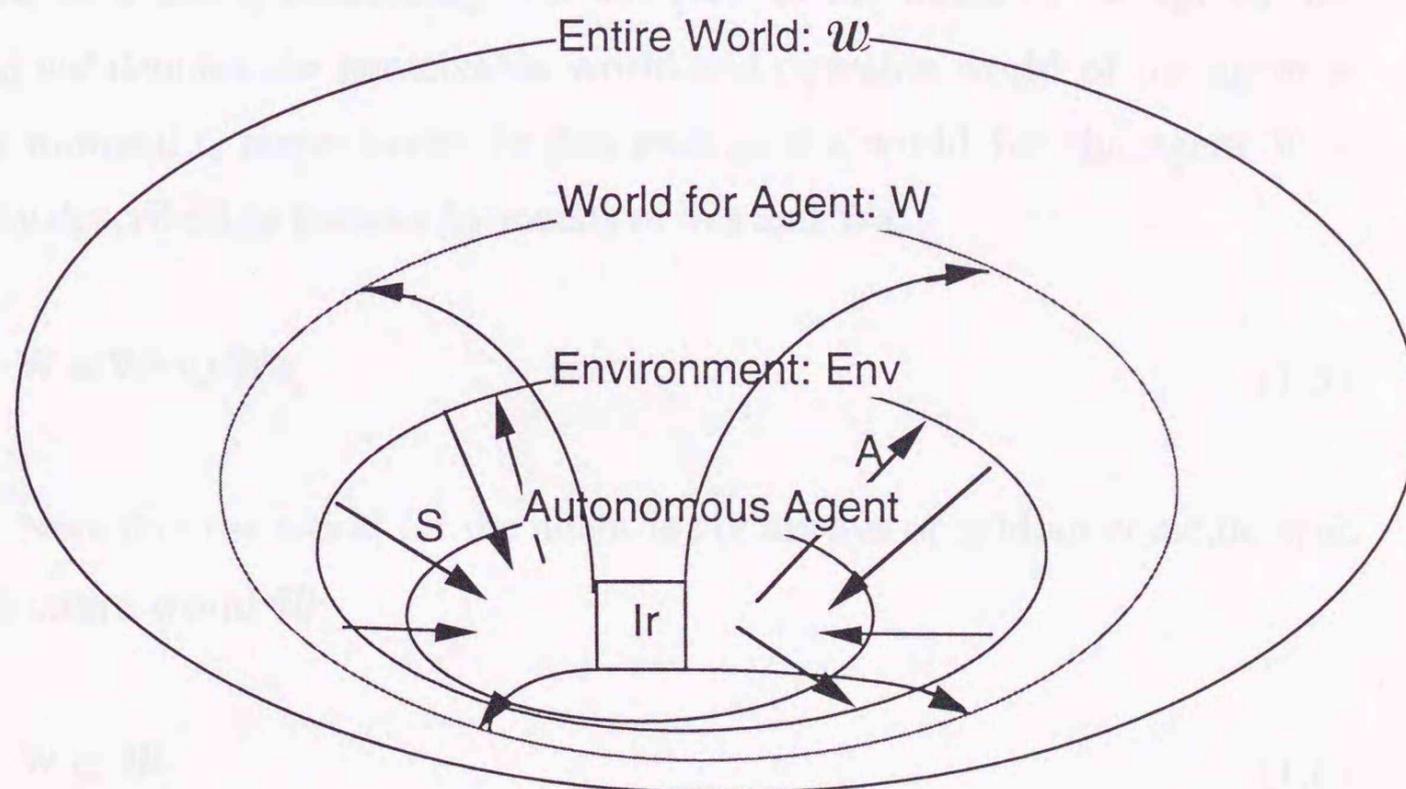
Fig. 1.6 Relationship among World-Environment-Agent

The world for an autonomous agent is a reflection of what it has in the inner representation system. The environment for the agent is also up to the sensory system and actuators of the agent.

Namely the environment Env for the agent at a moment t is defined as follows:

$$Env \equiv ws^t \cup wa^t, \tag{1.2}$$

$$ws^t \subseteq Ws, \tag{1.3}$$

$$wa^t \subseteq Wa. \tag{1.4}$$

where, Ws denotes the perceivable world for the agent, and Wa denotes the operable world of the agent. The details of each world is discussed in Chapter 2 and 3, concerning with the view of the world of the agents. ws^t and wa^t denotes the perceivable world and operable world of the agent at the moment t, respectively. In this section, the world for the agent W is only described as follows by means of Ws and Wa:

$$W \equiv Ws \cup Wa. \tag{1.5}$$

Note that the world for the agent is not always or seldom coincide with the entire world $\mathcal{W}$:

$$W \subseteq \mathcal{W}. \tag{1.6}$$

As Von Uexküll and Kriszat describe in their publication "Streifzüge Durch die Umwelten von Tieren und Menschen Bedeutungslehere" (von Uexküll 70) the view of the human and fly are completely different. The differences are mainly caused by the characteristics of their eyes. However, they both behave appropriately in the real world. It can be deduced that they have different perception mechanism and it is suitable

for the objective function of their own. They never have the same view of the world, so doesn't the artificial autonomous agents. The motivation of this thesis is deeply connected to this discussion. Namely, one of the aims of this thesis is trying to enable the autonomous agents to have its own view of the world, not that of Cartesian one applied to the conventional autonomous agents based on conventional AI.

The discussion on the background of the thesis have made in this chapter, and the mathematical formulation have been made for the sake of supporting the subsequent discussions in the following chapters. The details and more discussions are made in the following chapters of the thesis.

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CHAPTER 2

The Problems in Cartesian Style Perception

2.1 Introduction

In this chapter, the perception explained by the Cartesian System and the agent with perception mechanism based on it is described. As discussed by so many researchers in many fields, there are several problems in those agents such as Frame Problem (e.g., McCharthy and Hayes 69), (Pfeifer 95), Symbol Grounding Problem (Harnad 90), (Harnad 95), Lack of Situatedness (Pfeifer 96a), (Pfeifer 96b), and Embodiment Problem

(Dreyfus 93). I will investigate why these problem have occurred. These problems are considered as the main reason that limit the effective range of so-called Artificial Intelligence, and subsequently the agent based on it.

In the next section, a briefly description on the perception in the Cartesian System is made. Then, a brief summarize on the perception realized by the conventional Artificial Intelligence is described in Section 2.3. In Section 2.4, mathematical formulation of the general conventional AI is made by means of the formuli defined in Section 1.7. In Section 2.5 description on each problems in detail by means of the formulation at Section 2.4, so that the goals to be achieved by the non-Cartesian perception will be revealed.

2.2 Cartesian Style Perception

As shown in Fig. 2.1, the Cartesian style of perception as the realization of the agent's perceptual mechanism have two ways of information flow. The upper flow is used mainly in the agents with vision or connectionist approach. In this case, the agents are given the appropriate sensors suitable for the problem spaces. The sensors are sometimes given as the feature detector (e.g., Kuy 64) and sometimes as the specific ones sensitive to specific stimuli (e.g., Braitenberg 87). Those sensory inputs are unified into the space where the every sensory inputs are able to be treated in the same viewpoint. Then, the stimulus are analyzed to reduce the quantity of information so that the inference engine is able to handle the information.

In so called symbolic Artificial Intelligence (symbolic AI), these process are omitted. Instead of that, the designer should prepare appropriate symbols that represent the situation of the environment or the objects in the environment.
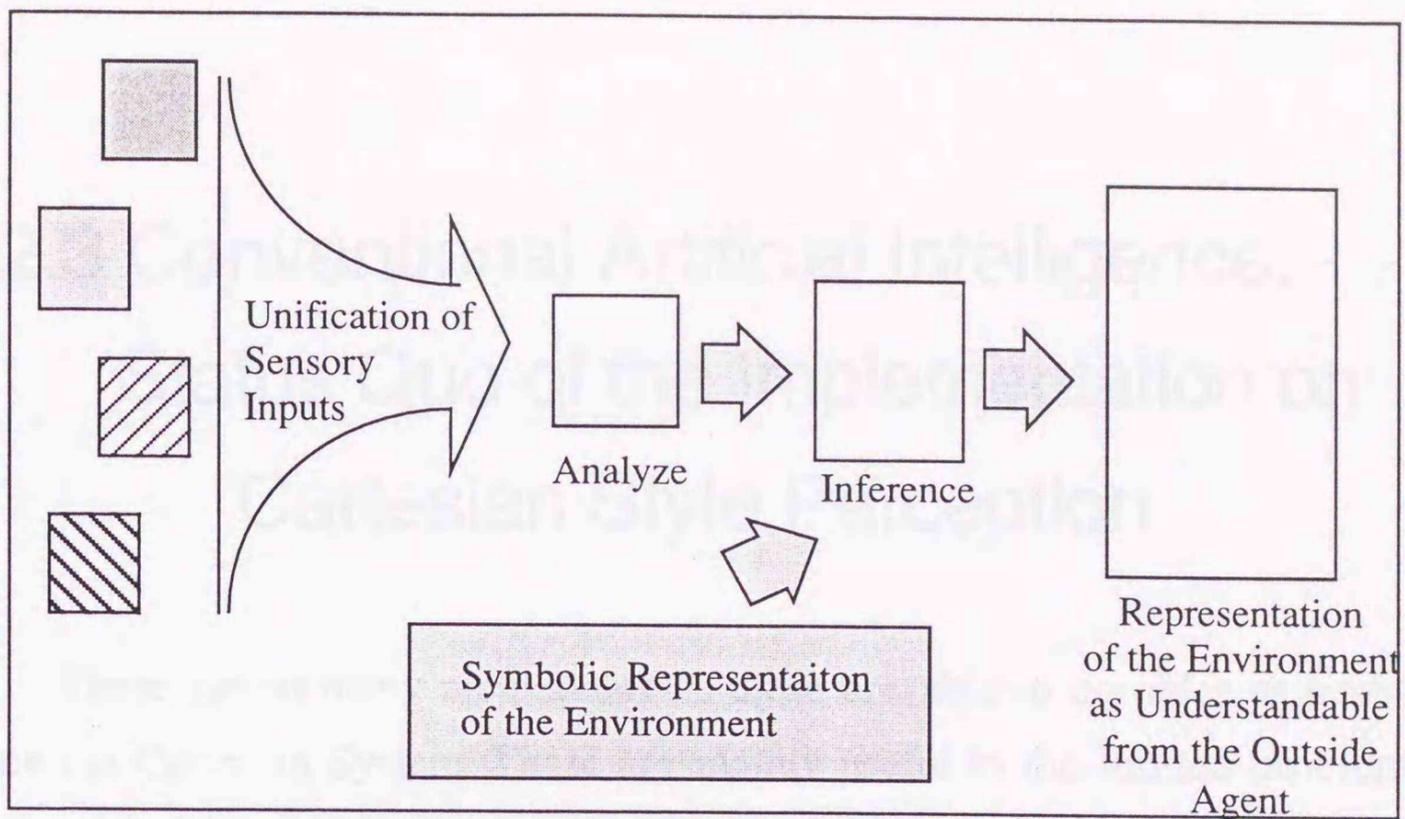
Fig. 2.1 Conceptual Outline of Cartesian Style Perception

The inference engine is now available. The use of the inference engine is often the interpolation of the knowledge acquired through the processes described above. The inference engine enables the agent to have the knowledge related with the current situation. In most cases, the observation for the reconstruction of the representation of the environment is done at a moment.

In the next section, a discussion on the conventional AI as examples of status quo of the implementation on Cartesian Style perception is made.

2.3 Conventional Artificial Intelligence: Status Quo of the Implementation on Cartesian Style Perception

There are so many methodologies those are able to consider as based on the Cartesian System. Those are mainly useful in the limited problem space such as so-called "Toy-world", and much efforts are made to make them available in the real environment. However , the problem space to be treated should often being accustomed to the agents.

This thesis have categorized the conventional AI from three point of views: Symbolic AI, Map-Generation, and Feature Detection. In this section, the overview of each categories to extract the characteristics and the problems of these methodologies is made. In short, the main objectives of these approaches are to have the precise and objective representation of the environment.

2.3.1 Symbolic AI

At the very beginning of the trials to achieve the intelligence in the computers, they are making much of the abilities of the computers of symbol processing. Their main purpose of these approaches are enrichment of the information on the situation facing with. There have been several ways of inferences such as inductive inferences (Holland 86),

(Shapiro 82), deductive inferences(Shortliffe 78), analogical reasoning (Carbonel 83), (Winston 79), and learning by discovery (Lenat 76).

These approaches mainly depend on the symbolic representation of the environment such as object as a concept and the relations among the objects as predicate logic. The problems they contains are remarkably described as the Symbol Grounding Problem (Harnad 90).

2.3.2 Map-Generation

The map generation based on the Cartesian System requires the designers to prepare the appropriate sensors for the purpose. The purpose of generating map in these approaches are to reconstruct the map of the environment as so to say, a bird's-eye view of the district. Namely, they are trying to make the physical map of the world as a inner representation of the environment.

The agent with this kind of inner representation of the environment (Kay 64; the aim of the paper is different) should read the map and much efforts are to be done to understand the situation it is facing with, or the use of the map is restricted(Elfes 87).

These approach is considered to be facing with the Frame Problem (McCarthy & Hayes 69), the Lack of Situatedness (Pfeifer 96).

2.3.3 Feature Detection

The purpose of the feature detection is often to enrich the information on the environment. The goal of feature detection is considered as to reconstruct the copy of the environment in the agents.

For example, the robot with vision system (Jarvis 83, Ayache 89, Hebert 88) should have objective or physical measurement to know the environment, and therefore, the same problem with those described in the previous subsection would occur.

Each problems listed above will be discussed in detail in the next section.

2.4 Formulation of Agents

Based on Conventional AI

In this section, the formulation on the information processing of the agents based on conventional AI is attempted so that the problems in them are formally revealed in the following sections. Some theorems are also deduced by the definition of the autonomous agents on conventional AI. These theorems are deeply related to the limitation of the conventional AI generally pointed out by many researchers.

2.4.1 Definition of Agent

Agents in this thesis is defined as (1.1) with 3-tuples: $< S, (X), A>$. X acts great role to determine the characteristics of the autonomous agent. Moreover, the world for the agent is deeply related with X

From above discussions, X of the agents based on conventional AI Xai are generally able to described as follows:

$$Xai = <Ir, Pe, L, R, Ev> \tag{2.1}$$

$$Pe \equiv < Pf, Ie > \tag{2.2}$$

$$Ir = \prod_{i=0}^{N} f_i \tag{2.3}$$

$$L = L1 \cup L2$$
$$L1 : A \times Ev \rightarrow R \tag{2.4}$$
$$L2 : A \times Ev \rightarrow Ie$$

$$R : Ir \rightarrow A \tag{2.5}$$

where, Ir denotes Inner representation of the environment, Pe denotes the perception mechanism, L is the learning mechanism, R is the rule base, and Ev denotes the evaluation from the environment determined by the task of the agents, f_i denotes the feature, and N is the fixed number of natural number (Fig. 2.2).

As in (2.2), the perception mechanism of the agent is able to divided into two parts: Pf is perception for the particular features in the environment, and Ie is inference engine designed for enriching Ir from observed features. Pf is also considered as the set of symbols assigned to represent certain concept in case of symbolic AI:

$$Pf: S \rightarrow Ir, \tag{2.6}$$

$$Ie : Ir \rightarrow Ir. \tag{2.7}$$
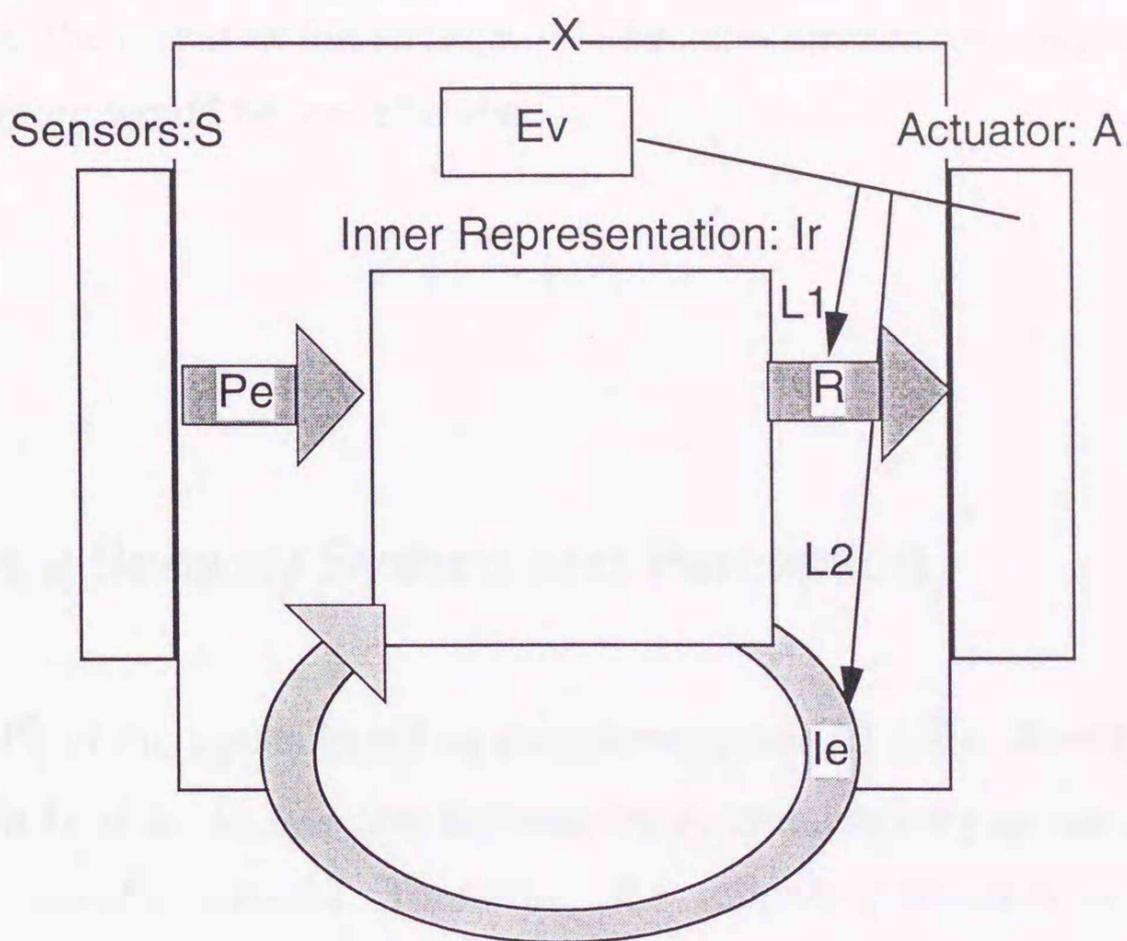
Fig. 2.2 X of Autonomous Agent Based on Conventional AI

The inner representation of the environment in these agents are not more than combinations of previously defined features, or symbols. The features are generally designed to be linearly independent and therefore, no approach has permitted the agent to generate new features. There are few if any, approach that designs the feature space as not being linearly independent. This means that in most cases the feature spaces, i.e., inner representation, of the conventional AI is fixed and should be designed by the designer of the agent.

Learning for the autonomous agents based on conventional AI is classified into two parts, i.e., improvement of R (L1) and improvement of rule set of Ie (L2). However, in most cases, these learning mechanism stands alone. Namely, the object of learning is fixed as one. It is because the available mechanism of learning works effectively only when the origin of the error is apparent. If these two are to be learned at the same

time, the origin of the errors would become ambiguous, and therefore the learning would be less effective.

2.4.2 Sensory System and Perception

Pe of the agents based on the conventional AI often directly connected with f_i of Ir. In this case the sensory system acts only as the detectors of the specific features. Therefore, the following theorem is able to be deduced:

Theorem 2.1

If inner representation Ir is defined as (2.3) concerning with certain problem and Pe is fixed, the sensory system is designed as detectors of f_i and the necessary sensors are determined by Ir.

Proof

From (2.3),

$$Ir = \prod_{i=0}^{N} f_i = f_0 \times f_1 \times \cdots \times f_N \tag{2.3'}$$

If a problem requires additional feature f_{N+1} to solve the problem, namely,

$$Ir \equiv Ir \times f_{N+1} \tag{2.3''}$$

The range of Pf will be change, because $Ie : Ir \rightarrow Ir$ is never expected to adapt to f_{N+1}. Therefore, Pf should be

$$Pf: S \rightarrow Ir \times f_{N+1}. \tag{2.6'}$$

However, Pf is fixed. Therefore, S should be

$$S \times f_{N+1} \tag{2.8}$$

This means that $s_i \in S$ is a detector for certain feature f_i. Moreover, the S should contain the detectors for all features required to solve the problem.   (End of Proof)

Theorem 2.2
   The world W of the agent is equivalent to Ir.

Proof
   From Theorem 2.1, the sensors of the agent is equivalent to the detectors for the features in Ir. Therefore, the perceivable world for the agent is equivalent to Ir. Namely,

$$W = Ir \tag{2.9}$$

and, the environment of the agent becomes as follows:

$$Env \in Ir \tag{2.10}$$
                                                             (End of Proof)

29

2.5 The Problems

In this section, the description on the four problems, i.e., Frame Problem, Symbol Grounding Problem, Lack of Situatedness, and Embodiment Problem, those are considered as depicting the remarkable problems those the agents based on the Cartesian System is made. Each subsection is assigned for the detail of the problems.

2.5.1 Frame Problem

The Frame Problem is first pointed out by McCarthy and Hayes in 1960's (McCarthy and Hayes 69) and is able to be defined as " Which objects should taken into account and which are not". This problem is considered to be a problem when the agent is given the measures of the environment. The measures of the environment are a kind of a model of the world that designers of the agent have given to the agent to perceive the environment. The agent, therefore, is forced to have the model of the environment quite as same as that of the designer's. A fine example to illustrate the Frame Problem is given by Dennett (Dennett 87) with three levels of "Unmovable" robots:

A good example that explains the Frame Problem effectively is given by Dennett with three levels of robots named R1, R1D1, and R2D1 respectively:
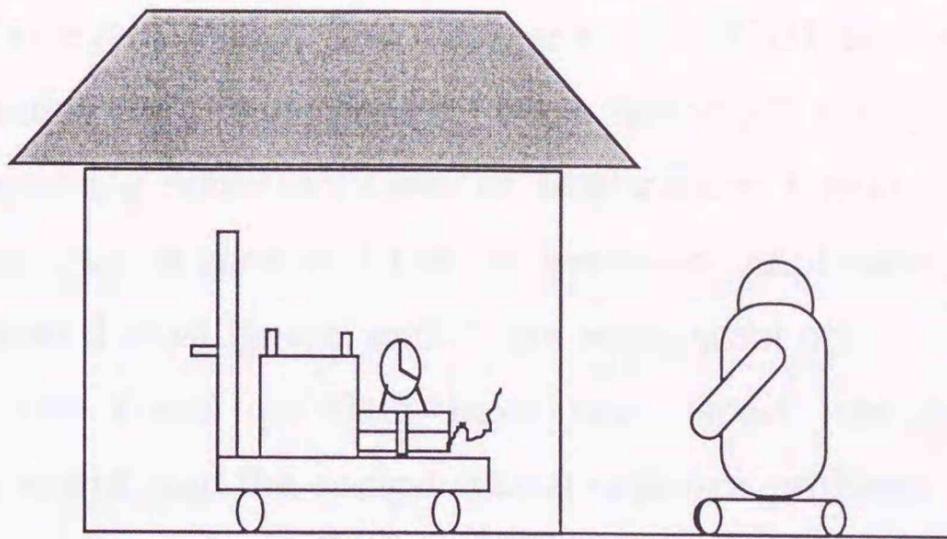
Command to the Robots :
" Bring the Battery on the Wagon Outside".

Fig. 2.3 Problem Given to the Dennett's Robots

The robot R1 has been told that its battery is in a room with a bomb and that it must move the battery out of the room before the bomb goes off (Fig. 2.3). Both the battery and the bomb are on a wagon. R1 knows that the action of pulling the wagon out of the room will remove the battery from the room. It does so and as it is outside, the bomb goes off. Poor R1 had not realized that pulling the wagon would bring the bomb out along with the battery.

The designers realized that the robot would have to be made to recognize not just the intended implications of its acts, but also its side-effects by deducing these implications from the descriptions it uses in formulating its plans. They called their next model the robot deducer, or short R1D1 and did the same experiment. R1D1 started considering the implications of pulling the wagon out of the room. It had just finished deducing that pulling the wagon out of the room would not change the color of the room's walls when the bomb went off.

The problem was obvious. The robot must be taught the difference between relevant and irrelevant implications. R2D1, the robot-relevant-

deducer, was again tested. The designers saw R2D1 sitting outside the room containing the ticking bomb. "Do something!" they yelled at it. "I am busily ignoring some thousands of implications I have determined to be irrelevant. Just as soon as I find an irrelevant implication, I put it on the list of those I must ignore, and..." the bomb went off.

Namely the frame problem have two aspect: the limitation on perceivable world, and the computational resource problem. As discussed in Theorem 2.1, the agent based on conventional AI is limited its perceivable world W as W = Ir. Therefore, it is applicable only when the world of the agent is well-known.

Then, to overcome the problem within the framework of conventional AI, we can expand the inner representation with larger number of features. However, as in Theorem 2.1, the sensor for each feature is required. This means that the all information from the all detectors should be processed. This force the agent cost too much time to perceive the environment.

There is more pessimistic fact that there is no theory that discloses the minimum set of features that is necessary and sufficient to represent our complex and dynamic real world.

From above discussions, it is impossible to overcome the frame problem within the frameworks based on the conventional AI. Therefore, it is apparent that the conventional AI is unsuitable for the X of the autonomous agents those are expected to behave in the real world.

In the next subsection, the another minus factor of the conventional AI as the X of the autonomous robots is revealed.

2.5.2 Symbol Grounding Problem

The Symbol Grounding Problem (Harnad 90) is the very problem that the symbolic AI is pointed out as symbol processor (Pfeifer 96). For this description, there is an good example called "Chinese Room argument"(Searle 80):

Searle challenges the core assumption of symbolic AI that a symbolic system capable of generating behavior indistinguishable from that of a person must have a mind. More specifically, according to the symbolic theory of mind, if a computer could pass the Turing test in Chinese - i.e., if it could respond to all Chinese symbol strings it receives as input with Chinese symbol settings that are indistinguishable from the replies a real Chinese speaker would make (even if we keep testing for a lifetime)- then the computer would understand the meaning of Chinese symbols in the same sense that I understand the meaning of Japanese symbols.

It arose from the fact that the meanings of the symbols in AI is almost always given externally by the designers. Therefore, the meaning of the symbols are known only to the designer and not to the agent itself. To save the agent from the Symbol Grounding Problem, the agent should acquire its own meanings of the environment according to the experience. This thesis considers that the use of the symbols is still enormous because a lot of useful mechanism is available to achieve the intelligence in the agent such as planning and predictions.

The source of the Symbol Grounding Problem is considered that the range of Pf of the agent is fixed. It means that the agent based on the connectionist approach in the framework on Cartesian perception style also come across this problem. Namely, fixed Pf leads the agent to have its inner representation of the world as the combination of features or the

symbols. Therefore, the intelligence by the conventional AI is not more than solving a combination problem in the finite space (Fig. 2.4).
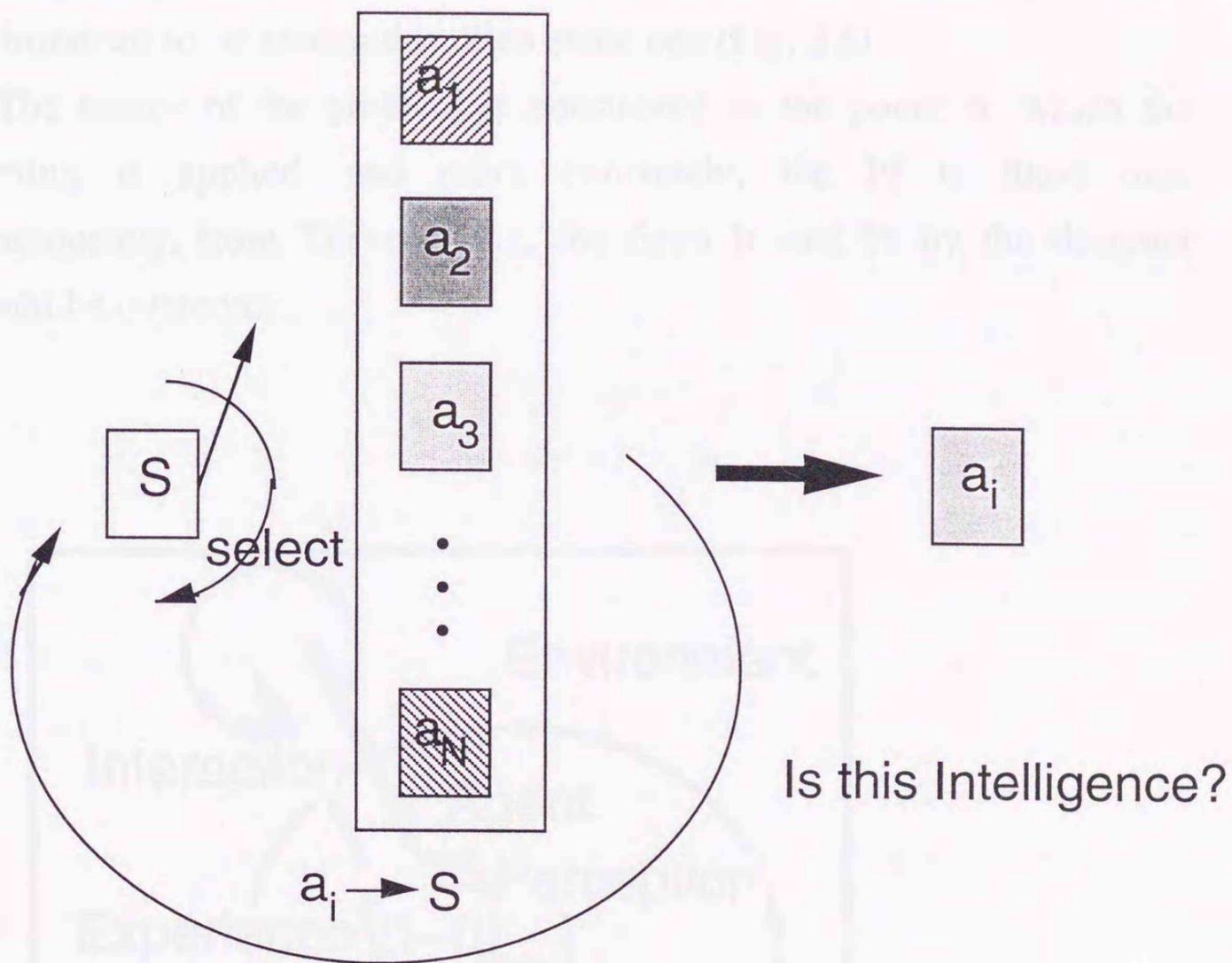
Fig. 2.4 Symbol Grounding Problem

2.5.3 Lack of Situatedness

Pfeifer (Pfeifer 96) describes the Situatedness in three parts. First, the world should be viewed entirely from the perspective of the agent not from the designer's. Second, make much of the interaction between the agent and the environment. The third, the experience of the agent should

be utilized by it to capture the current situation. Those three are considered to be deeply connected to the design principle of the agents.

However, the traditional AI has usually lost these point of view. Namely, they are often viewed from the designers perspective and the environment to be assumed is often static one (Fig. 2.5).

The source of the problem is considered as the points to which the learning is applied, and more concretely, the Pf is fixed one. Consequently, from Theorem 2.1, the fixed Ir and Pf by the designer should be overcome.
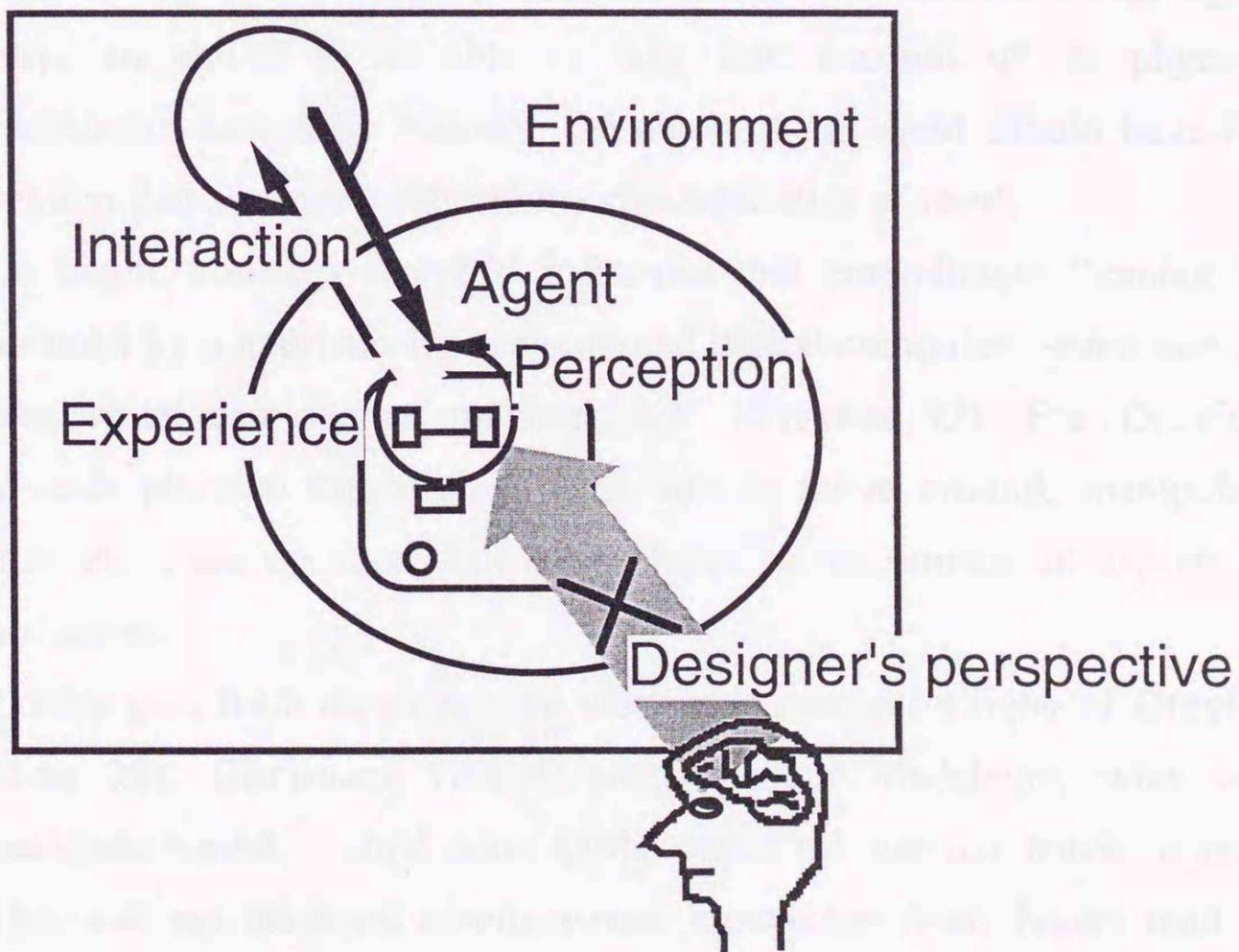
Fig. 2.5 Lack of Situatedness

The framework of the agent that allow it to have its own view of the environment would be required. Moreover, those view should be acquired through the learning to make the agent being autonomous.

2.5.4 Embodiment Problem

When we are designing the agent, we apt to lost the importance of the body of the agent. However, if we consider the agent expected to work in the real environment where the agent should interact with the environment, it is the fatal problem. This thesis consider that the autonomous agent is expected to have the framework that allows the agent to have an ability to be able to take into account of its physical characteristics naturally. Namely, the autonomous agent should have the perception that somehow reflects the characteristics of itself.

To begin, consider Dreyfus' insistence that embodiment ``cannot be reproduced by a heuristically programmed digital computer---even one on wheels which can operate manipulators'' (Dreyfus 93). For Dreyfus, large-scale physical capabilities (being able to move around, manipulate objects, etc.) are necessary but not sufficient to encompass all aspects of embodiment.

Collins puts forth an alternative view in his recent critique of Dreyfus (Collins 96). Discussing Oliver Sacks' patient Madeleine, who was "wheelchair-bound..., blind from birth, could not use her hands to read Braille, and yet acquired commonsense knowledge from books read to her", Collins asks whether a body is not so much a physical thing as a conceptual structure? If you can have a body so unlike the norm and as unable to use tools, chairs, blind person's canes and so forth as Madeleine's, yet you can still gain commonsense knowledge, then something like today's computers---fixed metal boxes---might also acquire

commonsense given the right programming... It is no longer necessary for machines to move around in the world like robots in order to be aware of their situation and exhibit "intelligence"... Human-like bodies are not necessary for human-like socialization. Thus for Collins, our physical bodies are one (but not the only) way we can become embedded in and engaged with our world. Physical capabilities, then, are sufficient but not necessary for embodiment.

This thesis considers both are true, but in the different stand point. However this thesis supports Dreyfus' point of view when considering the design of an autonomous agents. They are expected to be independent from the others and they should be adaptive to the environment.

The problem can be characterized by the following relations between the phenomena and the causes. Suppose the agent that is designed to be suitable for the problem space as depicted in Fig. 2.6a, and the task for the agent is to pass through the opening among the walls.
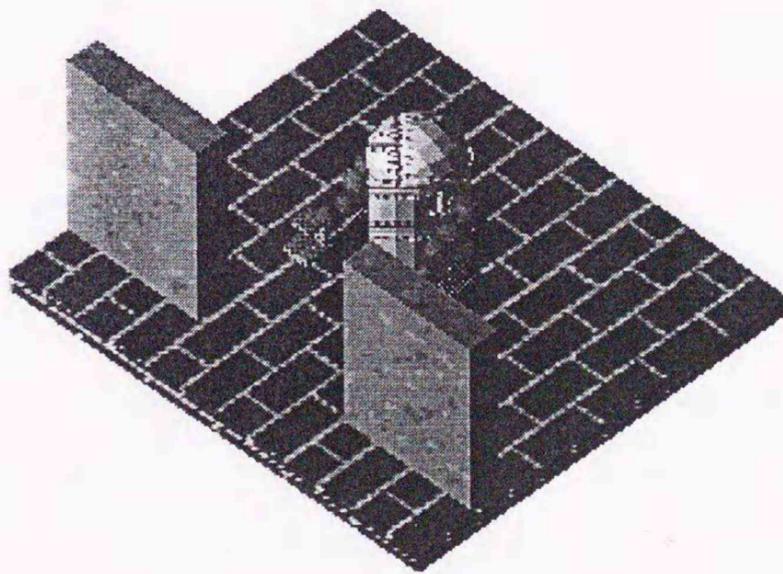
Fig. 2.6a Desired Problem Space for Agent

Then, It has fixed Pe, Ir, and R. The fixed Pe and R is result in the failure in the situations depicted in Fig. 2.6b and 2.6c. The agent in these

cases is lacking adaptability to the change of its physical characteristics nor the relation between the environment and itself.
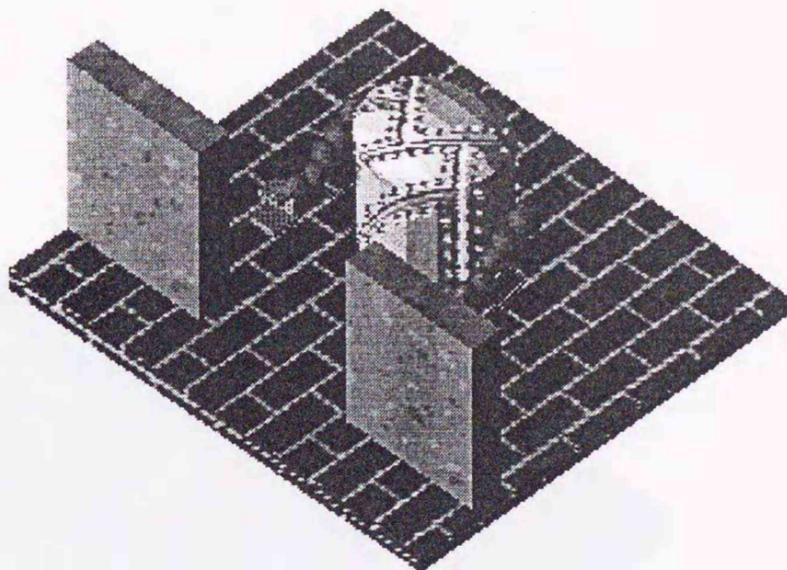
Fig. 2.6b   Incapacity for Change of Physical Characteristics
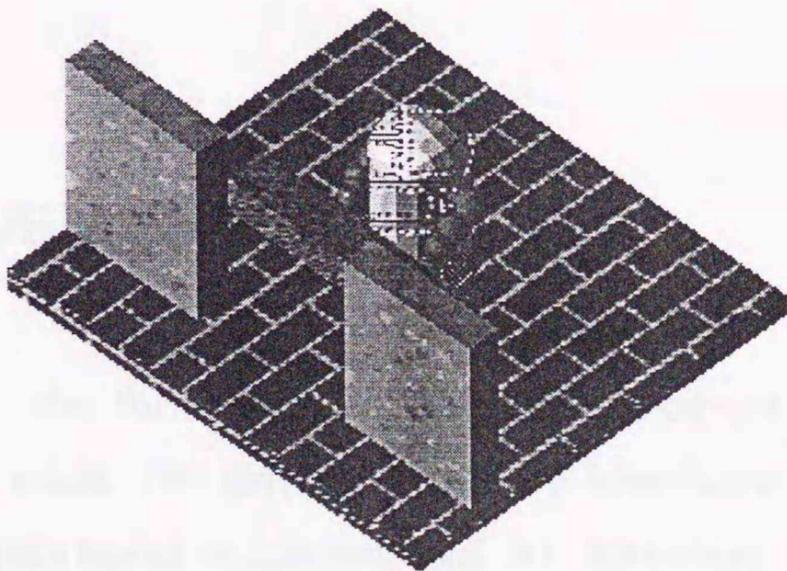
Fig. 2.6c Incapacity for Change of Self-States

In the conventional AI, the move of actuator is assumed to make the desired physical movement of the agent. Therefore, the agent is become paralysis in the situation such that As effect is unexpectable as depicted in Fig. 2.6d.

Slippy Floor
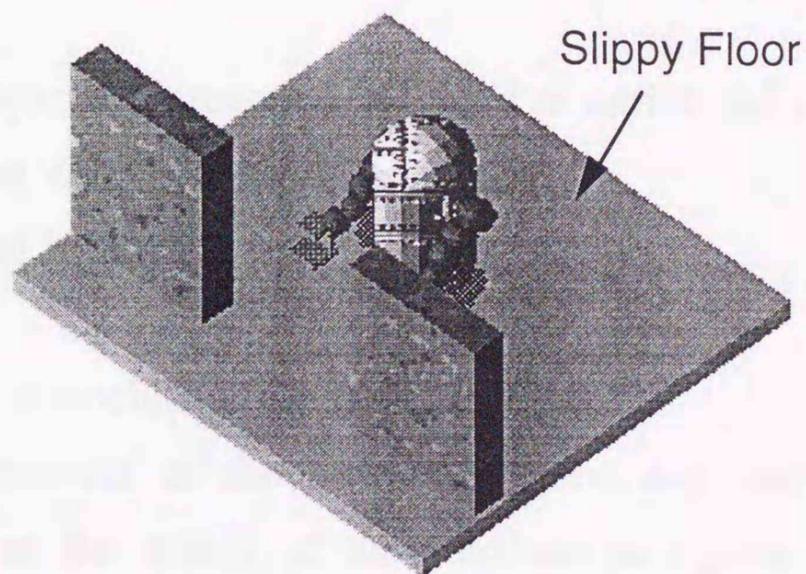
Fig. 2.6d Incapacity for Change of Environment

2.6 Conclusions

In this chapter, the formulation of autonomous agents based on the conventional AI is made. The two theorems have introduced to discuss the limitation of the agent based on conventional AI. Moreover, overviews on the problems pointed out for the agents with the Cartesian Style perception, and the four problems, i.e., Frame Problem, Symbol Grounding Problems, Lack of Situatedness, and Embodiment Problems, are described and discussed in detail by means of the formulation and the theorems.

This thesis come to consider that design of the agents based on the Cartesian view of the world harms in that:

- It requires the agent to have the perception interpretable by the designer or the others:
    Pf is fixed.

- The object of perception is settled to enrich the reconstruction of the interpretable view of the environment.
    Pf and Ie is fixed

Finally, a conclusion for this chapter is:

The framework of the Cartesian System, e.g. conventional AI, makes limitation on the ability of the autonomous agents. The factors of the limitation is concluded as:

- Pf, Ir are fixed.
- The point to which L is applied is not enough.
- Ir is given from the perspective of the designer.
- Ir is represented as the Cartesian Product of defined features (2.2).

However, each methodology introduced in the Cartesian System will not limit the abilities of the agent, but the view of the world limits the range of the agent's activity space(e.g., toy world). Therefore, changing the view of the world will enlarge the activity space of the agent (e.g., real world).

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CHAPTER 3

Non-Cartesian

Perception

3.1 Introduction

This chapter concentrates on the perception explained by the non-Cartesian System and the requirements for the realization of emergent perceptibility of the Affordance for the autonomous agent. Recently, the non-Cartesian Style has been in the limelight as a basis of thinking when designing the intelligence on the agents (e.g. Pessis-Pasternak 91). This chapter, then concentrate on the Affordance Theory introduced by an American cognitive scientist Gibson (Gibson 79), as one of the most important theories on non-Cartesian way of perception that will be effective when being able to achieved in the autonomous agents.

In the next section, Affordance is introduced as the explanation on human cognition from the non-Cartesian perspective. Moreover, the studies by the successors of Gibson, so-called Gibsonian are introduced in Section 3.2. A mathematical formulation of Affordance is attempted so that the possibilities of the engineering implementation is revealed in Section 3.4. In Section 3.3, a brief survey on the agents that would have perceptibility on Affordances is made. Discussions the difficulties and requirements to make an agent to have emergent perceptibility on Affordances is made, in Section 3.5.

3.2 Affordance

In this section, Affordance is introduced as the explanation on human cognition from the perspective of non-Cartesian System. For this purpose, a explanation is made with the three terms introduced by Gibson (Gibson 79) first. Then, the works by the successors of Gibson is introduced to clarify the concept more clearly.

3.2.1 Gibson's Original Theory

James J. Gibson was a cognitive scientist who deeply contribute to the development of the theory concerning with the human perception. He was first affected by the Gestalt psychologists. Then, he came to analyze the retina images and he found the limits on the explanation of human perception from the retina image as the stimulus from the environment. He then found the importance of the movement of animals for perception and came to be interested in the optical structure of the environment.

Finally, he had succeeded in explaining our human perception phonemically by introducing the term Affordance.

In this subsection, the essence of the Theory is described by introducing the three characteristic terms by Gibson, i.e., Ambient optic array, Invariant, and Affordance.

Ambient Optic Array
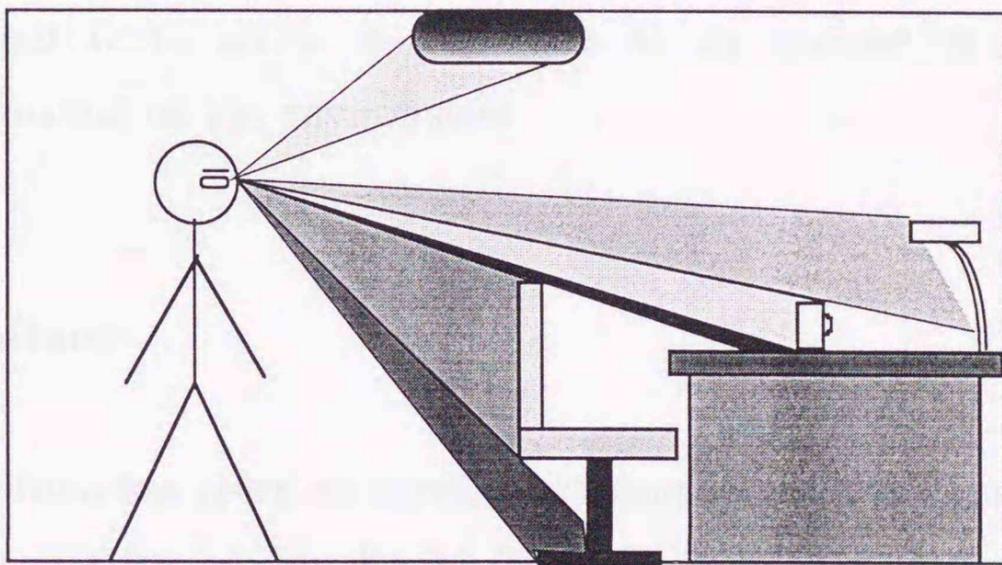
View of the environment (From the last surface of reflection)
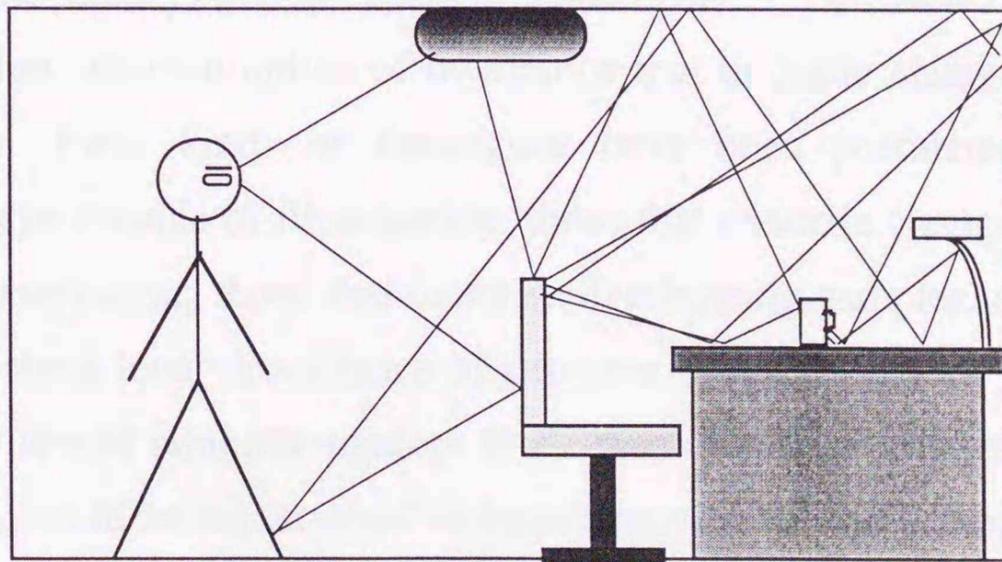
Locus of a ray before reaching to observer

Fig. 3.1 Concept of Ambient Optic Array

We are surrounded by the optical rays reaching to us through very complex locus as shown in Fig. 3.1. These optical rays contains the wide range of information on the environment because the all surfaces constituting the environment affect to the rays by reflection. While Descartes considered these rays as only the stimulus, Gibson considered them as the information. Therefore, Gibson treats the rays as constituting the structure of the optical array. He come to conclude that the retinal image is not important to us in perceiving the world but the ambient optic array is important to us because it contains the information on the environment.

Invariant

Gibson has given an excellent explanation on the term Invariant in the appendix of his book, "The Ecological Approach to Visual Perception. A part of his explanation is described for the explanation of Invariant:

The theory of the current awareness of persistence and change requires the assumption of Invariance that underlie change of the optic array. Four kinds of Invariance have been postulated: those that underlie change of illumination, those that underlie change of the point of observation, those that underlie overlapping samples, and those that underlie a local disturbance of structure.

It would simplify matters if all these kinds of change in the optic array could be understood as transformation in the sense of mappings, borrowing the term from projective geometry and topology. The Invariance under transformation have been worked out. Moreover, it is easy to visualize a form being transposed, inverted, reversed, enlarged and reduced, or foreshortened by slant, and we can imagine it being

deformed in various ways. But, unhappily, some of these changes cannot be understood as one-to-one mappings, either projective or topological. (omission of a middle part).

The theory of the extracting of Invariance by a visual system takes the place of theories of "constancy" in perception, that is, explanations of how an observer might perceive the true color, size, shape, motion, and direction-from-here of objects despite the wildly fluctuating sensory impressions on which the perceptions are based. With Invariance there is no need for theories of constancy. (omission of the last part).

Affordance

Affordance is the "value" that the environment affords to the animals. As shown in Fig. 3.2, it is possessed by the environment to be informed to the animals in the environment no matter whether it is good or bad. Affordance is the functional utility of the environment but not the physical property of the environment. Therefore, it should be the information directly understood by the animals. This leads the concept of "direct perception (for example McClamrock 95). In this aspect, Affordance is very different from the way of perception in the Cartesian System because Cartesian System makes much of the physical properties of the environment.

Affordance, however, is not the stimulus that force the animals to do certain behavior. Therefore, the animals are not to responding to the Affordances, but to explore the environment to pick up the Affordances as information. As a result, the animals are expected to perceive the Affordances of the environment to survive. However, the way to accept the perceptibility of the Affordance is the problem in my

aim, i.e., to design the mechanism that allow agent to have perceptibility on the Affordances, as discussed throughout this thesis.

you may sit down
you may not carry
:
you may avoid

Affodances from the Chair
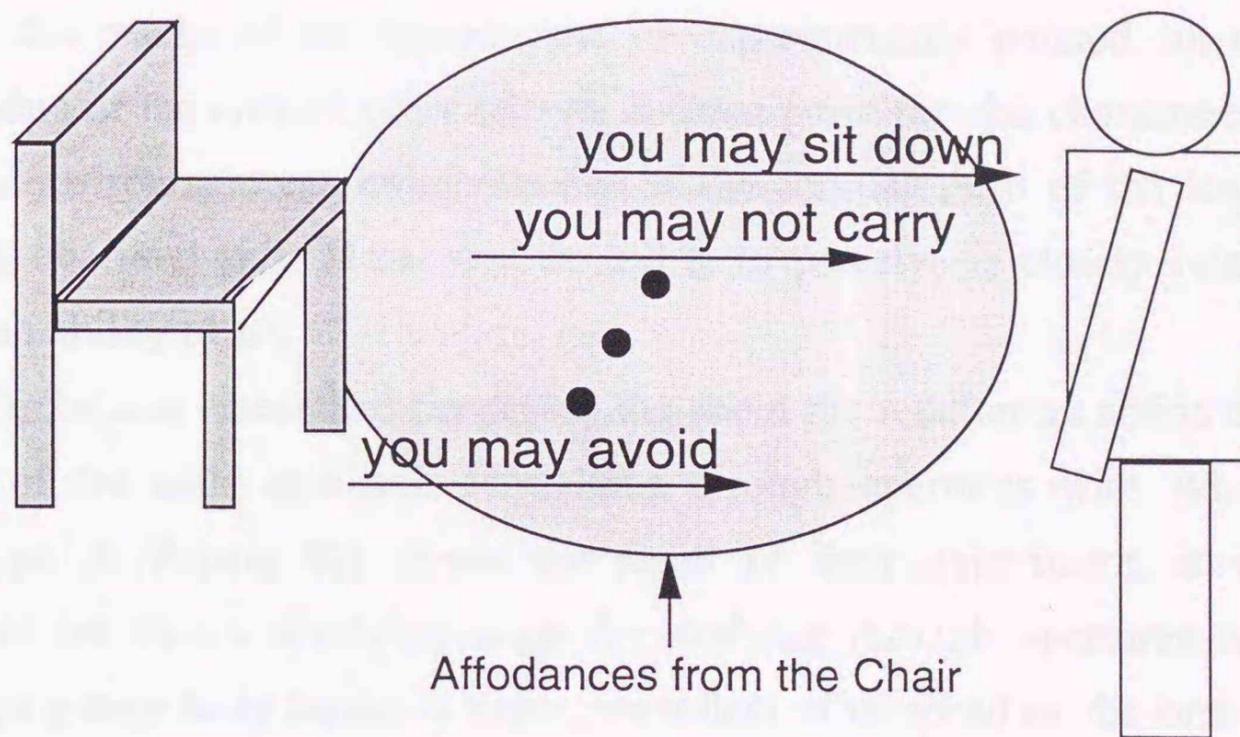
Fig. 3.2 A Simple Explanation on Affordance

3.2.2 Affordance after Gibson:
a Survey on Psychology

A survey on the studies by the psychologists so-called Gibsonian is attempted in this chapter. Gibsonians develops the theory of the Affordance by Gibson.

To begin, Warren (Warren 84) studied about the action of the stair Climbing. In the action of stair climbing, an qualitative characteristic of the action transforms itself at a point of time, according to its height. The first is the time which the observed self must use not only his legs but also

his hands and knees, namely critical point (α C). The second is the optimal point which is stable area to consume a little energy. (The π C is a ratio the height of the stair to the length of legs)

He made three experiments to demonstrate the above assumptions. From the results of the experiments, he experimentally pointed out that the value of the critical point and the optimal point for the characteristic of the environment can be represented as the constant ratio of the length of the observed self. Moreover, an ability to perceive is closely related with an ability to act.

Warren also researched the perception about the relation an action to a scale of the body at a unit of walking through apertures with Whang (Warren & Whang 87). From the result of their experiment, it was pointed out that a revolving angle for dodging through apertures with swinging their body becomes larger, regardless of its speed or the breadth of their shoulders, when the value (α) which is divided the width of the aperture by the breadth of their shoulders is constant (= about 1.3). It should be noted that the judgment whether one can walk through apertures or not is decided by a criterion of their body size.

Ingle and Cook (Ingle & Cook 77) investigated on the relation of the width of frog head to a frequency of its jumping. A frequency that a frog jumps to a orifice decreases quickly in proportion to getting narrow and drawing near to the frog head.

Michaels, Prindle, and Turvey (Michaels et. al. 85) investigated the relation between the distance to the feeds and a mantis' length of the front legs. A mantis starts to attack if some feed draws near within a certain distance, however, the distance is constant and 80% of the length of its front legs.

Lee(Lee 76, 80) indicated that a primary derivative function of $\tau(t)$ specifies a quality of collision. If the Lee number < 0.5, the collision

should be vehement insufficiency of slow down), and if the Lee number < -0.5, the collision should be soft(sufficiency of slow down).

This model is fit for a real driving data. Let assume the driving on the road. The visual enlargement of a front car leads to its deceleration and the reduction leads to its acceleration. The assignment for drivers is to preserve the Lee number than the critical value, 0.5. This existence of the information makes it possible control of the collision.

Lee also experimented on that a testee hits a ball which let it fall from various height (Lee et al. 83). In this experiment, Lee observed the jumping action of the testee actually, and found out that the time which tau is 250-300 ms is important for its organization of the action.

Runeson and Frykholm, observed the following experiment (Runeson and Frykholm 81). Some reflecting tapes were put on some principal joints(shoulder, elbow, wrist, waist, knee, leg) and head. When a observer judged an action which lifts up box on only a movement of light, the observer could find out its weight correctly.

3.3 A Formulation on Affordance

As discussed in Chapter 2, the conventional AI is unsuitable for the information processing mechanism of the autonomous agents expected to work in the real world. The origin of the unsuitability is considered as the inner representation of the environment based on the fixed number of the features with linearity. This makes the agents alienated from interaction with the environment. Moreover, this also makes the agents being limited its applicable space to the known regions, i.e., $W = Ir$. The basic problem, therefore, can be regarded as lying in the fixed and defined Ir.

In this subsection, a mathematical formulation of Affordance is attempted to confirm that the Affordance, consequently the non-Cartesian System, have the possibilities to realize the unfixed and undefined Ir.

3.3.1 Information on Functionality of Agents

As described in the previous subsection, Gibson had considered the environment as the pool of information that is perceived by the animals as the available behaviors. This means that the information in the environment is considered as on the functional property of the animals. This means that the world for the agents is regarded as follows:

$$W = \mathcal{J}f \tag{3.1}$$

where, $\mathcal{J}f$ denotes the set of information on the functional properties of the animals, i.e., agent in this context and is regarded as agents thereafter.

The agent should then somehow perceive the

$$If \in \mathcal{J}f, \tag{3.2}$$

to behave appropriately in the environment. Affordance α is considered as equivalent as If.

3.3.2 Agents Perceiving Functional Properties as Information from Environment

One way to achieve the agents those could perceive the functional properties of the environment is proposed by Brooks as SSA as described in the next section. However, the omission of inner representation of the environment made the agent as reactive one. An autonomous agent is not merely the reactive system but it should think before behave. In this subsection, the agents those perceives Affordance are revealed by means of formulating the three terms in the previous section proposed by Gibson.

Ambient Optic Array: Oa

The ambient optic array is the result of the exploration for the explanation of sensory system by Gibson. He make less of each stimulus detected by the cells in the retina but he made much of the structure of the stimuli. The ambient optic array Oa is defined as follows.

$$Oa = <x, \sigma_x>,$$
$$x = r \times r, r \in R,$$
$$\sigma_x \in R,$$

(3.3)

where, R denotes the real number.

Invariant: ω

The Invariant is considered as the unchanged part of the ambient optic array. However it is not restricted by the position in the retina nor the exact amount of the stimuli. Invariant ω is defined as follows:

$$\omega = \{ \iota_b \mid \iota_b \subset \mathcal{B}(O a) \},$$

$$O a = \{ oa \mid oa \subset \mathcal{B}(Oa), rel(\prod_{t=0}^{Tb} oa_t) = const\}, \tag{3.4}$$

$$rel: \prod^{N} Oa \times Tb \to R,$$

$$Tb_i = \tau(B_i), B_i \in B, \tau: B \to \mathcal{J},$$

where, Tb_i denotes the number of frames to accomplish certain behavior, $\mathcal{B}(X)$ is the power set of X, B denotes the behavior set of the agent, and $\mathcal{J}$ is the set of integer.

The Invariant in the theory of Affordance is not merely the invariant set of the images, but the structure of the images that will be unchanged even though each σ_x is affected by the change of the environment.

Affordance: α

Although Affordance is treated as the information, it should be perceived by means of information processing that is defined from above discussion as:

$$\Pi = \Pi\omega \circ \Pi\alpha,$$

$$\Pi\omega : Oa \to \Omega, \tag{3.5}$$

$$\Pi\alpha: \Omega \to B.$$

where, Ω : set of Invariant.

Then, the Affordance for certain behavior is defined by means of the inverse mapping of Π as follows:

$$\alpha = \Pi^{-1}(B_i) \tag{3.6}$$

From the formulation process of Affordance, it is apparent that the information processing should be possessed by the autonomous agents those have the perceptibility of Affordance. Information processing is fatal for the autonomous agents, even though Gibson had made less of it in his theory of Affordance.

In the next section, the autonomous agents, especially those based on SSA, are briefly described.

3.4 Affordance and Agents: A Survey

Unfortunately, any remarkable study that apparently tries to realize the perceptibility of the Affordance in the autonomous agent is hardly found so far. However, there are several studies those are considered to realize the perceptibility in some respects.

3.4.1 Sub-Sumption Architecture (SSA)

As a remarkable agent that is considered to have been realized the Affordance phonemically, the Sub-sumption Architecture (SSA) proposed by Brooks (Brooks 95), (Brooks 91), (Brooks 90) is described. As depicted in Fig. 3.3, he changed architecture itself to realize the movable robot in the real environment. The architecture consists of sensors and the modular programs that concrete the functions of information processing. The modules are connected directly with both sensors and actuators, therefore, those modules are able to take part in the behavior of the robot

directly (this will realize the direct perception). Moreover, the interaction among the modules produces the real behaviors of the robot being able to be observed from outside the robot.

The SSA is a clever architecture in that it omits the difficulties to make the agent to have the mapping Π. It is apparent that the agent based on the SSA have limitation in the adaptability, because the Π in the SSA is previously given by the designer. The SSA is considered as an architecture that renounce the adaptability to some extent, but concentrates on the acquisition of the quick response.

The dynamics of the interaction is considered as originally pre-defined by the designer, but there are attempts to make the dynamics adjustable to introduce the diversity into the behavior (e.g., Gomi 96). However, the connections among sensors and the modules, and modules and actuator are fixed because of the architecture itself.

However, it is often pointed out that the SSA is able to realize only the Stimulus-Response behaviors. In this point, the SSA is not considered as having the perceptibility of the Affordances as described in the previous section. However, it provides us a great hint for the realization of perceptibility of the Affordance in the autonomous agents.

[boxes with arrows]

Sensory Inputs → Perception → Modeling → Planning → Decision → Control → Action

Architecture of Agent with Serial Information Flow

Modules

Reasoning
Planning
Identifying
Monitoring
Map Generation
Searching
Obstacle Avoidance
Avoiding Collision

Sensory Inputs → [Modules] → Action

Architecture of Agent with Parallel Information Flow (SSA)
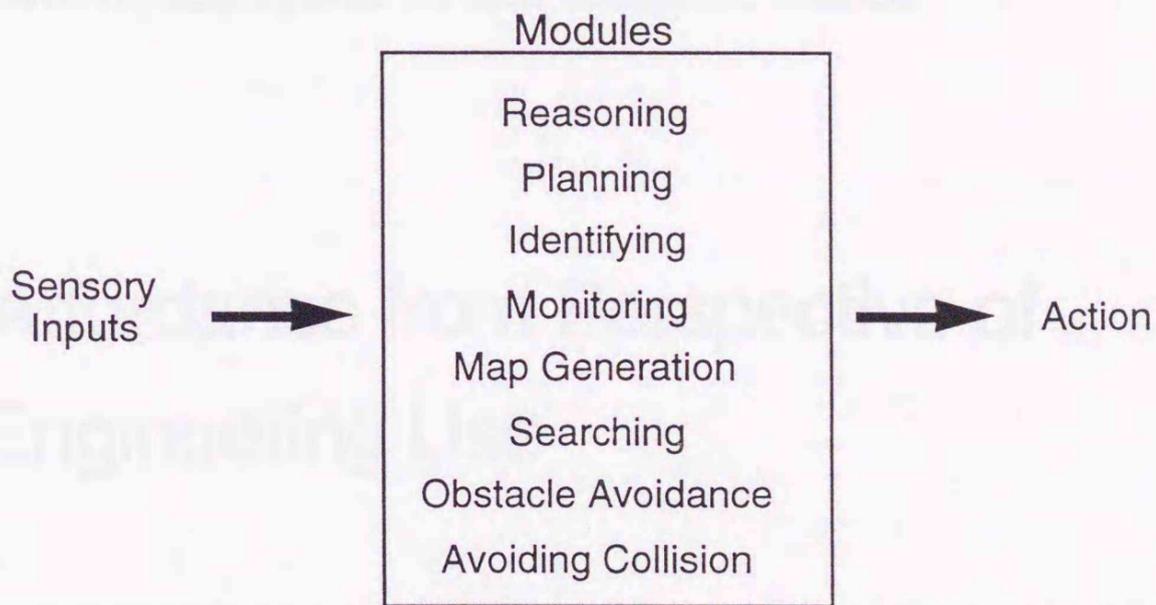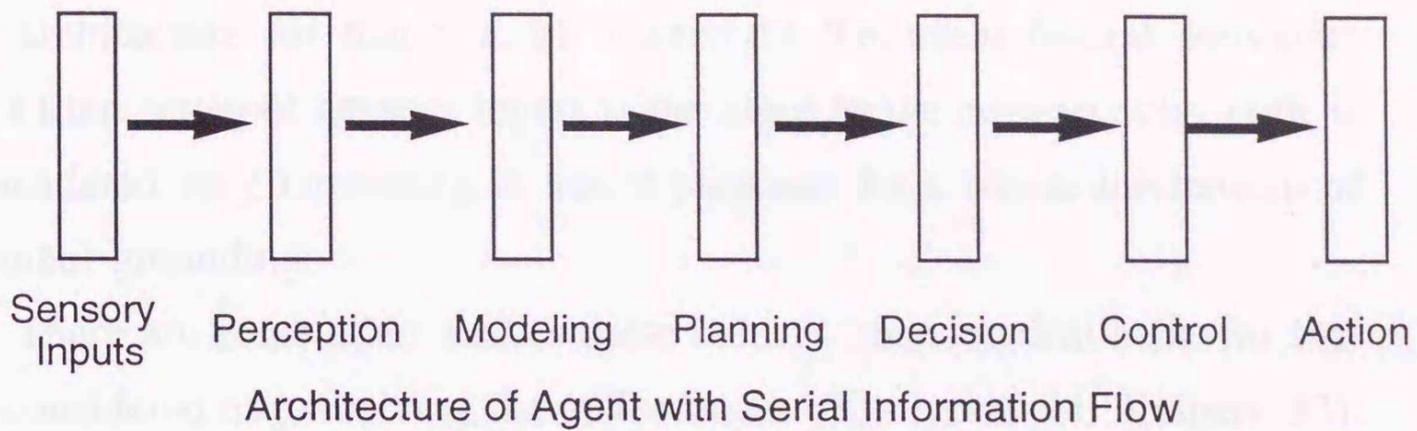
Fig. 3.3 Information Flow in the SSA

3.4.2 Other Methodologies

Maes (Maes 90) seems to have realize the same way of dynamics by means of Behavior Network (BN). Behaviors in the BN can be regarded as the modules in the SSA and Maes realizes the interaction among the behaviors by the networks. A learning mechanism of the network for the change of the dynamics is also proposed by herself (Maes 92).

Tani (Tani) has proposed a perception mechanism that would lead the deliberate thinking of the agent by constructing the "symbolic process". As an architecture for that aim, he utilizes the Recurrent Neural Networks and time series of sensory inputs is the input to the network. His work is considered very interesting in that it proposes the concrete mechanism of symbol grounding.

There are some other studies those realizes phenometical behavior that is considered as perceiving the Affordances (Kuniyoshi 94, Kuipers 93). However, their point of discussion seems little bit different from the aim here, therefore, descriptions on their details are omitted.

3.5 Affordance from Perspective of Engineering Use

The engineering use of Affordance is made mainly in the field of industrial design (e.g., Norman 88). Their point is that the designer's should design the products as to afford the use of them. However, the realization of the Affordance in this field in depending on the agreement between human being, such as common sense.

Beyond that, what is meant by the engineering use in this thesis, is the realization of the perceptibility of the Affordance to the autonomous agents. However, we ought not expect on the common sense between the designer and the agents, because we should design the agent itself. Therefore, the mechanism to emerge the perceptibility of the Affordance is the topic I should handle with. In other words, I should somehow explore the mechanism that would realize human perceptibility if Gibson tells us the truth. Unfortunately, Gibson had not mentioned on the

mechanisms of human being that enables us to perceive Affordances, but given an explanation on the perception phonemically.

This section will concentrates on the problems above. Namely, a discussion on the requirements and difficulties lie in front of us to have an autonomous robot that perceives the Affordances is made. Then, a discussion on the desired shape of the autonomous robot in this thesis is revealed.

3.5.1 Difficulties

To make an autonomous agent to have the perceptibility of the Affordance is the problem. As discussed so far, Gibson had never provide the explanation on the concrete mechanism of human perception. However, at least the mechanism that will enable the agent perceivable of the Affordance should be considered in this thesis, because the theory doesn't work in the autonomous agents without the mechanisms.

Namely the realization of the information processing mechanism that enables the autonomous agents to achieve the two mappings described in (3.5). It is obvious that even if the information concerning with function, i.e., the Affordance, exists in the environment, the agent should perceive it through the way of (3.5).

Brooks somehow realized Affordance-like behavior in the agents by previously relating the sensory information with the behaviors, namely Π is given by the designer. However, it is not more than realizing the Stimulus-Response phenomena when analyzing inside the agents.

The agent should have a kind of perception mechanism to be able to realize the perception as discussed in Affordance theory as it is not like realized in the SSA. Namely, to realize the direct perception not just realizing the stimulus-response behavior, the perception mechanism is

considered to be required for the realization of the autonomous agents. Moreover, at the same time, the autonomous agent should clear the problems described in Section 2.4 to achieve the autonomy. For these reasons, the agent should emerge the perceptibility of the Affordance through experience (See Fig. 3.4).
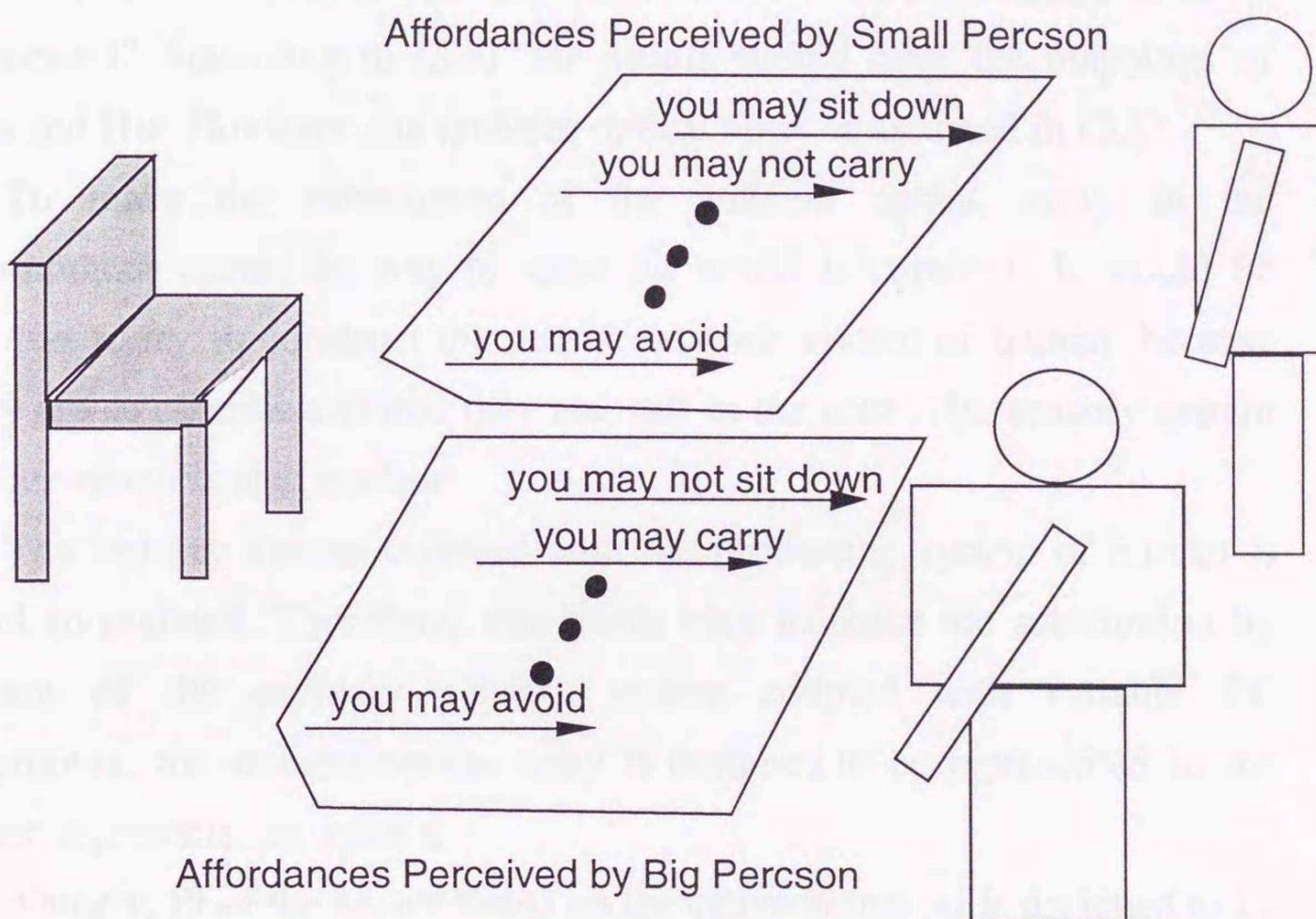
Fig. 3.4 Learning Will Emerge Perceptibility for Affordances

3.5.2 Requirements for Perception Mechanism

From above discussions, it is apparent that the agent should somehow achieve the two mappings described in (3.5). In this subsection, a discussion on the functional requirements to the perception mechanism for the autonomous agents.

As in Section 3.3, the information processing mechanism is fatal for the autonomous agent to perceive Affordance. What information is to be processed? According to (3.5), the agents should have the mappings of $\Pi\omega$ and $\Pi\alpha$. However, the ambient optical array is assumed in (3.5).

To make the substitution of the ambient optical array in the autonomous agent, the way to sense the world is required. It would be aimless to try to construct the neural network system of human, because they are so complicated that they are still in the mist. The sensory system of our vision is also unclear.

The sensory system together with the processing system of human is hard to realized. Therefore, this thesis tries to make the substitution by means of the ordinary sensory system coupled with variable Pf. Moreover, the ambient optical array is designed to be represented in the inner representation system.

Namely, Pf of the agents based on the conventional AI is designed to be acquired. To satisfy above requirements for the perception mechanism of autonomous agents, the following systems are required:

Sensory System

The mechanism should sense the world not by means of the appropriate sensors suitable for the information to be extracted, but by means of only the innate sensors to the agent. Therefore the kinds and the number of innate sensors are not to be fatal for the agent.

Learning Mechanism

The object of the learning with in the aimed perception mechanism should be on acquiring the meanings of the sensors to the agent as Kuipers tried (Kuipers 93). This means that the row sensor data gives no information without the experience of the agents, but would give more than just sensed when the learning proceed.

Information Processing System

Although Gibson had make less of the importance of the information processing, and nor Brooks. However, the information processing should not be omitted to achieve the perceptibility of the Affordances in the environment as discussed above.

Inner Perceptual Model

As discussed in the previous subsection, the inner perceptual model is fatal for realizing the agent to make the deliberate think not just stimulus-response system. The inner perception allow the agent to have the grounded symbols that is intrinsic to the agents. Again the representation of the inner perception should be unpredictable by the outside agent to be autonomous as McFarland argues (McFarland 95).

3.6 Conclusions

In this chapter, I have discussed that Affordance can be regarded as the explanation on the non-Cartesian Perception in that

- It denies the importance of the retinal image as a stimuli but makes much of the information in the environment.

• It makes importance on the functional properties of the environment while the Cartesian System makes much of the physical properties of the environment.

From the mathematical formulation of Affordance, the use of Affordance as a perceptual object of the autonomous agent is to be achieved by means of information processing. The perception mechanism should be achieved as an emergent perceptibility. For the realization of the emergent perceptibility of the Affordances, the mechanism for the autonomous agent should have the following components in the way that:

Sensors

A set of devices that is able to translate the environmental information in some way into the inputs of the agent.

The mechanism should sense the world not by means of the appropriate sensors suitable for the information to be extracted, but by means of only the innate sensors to the agent. Therefore the kinds and the number of innate sensors are not to be fatal for the agent.

Learning Mechanism

The object of the learning with in the aimed perception mechanism should be on acquiring the meanings of the sensors to the agent. This means that the row sensor data gives no information without the experience of the agents, but would give more than just sensed when the learning proceed.

Information Processing

Although Gibson had make less of the importance of the information processing, and nor Brooks. However, I insist that the

information processing should not be omitted to achieve the learning described above.

Inner Perceptual Model

An inner representation system of the agent. The reconstruction of the Inner Perceptual Model is to be intrinsic to the agent. The agent, therefore, should learn the reconstruction of the Inner Perceptual Model. The outside the agent unable to interpret the representation reconstructed in the Inner Perceptual Model.

The inner perceptual model is fatal for realizing the agent to make the deliberate think not just stimulus-response system. The inner perception allow the agent to have the grounded symbols that is intrinsic to the agents.

These four are indispensable when designing the autonomous agent because of the discussions above.

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CHAPTER 4

Mechanism of Emergent Perceptibility

4.1 Introduction

In this chapter, the explorations for the mechanisms those would make an autonomous agents to have its own object for perception for achieving the appropriate behavior in the real environment are attempted. It is deduced that the mechanisms consist of sensory systems, information processing systems, and learning mechanisms in common. Although this seems equivalent to that of Cartesian System, the quality of the information treated in the mechanisms are very different. Namely, the agents with these mechanisms would acquire the its own measurement of the environment with respect to its behaviors empirically. Therefore, it will develop the independency and the adaptability of the agent, those are the essence of the autonomy and quite difficult to achieve in the

conventional autonomous agents as described in the previous chapters. Moreover, these mechanisms are expected to overcome the problems observed in the conventional AI as described in Section 2.5.

The point is that those mechanisms enable the agents to capture the environment from its own perspectives. Furthermore, as described above, the agents emerge their own empirical measurement of the environment. The empirical measurement of the agent enables the agents achieving their own view of the world concerning with their own behaviors. The main difference of the perception mechanisms proposed in this thesis from the Cartesian perception, is that they do not require to know the exact picture of the environment. Instead of that, they perceive only the useful information of the environment related with the behaviors they are expected to make. Moreover, the object of perception has extremely different from that of the Cartesian perception. The agent perceives the environment as the candidates of the behaviors available in the environment. Again, the perception for my agents is not a map that represents the environment as it is, but the availability of the behaviors.

Speaking of the objects for the perception of my agents, the mechanisms often possesses the inner perceptual model of the environment. As described above, the objects to be perceived is quite different. Namely, the thinking space of the agent will be changed. In Cartesian agents, they are making the mapping of the environment to environment. While in the agents with proposed mechanisms are expected to acquire the mapping the information on the environment onto the behaviors.

Another advantage of the mechanisms is that they don't have to analyze the environment in every observable detail. They are, so to speak, observing the atmosphere of the environment. They never observe every each objects in the environment, but observe the environment as a whole. This is very important advantage in not only the processing speed of the

information, and also in the divergence of the observations. The mechanisms will not be required the pre-defined state space such as feature space. Instead of that, they generates appropriate pattern information that would be a clue for the decision making on the behavior selection. It is not in Cartesian System any longer, even though the tectonics used in the mechanisms are from the Cartesian System.

In next section, the requirements for the realization of the mechanism is discussed in detail on the component and on the demands altogether. The requirements in the next section results in the outline of the common characteristics of the mechanisms in Section 4.3. The following sections are assigned to the descriptions of each mechanism that would emerge the perceptibility to the agents. Namely, a mechanism based on the construction of the Inner Perceptual Model with Internal Simulator is described in Section 4.4. A mechanism based on the Inner Perceptual Model with reinforcement learning is described in Section 4.5. A trial to achieve the mechanism based on the vision sensors are described in Section 4.6.

4.2 Requirements for Realization of the Mechanisms

In this section, the requirements for the realization of the mechanisms for emergent perceptibility of the autonomous agents are argued. First of all, the requirements to the mechanism from the viewpoint of the realization of the non-Cartesian Perception is discussed. Then, the requirements to the components of the mechanism is discussed.

4.2.1 Requirements from the Viewpoint of
Realization of Non-Cartesian Perception

As discussed above, there are several requirements for the architecture of the mechanisms. This section is assigned to discuss on such requirements for the design of the mechanism that achieves the emergent perceptibility of the autonomous agents.

As a system, the autonomous agent should somehow observe the environment and should make appropriate outputs suitable for the environment. There were a millions of approaches for the purpose. However, they are mainly based on the Cartesian System. Therefore, the purposes of the perception is mainly for the making the map of the environment so that the agents are able to refer to the map when making the decision or planning action and so on. The preciseness of the map of the environment affects directly to the ability of the perception in those approaches as discussed in Chapter 2. It have been discussed that the perception mechanisms based on the Cartesian System cause the limitation to the activity space of the autonomous agents as in Theorem 2.2. The activity space of these agents is restricted to so called "Toy World". As in Theorem 2.2, the world for the agent is equivalent to the inner representation of the environment:

$$W = Ir \tag{4.1}$$

The conceptual solution to the limitation is discussed as a change of the view of the world, i.e., non-Cartesian System. Introducing the non-Cartesian point of view would make us free from the limitation because they never requires the pre-defined meanings to the sensory inputs. As the same time Ir is not required to be defined as,

$$Ir \; = \prod_{i=0}^{N} f_i = f_0 \times f_1 \times \cdots \times f_N$$

<div align="right">(4.2)</div>

Instead of the pre-defined meanings, they are required to have some learning mechanism for the acquisition of the meanings of the sensory information. This will lead the increase of the degree of freedom on the number of the ways of capturing the environment. The acquisition of the meanings of the sensors is equivalent to creation of the agent's own view of the world. Therefore, the agent with this way is free from the Frame Problem.

This will lead the changes in the inner representation of the environment at the same time. The inner representation of the environment with this way of thinking is free from that of designer's because the measurement of the environment and the purpose of the perception has changed. The designer is not expected to consider the all possible situations those agents are expected to be facing with. In stead of that agents acquire the empirical measurements reflecting the situations of the environment they have faced with. This do lead to achieve the perception really acquired from the perspective of the agents themselves.

The purpose of learning is also very different in the non-Cartesian System, as easily reason from the previous discussion. The learning should not be a parameter tuning nor making relation to the instances as achieved in the Cartesian perception mechanism. It should be used in the acquisition of the empirical measurement.

To achieve the empirical measurement, field for the representation of the environment as the agent's own space. It is corresponding to the inner representation of the environment. The agent is required to have the representation field so that it can ground the representation onto the sensory inputs. The representation of the environment should be able to have sufficient capacity to represent environmental information. With

respect to this aspect, the representation is ought to be a pattern. The pattern may treated as the symbols in the conventional AI. While, they are agent's own symbolic representation of the environment, i.e., the grounded symbols.

To summarize the above, the mechanism requires the acquisition mechanism of the empirical measurement. For the purpose, sensory system, inner perceptual model, and the learning mechanism are required. Furthermore, information processing system is required to achieve the translation of the information throughout the systems. In the next sub-section, a discussion on the requirements for each of the components of the mechanism is made respectively.

4.2.2 Requirements for Components of the Mechanism

As discussed in the previous sub-section, the mechanism requires sensory system, inner perceptual model, the learning mechanism, and information processing system as components. In this section, the further discussion on each components are made.

Sensory System:

While it had been essential factor to select the suitable sensors in the Perception Mechanisms based on the Cartesian Systems, the selection of the number and object of the sensing is not so important in my mechanisms. Of course, the kinds of sensors influence on the perception realized in the agents as the characteristics of the agents. For example the agents with sonar sensors can utilize only geometric information, while the agents with vision sensors can utilize the texture of the environment. The number of sensors are affect on the

preciseness of the observation. However, the agents are expected to acquire their own view of the world according what they have experienced.

Inner Perceptual Model:

The inner perceptual model is an inner representation field of the environment. However, it is not a map of the environment reconstructed based on the designer's objective and physical measurement to make precise description of the environment, but it should be a representation of the environment. It is expected to act as a field and reconstructed without the designer's intention. In other words, the reconstructed inner perception has the characteristics that the outside the agents is unable to control nor forecast the reconstructed representation of the environment.

I have settled four necessary conditions to be satisfied by the reconstructed inner perception for the sake of the inner perceptual model would be an inner representation of the environment in the way that discussed above:

1. **Distinction ability of the difference among the environment**.

    IPM corresponds to the environment itself for the agent. Therefore, it is expected to represent the difference among the environment more or less.

2. **Successiveness in accordance with action.**

    The move of the agent is expected to change the IPM. The change should be occurred in accordance with the degree of the movement.

3. Dependence on the environment.

The environment is consisted of a lot of parameters to be changed such as permeability of the air, noises in the environment, and so on. The environment to the agent should change in accordance with these parameters.

4. Successiveness on the experience.

IPM is based on the conviction of the agent because the reconstruction method of it is considered to be acquired through learning. Namely, what should be perceived is different in accordance with the experience.

To make the inner perceptual model available, learning mechanism and the information processing system is required.

Learning Mechanisms:

The learning required to the mechanisms aimed here, is not just for the parameter tuning in the fixed structure, but for the acquisition of the agent's own empirical measurement of the environment. The new learning mechanism based on the non-Cartesian System might be desired. However, the combination of the learning mechanisms based on the Cartesian System as a whole would satisfy the requirements for our goal, i.e., emergent perceptibility. Requirements for the learning mechanism is allow the agent to have its own empirical measurement that enable the agent to perceive the useful information such as Affordances of the environment for the making behavior.

Information Processing System:

As Marr (Marr 82) had pointed out that Gibson had make less of the importance of the information processing (McClarnrock 95), this thesis

considers that the information processing system is essential for the perception mechanism. The adaptability of the agents are considered to be arisen from the learning, not just by the inheritance. Then, there should be some information processing such that allow acquisition of the mapping between sensory system and the actuator of the agents. As discussed in the previous chapters and by Brooks, the information processing might harm the response of the agents in decision making. However, who can make quick response from the very beginning of their lives? To be adaptive, the agents should acquire the empirical measurement by trial and error, and become able to achieve the quick response. In other words, the agents are allowed to have their infancy.

Again, the information processing system is required for the sake of the acquisition of the empirical measurement together with the behaviors.

In the next section, the overview the outline of the general design of the mechanisms for the emergent perceptibility in this thesis is described.

4. 3 General Outline of
Proposed Mechanisms

As a result of above discussions, a general outline of the design of the mechanisms for the emergent perceptibility has been clearly appeared. This section assigned for summarize the outline of the proposed mechanism of the emergent perceptibility for the autonomous agents.
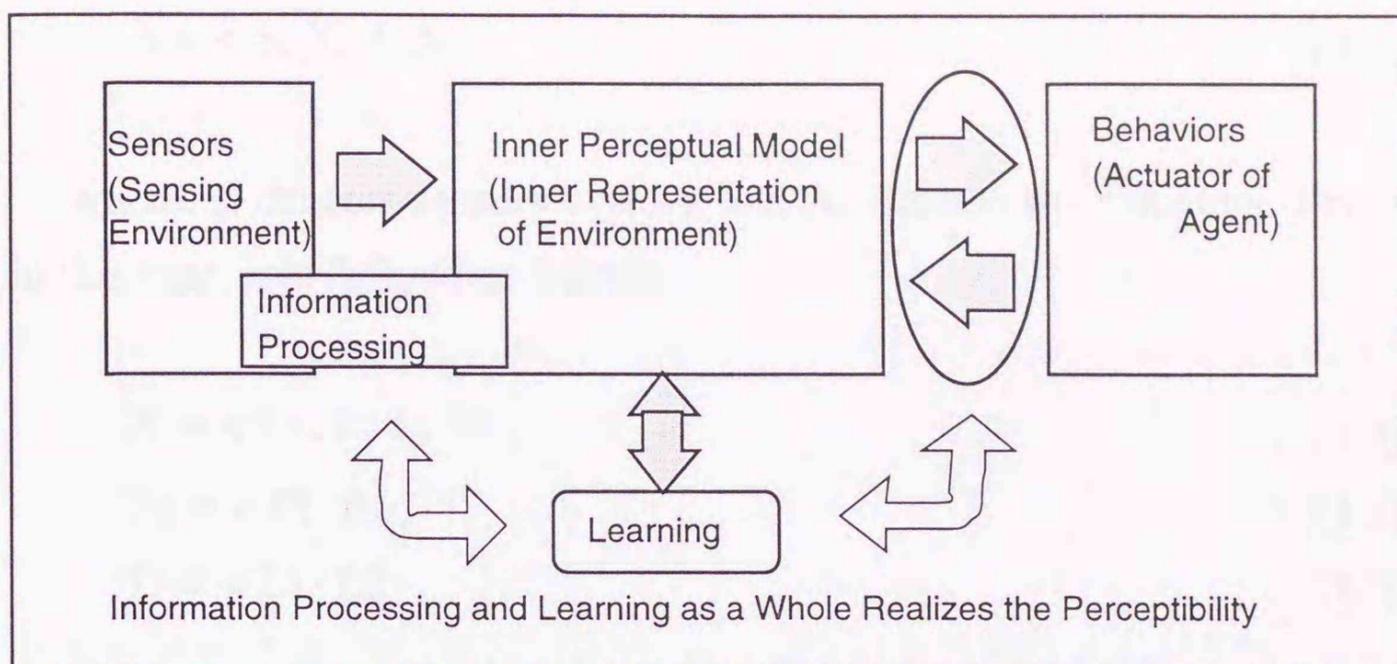
Fig. 4.1 General Outline of Proposed Mechanisms

As discussed in the previous section, the learning as a whole together with the information processing system enables the perceptibility of the autonomous agent. Each mappings are acquired by means of the techniques proposed in the Cartesian Systems. However the architecture allows the agent to have learning mechanism for the non-Cartesian perception.

In this section, the mathematical formulation of the proposed mechanism is attempted first. Then, it is shown that the proposed mechanism will realize the two mappings of (3.5) in the different form from Gibson's original theory.

4.3.1 A Formulation of Perception Mechanism

An autonomous agent A with this perception mechanism is defined as follows:

$$A = < S, X, Ac> \tag{4.3}$$

where, S denotes sensory system, and Ac denotes the actuators. For X in this case, it is defined as follows:

$$X = < Pe, Ir, L, M>, \tag{4.4}$$
$$Pe = < Pf, R>, \tag{4.5}$$
$$L = < L1, L2>, \tag{4.6}$$

where, Pf is a mapping between sensory inputs and Ir, R is a rules that is used for the evaluation of Pf. L1 is the learning mechanism for Pf, and L2 is the learning mechanism of mapping between Ir and Ac. M denotes the mapping between Ir and Ac.

There should have another mappings to be acquired through learning, i.e., mapping between Ac and Ac'. Ac' is corresponding to the actual movement in the real environment. This mapping is essential for overcoming the embodiment problem of described in Fig. 2.6d. However, because the main object of this thesis is to realize a perceptibility of the autonomous agents mainly concerning with the environment, it is beyond the scope of this thesis.

Learning in this context, is applied to the both mappings, i.e., Pf and M while the learning in the conventional AI is only applied to one of the two mappings, i.e., M or R in this framework. It is important that the Pf is acquired in self-organizing style and that both Pf and M are able to learn at the same time.

4.3.2 Advantages of the Mechanism

The proposed mechanism will be able to realize the perceptibility of Affordance. In this subsection, it is confirmed theoretically that the proposed mechanism have an ability to perceive Affordance by reconsidering the mechanism and the Affordance formalized in the previous chapter.

In Chapter 3, the perceptibility of Affordance is formalized by means of two mappings:

$$\Pi\omega : Oa \rightarrow \Omega, \tag{4.7}$$

$$\Pi\alpha: \Omega \rightarrow B.$$

where, Oa denotes the ambient optical array, Ω denotes the set of Invariants, and B denotes the set of behaviors.

As described in the previous chapter, Oa in this framework is achieved in the inner representation of the environment, i.e., IPM. For this aim, IPM represents the environment as patterns. Each elementary unit in the IPM have the same structure with that of defined in (3.3) but different in

$$\sigma_x \in \{0, 1\}. \tag{4.8}$$

The acquisition of the mapping Pf through learning, realizes the patterns in the IPM as a position irreverent retina.

The learning mechanism L2 then allow the agent to have the Invariant for each behavior. The learning is carried out in the form of trial and error and the coupling of the patterns of the IPM and the selected behavior B_i is achieved. As a result, the Invariant together with the

Affordance is achieved as the empirical measurement described in the subsequent sections.

From above discussion, the mechanism has an ability to emerge the perceptibility of Affordance. Within this framework, there are the other advantages those are required to the autonomous agents in the real world:

• It is expected that the agent with this mechanism is able to generate concepts by clustering the patterns reconstructed in the IPM.

• It is also expected that the agent is able to achieve the higher intelligent processes such as inference and planning when regarding the concepts as the symbols.

• It is also expected that the world for the agent is not always a subset of the entire world. It is because of the possibility that the concepts generated by the agent together with the higher intelligent processes listed above will not be just the representation of the environment. The agent will possess the creative abilities when this would be realized.

4.4 A Mechanism Based on Inner Perceptual Model with Internal Simulator

A mechanism that will be a realization of the mechanism is introduced in this section. The perception achieved in this mechanism is restricted to

the geometric one because of the characteristics of the sensory system. This mechanism is designed mainly for emergent perceptibility of the Affordance for the autonomous agents. The mechanism consists of roughly four parts:

a. Active observation system of the environment:

An agent senses the reflection wave of the pulse wave generated by the agent itself. This reflection wave reflects the situation of the environment because the pulse wave reflects the all objects existing within certain range. Therefore, the agent is able to observe larger environment than those are observed only through a local search. The sensory inputs in this sensory systems contents more than just the local information.

b. Inner Perceptual Model (IPM) with Internal Simulator of the Environment:

A kind of the inner representation of the environment that is not able to interpret as the style we can understand, is reconstructed in this component. In other words, the patterns reconstructed in the IPM would be treated as a kind of feature that the environment affords. The characteristic of this mechanism is introducing the simulator of the environment for the reconstruction of the inner representation of the environment. The representation is acquired as the patterns These patterns are considered to include the information on the availability of certain behaviors those are executable when certain patterns are observed. The resulting pattern for certain pattern is corresponding to the Invariant in the Affordance theory.

c. Processing system referring to the IPM:

To reconstruct the inner representation of the environment, i.e., IPM, and to recall the available behaviors, some mapping processes are required. The processing system realized by means of learning participates in these roles.

d. Learning Mechanism:

The learning mechanisms used in this perception mechanism are not new when used respectively. However, each learning mechanism works well for the acquisition of the perceptibility of the Affordance. The learning mechanism is based mainly on ANNs such as ART(Carpenter & Grossberg) and the simulator works effectively as an evaluator for the learning. Learning mechanisms in this mechanism are achieved as the "Unsupervised Learning (e.g., Kohonen)".

To make the mechanism simple, a ring of sonar sensors (for example, Burshan 90, Kay 64, and Kleenman 95; but the aim of the study seems different from mine) is selected as the sensor system of the mechanism. Therefore, the information to be processed is restricted as geometric ones. In the rest of this section, details of the mechanism are described.

Before we go into the detail description of each mechanisms, I will make a brief survey on the mechanisms related to the proposed mechanism(Table 4.1).

Category	Authors	Meaning of Sensor Patterns	Inner Representation of Environment	Destination of Study
Sonar Sensing	Kleeman&Kuc 95 Burshan&Kuc 90 Elfes87	Given by designer	Geometric Map Probablistic Map of Obstacle	To create Correct shapes of object inside Probability Map of the environment
	Pierce&Kuipers 94 Pierce&Kuipers 91	Aquired though Learning	Finite State Automaton	Achieving apparent goals in Navigation Problem
Sensory-Motor System	Brooks	Given by designer	Not Exist	Real Time Robot
	Pierce&Kuipers 94 Pierce&Kuipers 91	Aquired though Learning	Finite State Automaton	Achieving apparent goals in Navigation Problem
Symbol Grounding	Harnad 90 Gasser 95 Dorffner&Prem93 Dorffner&Prem93		Symbols Semantic Network Concepts / Symbols	Symbolic Representation of Scene

Table 4.1 A Brief Survey on Related Works

4.4.1 Active Observation System

Fig. 4.2 shows the outline of the Active Observation System. The agent generates a pulse wave that corresponds to a reference light in the hologram. The wave is like a drop of water or a sound, and therefore, it propagates the environment omnidirectionally equal with certain damping force. The wave is assumed to have appropriate width and intervals to cause wave interference.
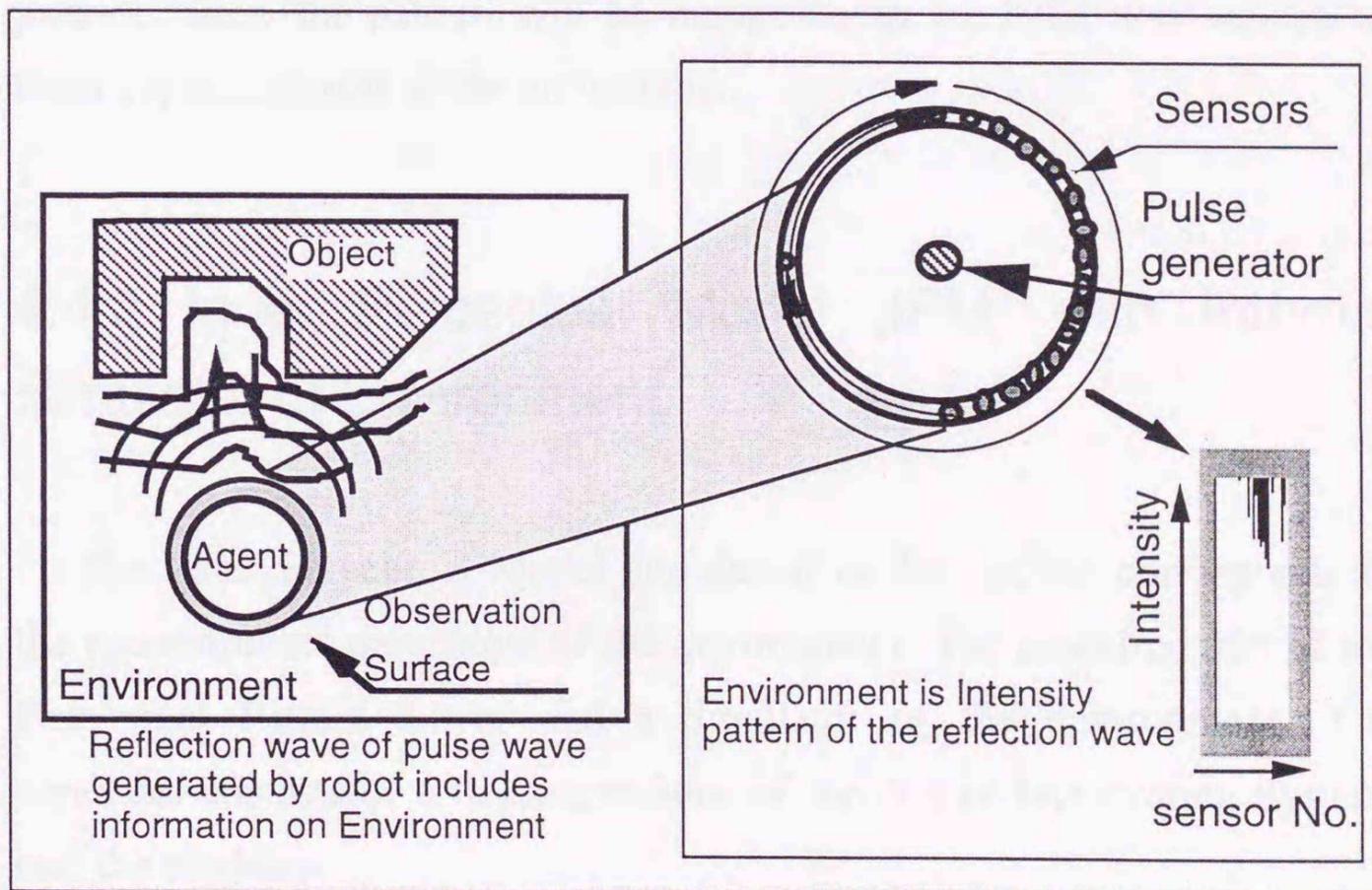

Fig. 4.2 Active Observation System of Environment

The reflection wave includes the geometric information of the environment. Moreover, the reflection wave includes the geometric information of the environment. Moreover, the reflection wave corresponds to the geometric information of the environment. Moreover, the reflection wave corresponds to the Optical Array in the Affordance Theory. The sensors arranged uniformly around the agent observes the

strength of the reflection wave. Each sensor integrates the strength of the wave through a certain time as formalized in Eq. (4.9).

$$s_i = \int_{T}^{T+OT} o_i(t) \, dt \qquad (4.9)$$

where, s_i denotes the output value of the i-th sensor, $o_i(t)$ is a wave strength of the i-th sensor at time t, and OT corresponds to the refractory period of the sensor. This input pattern is treated as a 2-dimensional pattern. Then, the pattern will be mapped onto the IPM, and will be an inner representation of the environment.

4.4.2 Inner Perceptual Model (IPM) with Internal Simulator of Environment

The Inner Perceptual Model introduced in this section corresponds to the reconstructed perception of the environment. The model consist of the Perceptual Pattern Layer and a Simulator of the environment. The simulator consists of a field, simulator of the Active Observation System, and the modules.

The field is an inner environment that will be a medium of the wave generated by the simulator. It has a damping factor as a parameter to be settled by the designer. It will be, however, the agent's job to decide the parameter in the future work. The simulator observes the IPM under reconstruction quite as same way as the real observation system. The IPM is evaluated by means of the simulator under the simple rule described in the next section. The module is regarded as a symbol and the pattern consists of the modules corresponds to the inner representation of the environment. As physical characteristics of the module in the IPM, it has a

reflection body with a certain size and shape. The module can be treated as a symbol when assigned a coordination. In this chapter, the reflection rate of the module is fixed as 100%, and the shape of it is also fixed as a square. The module is placed by the agent itself on the field.

In this chapter, we will call the pattern reconstructed in the IPM as Perceptual Pattern. The experience of the agent affects the Perceptual Pattern because the order of placing the module is modified by the learning described in Subsection 4.4.5. Therefore, the Perceptual Pattern is particular to the agent and may hard to interpret by the designer. The Perceptual Pattern is able to regarded as the "grounded" symbol. This inner representation would enable the agents acquiring the empirical measure when coupling with the behaviors, because it is expected that some essential pattern for a certain behavior may occur through trial and error. We consider this essential pattern will be corresponding to the Invariant. An information processing system, that will make the agent available of the IPM and will grow the possibility to realize a direct perception, is described in the next sub-section.

4.4.3 Information Processing System

The outline of the processing system referring to the IPM is illustrated in Fig. 4.3. As described above, the sensor pattern is regarded as a 2-dimensional pattern and mapped onto the output layer of ART (Carpenter & Grossberg 87: Fig. 4.4). ART is suitable for this framework in that it can identify the quite new pattern as mapping onto the virgin unit in the output layer. Moreover, the stored pattern is never disturbed by the less corresponding input pattern. The output of ART in this chapter slightly
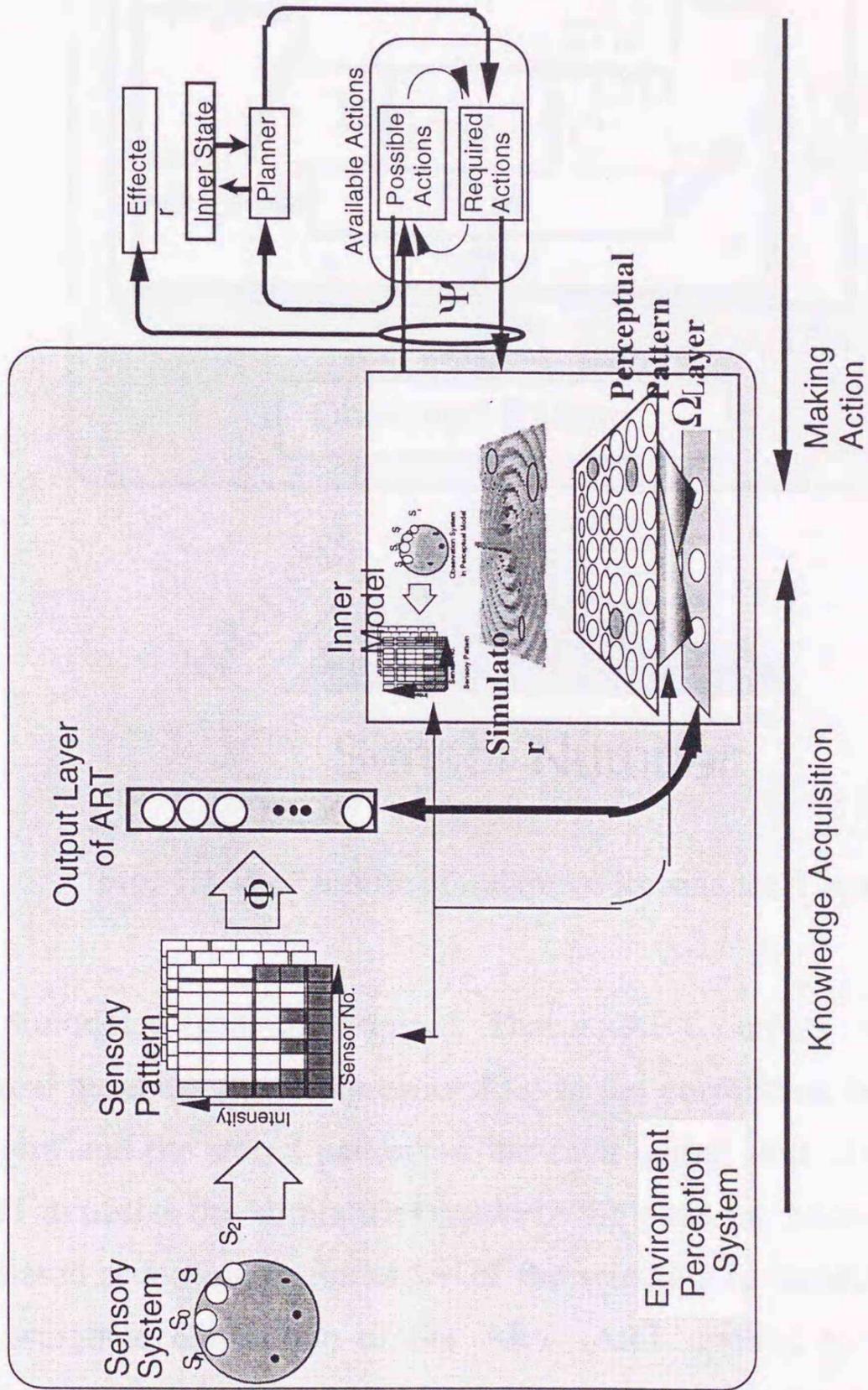
Fig. 4.3 The Outline of Information Processing System with Inner Perceptual Model

The sensory pattern is input to the ART. Output layer of ART outputs the real value, i.e., [0, 1], according to the similarities between the stored pattern of the output unit and the current pattern. Perceptual Pattern layer is connected with the output layer of the ART by the weighted links. In the perceptual pattern layerm the unit that have the strongest output value is covered by the module. Then, evaluated according to the criteria, i.e., $S^{re} \supseteq S^{in}$, by means of the simulator in the inner model. The perceptual pattern acquired through the above process and the available actions/behaviors are coupled by means of a reinforcement learning. To the contrary, subset of the pattern that is observed every time a specific action /behavior is available would be corresonding to the Invariant.
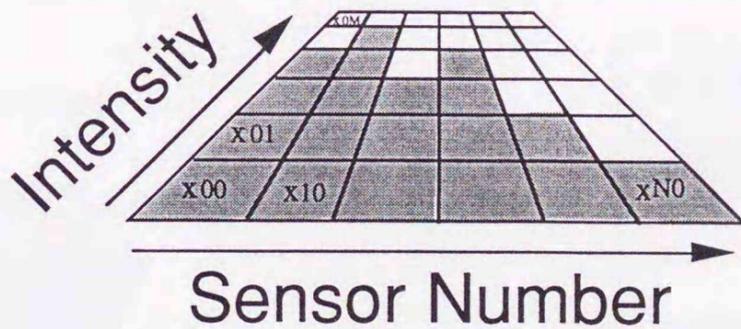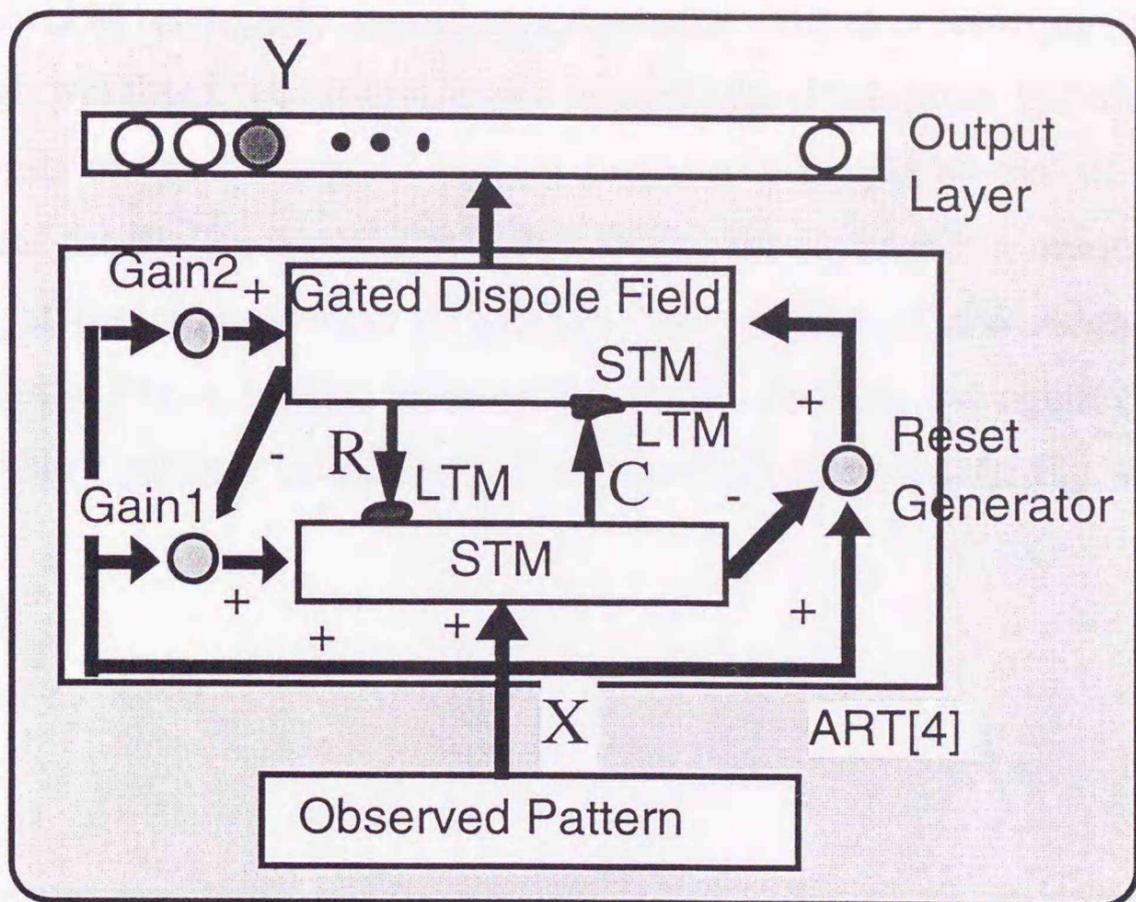
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Fig. 4.4 The Outline of Adaptive Resonance Theory (ART)

remodeled from the original. That is, ART outputs vectors consisting of real numbers [0, 1] corresponding to the correlation between the input pattern and the stored pattern of the each output unit. This might enable ART to utilize the similarities between the patterns. Moreover, the output is biased according to the order of the selection to respect for the bottom up weighted connection of the ART. ART applied to this framework differs from the original also in that it requires candidate of the output unit until a certain number of candidates are collected or a virgin unit is selected.

The IPM is treated with respect to the output vector of the ART through weighted connection to all units on the Perceptual Pattern Layer. The units on the Perceptual Pattern Layer correspond to the all grids of the field for the modules in the IPM. Then, the agent put a module in the order of the strength that a grid has. The outline of the mechanism is depicted in Fig. 4.5. With the new Perceptual Pattern, the agent compares the sensory patterns of the inner and real world as shown in Fig. 4.6.
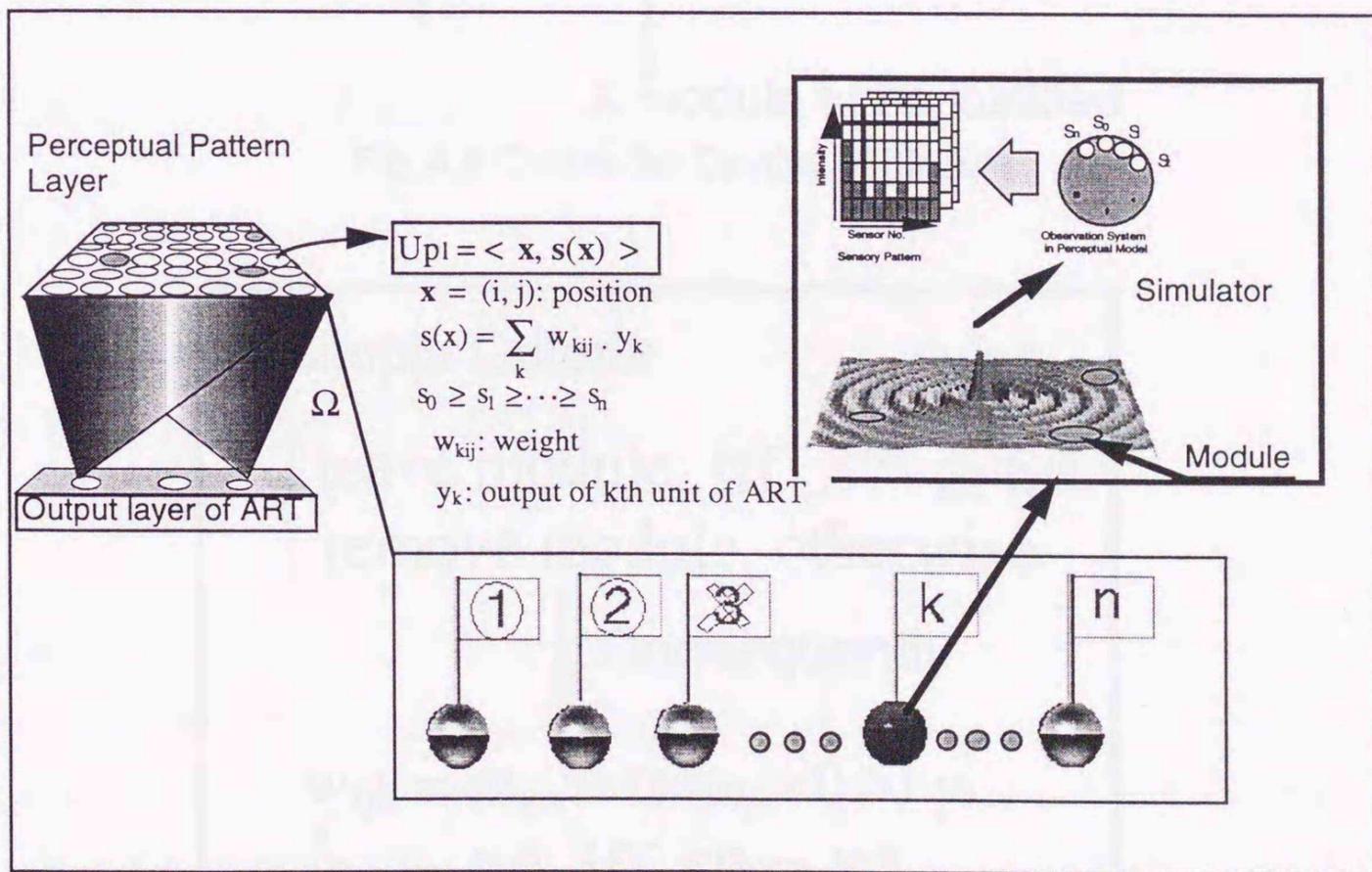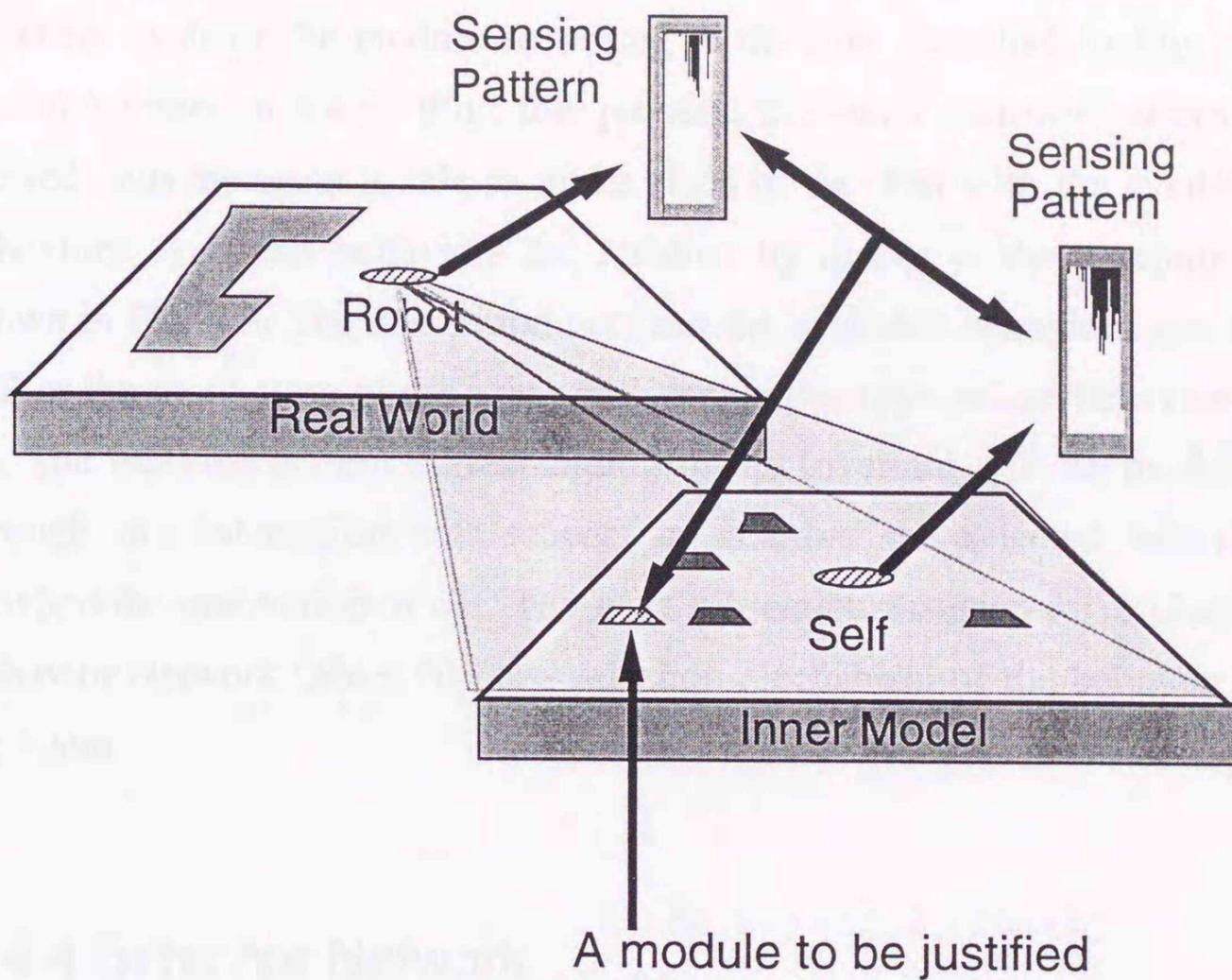

Fig. 4.5. Reconstruction of IPM by Means of Simulator

Fig. 4.6 Criteria for Destiny of Module

A Simple Criteria

$$\begin{cases} \text{leave module, iff } S^{re} \supseteq S^{in} \\ \text{remove module, otherwise} \end{cases}$$

Consequently

$$w_{ijk} = w_{ijk} + \alpha \cdot (o_{ij} - 0.5) \cdot y_k$$

$$\begin{cases} o_{ij} = 1.0, \text{ iff } S^{re} \supseteq S^{in} \\ o_{ij} = 0.0, \text{ otherwise} \end{cases}$$

The order will be changed

Fig. 4.7 Criteria for the Destiny of a Module

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Then, evaluate the module according to the rule described in Fig. 4.7 and in Subsection 4.4.5. With this process, the inner sensory pattern is created, thus the agent is able to make plans in the IPM with the available behaviors. Available behaviors are recalled by means of the mapping Ψ shown in Fig. 4.3. The interaction between the available behaviors and the will or the motivation of the agent will decide the appropriate behavior to do. The essential pattern corresponding to the Invariant will be modified through this interaction with respect to whether the selected behavior satisfied the motivation or not. The next subsection assigned for a kind of Behavior Network (Maes 90) as a selection mechanism of the behavior of the agent.

4.4.4 Behavior Network

The Perceptual Pattern reconstructed in the Inner Perceptual Model is the inner representation of the environment as described above. However, each pattern correspond to the situation of the environment at a moment and therefore, it is not more than an inner representation of the environment that might include so many Invariant for certain Affordances. To identify the Invariant for certain Affordance will enable the agent to emerge the perceptibility of Affordances. For this purpose, I prepare a kind of behavior network connected with the Perceptual Pattern Layer as shown in Fig. 4.8.
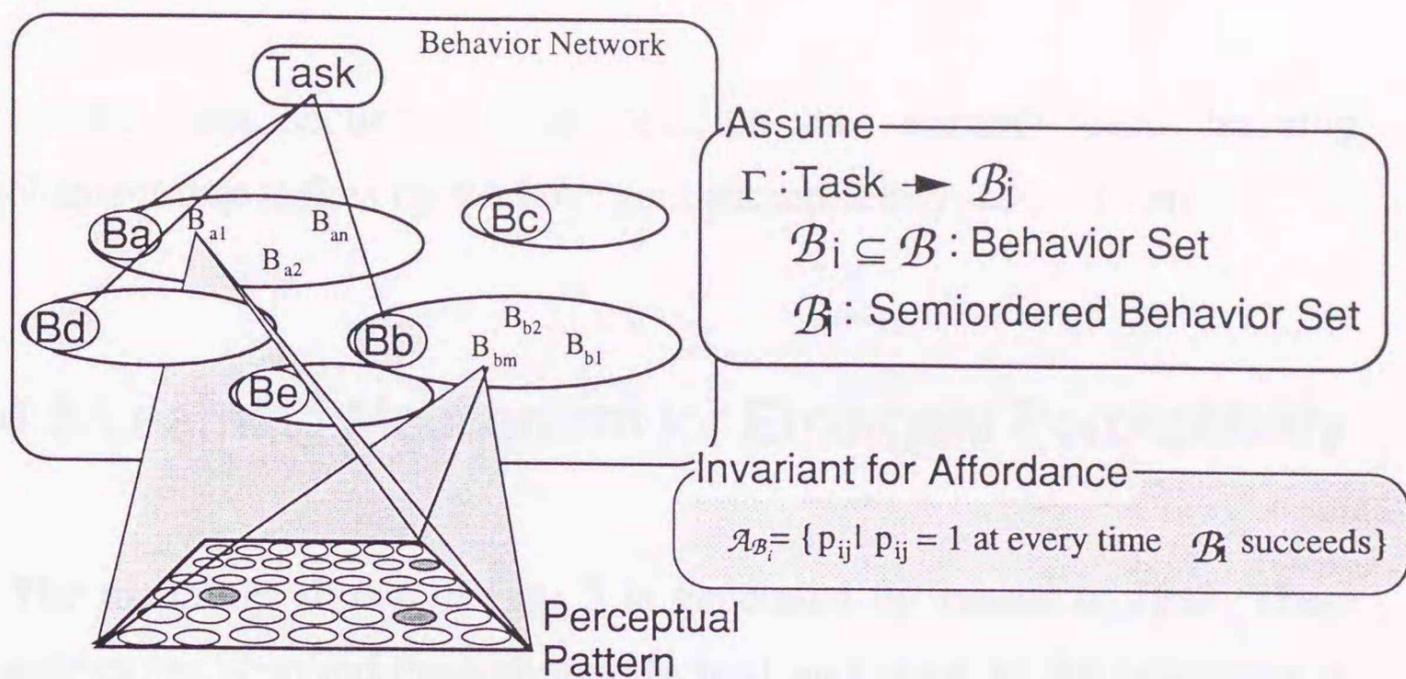
Fig. 4.8 Behavior Network for Identification of Invariants for Affordance

The agent allowed to capture the Invariant for Affordances of certain behaviors by means of the reinforcement learning achieved by the trial and error style weight tune of the connections. The ANN that realizes the coupling will contains the Invariant for certain Affordance as the set of weights. As learning proceed, the more complete perceptibility of the Affordance will be acquired.

Throughout the processes with the components, agent is considered to be able to emerge the perceptibility of the Affordances. Namely, the proposed mechanism is able to realize the non-Cartesian Perception as a whole when the learning has completed.

Without the learning mechanism, the emergent process will never be occurred. The learning mechanism will provide the mechanism the emergent perceptibility. Moreover, the following three effects (Hakura 96a).

- The quickness in reconstructing the Perceptual Pattern in the IPM.
- The connections between the Perceptual Pattern and the
    action/behavior.
- The expectation to catch the Invariant in a concrete representation.

In the next section, I will describe the learning each learning mechanism that makes up the emergent perceptibility, respectively.

4.4.5 Learning Mechanism for Emergent Perceptibility

The mappings shown in Fig. 3 is generated by means of IPM. These mappings are acquired through mainly trial and error in the beginning of the activity. As learning proceeds, the agent is able to reconstruct the IPM quickly and the available behavior set recalled in accordance with the Perceptual Pattern in the IPM, would be more correct one. In this subsection, each learning mechanisms that enable the mappings in Fig. 4.3 are described respectively in detail.

Acquisition of Mapping Φ

As described in the previous section, mapping Φ is realized by means of the ART. The learning mechanism of this mapping is, therefore, quite the same as that of ART's. However, it differs from the original in that each output unit that has a stored pattern will output a value [0, 1] according to the similarities between the input pattern (as a vector) and the vector C from the input layer. Vector C. is generated by the 2/3 rule (Carpenter & Grossberg 87) in reference with the resonance signals.

Acquisition of Mapping Ω

Mapping Ω is realized by the weighted links between the output units of the ART and the units on the Perceptual Pattern Layer in the IPM. The units on the Perceptual Pattern Layer are ordered with respect to the output value y_{ij} defined as:

$$y_{ij} = \sum_k w_{kij} \cdot x_k \qquad\qquad (4.10)$$

where, x_k is the output value of the k-th unit of the ART, w_{kij} is the weight on the link between i-j th unit in the Perceptual Pattern layer and the k-th unit of the ART.

Because the agent selects the single unit in the Perceptual Pattern layer according to the output value of the unit to put a module, each place corresponding to the unit is evaluated by means of the simulator. The evaluation is carried out under a simple rule: left the module, if the sensory pattern from the simulator S^{in} is included in the sensory pattern observed in the real world S^{re}. Otherwise, remove the module from the layer (see Fig. 4. 9). Within this procedure, the learning process is carried out in parallel according to the following rule:

$$w_{kij} = w_{kij} + \alpha \cdot (o_{ij} - 0.5)x_k,$$
$$\begin{cases} o_{ij} = 1.0, \text{ iff } S^{re} \supseteq S^{in} \\ o_{ij} = 0.0, \text{ otherwise} \end{cases} \qquad (4.11)$$

where, α is a learning coefficient. The same procedure is applied when the accepted module is turned out to be a rejected one by the movement of the agent.
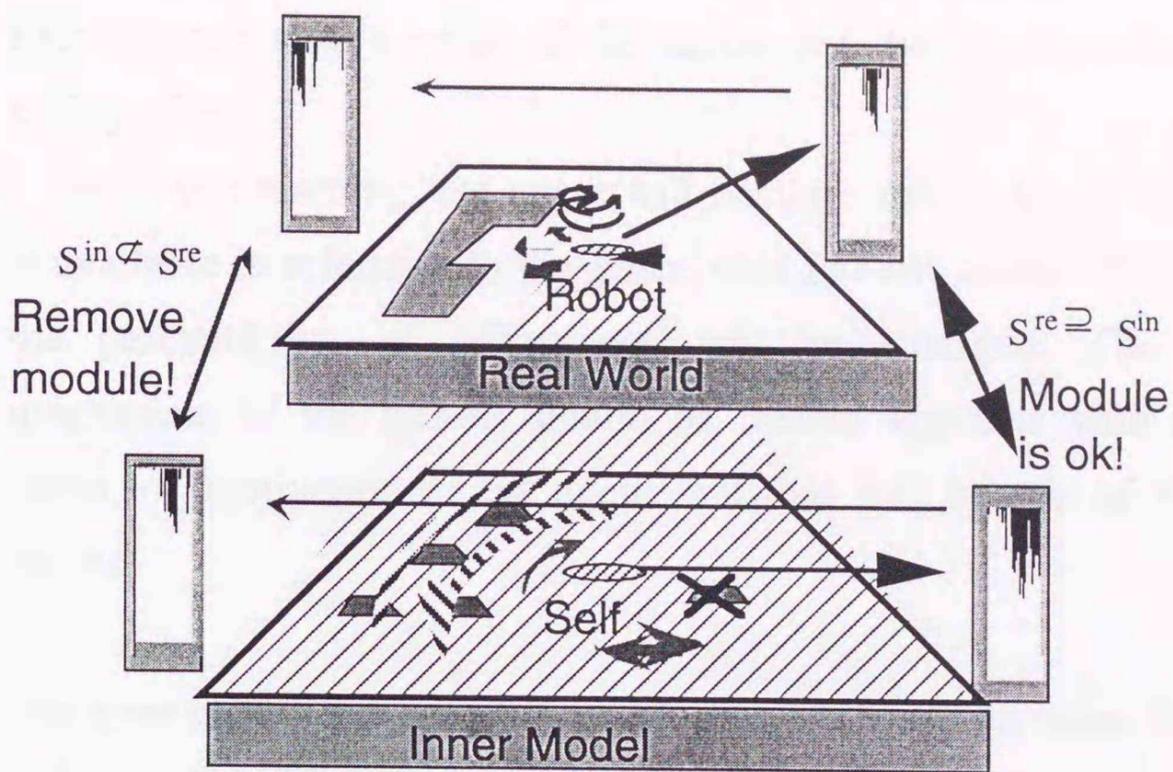
Fig. 4.9 Complete Perceptual Model with Move

A module that satisfied the criteria sometimes turn out to be irregal in accordance with the movement of the robot. The same rule is applied to both the learning and the module; in this case robot tries to remove the nearest module in the inner model.

Acquisition of Mapping Ψ

Once the *Perceptual Pattern* is captured in the IPM, the agent is able to make behaviors. In this chapter, the available behavior of the robot are fixed and a kind of reinforcement learning is introduced to couple the Perceptual Patterns with actions. The coupling is also represented by the weighted links, and the output of the coupling will be the available candidates of the behavior. Learning in this mapping is achieved through the trial and error fashion: try all the actions given by the designer when a tabula rasa unit in the output layer of the ART is assigned a new output unit. Moreover, weaken the weights on the linkage toward an action that is unsuitable, i.e., some undesirable

situation occurs as a result of the action, for the situation the agent is facing with.

With this learning, the agent will become able to know what action is available in reference to the Perceptual Pattern in the IPM. Namely, the perceptibility of Affordance will be emerged. The selection mechanism of the actions should be treated together with the inner states, or motivation of the agent, but that will be one of the future works.

The next section assigned for the Mechanism based on Inner Perceptual Model with Reinforcement learning.

4.5 A Mechanism Based on Inner Perceptual Model with Multi-Agent System

In this section, I will introduce the mechanism based on Inner Perceptual Model with Reinforcement learning for the emergent perceptibility. The mechanism also consists of sensors, Inner Perceptual Model, Learning Mechanism, and Information Processing System.

The remarkable point of this mechanism is that it is able to update roughly its Inner Perceptual Model by itself without observing the environment. For this purpose, the Inner Perceptual Model is constructed as a multi-agent system. Each agent in the multi-agent system is a quite simple and are not autonomous but works as the component of the Inner Perceptual Model of the autonomous agent that behaves in the real world. The characteristics of the both types of agent is quite different(Fig. 4. 10).
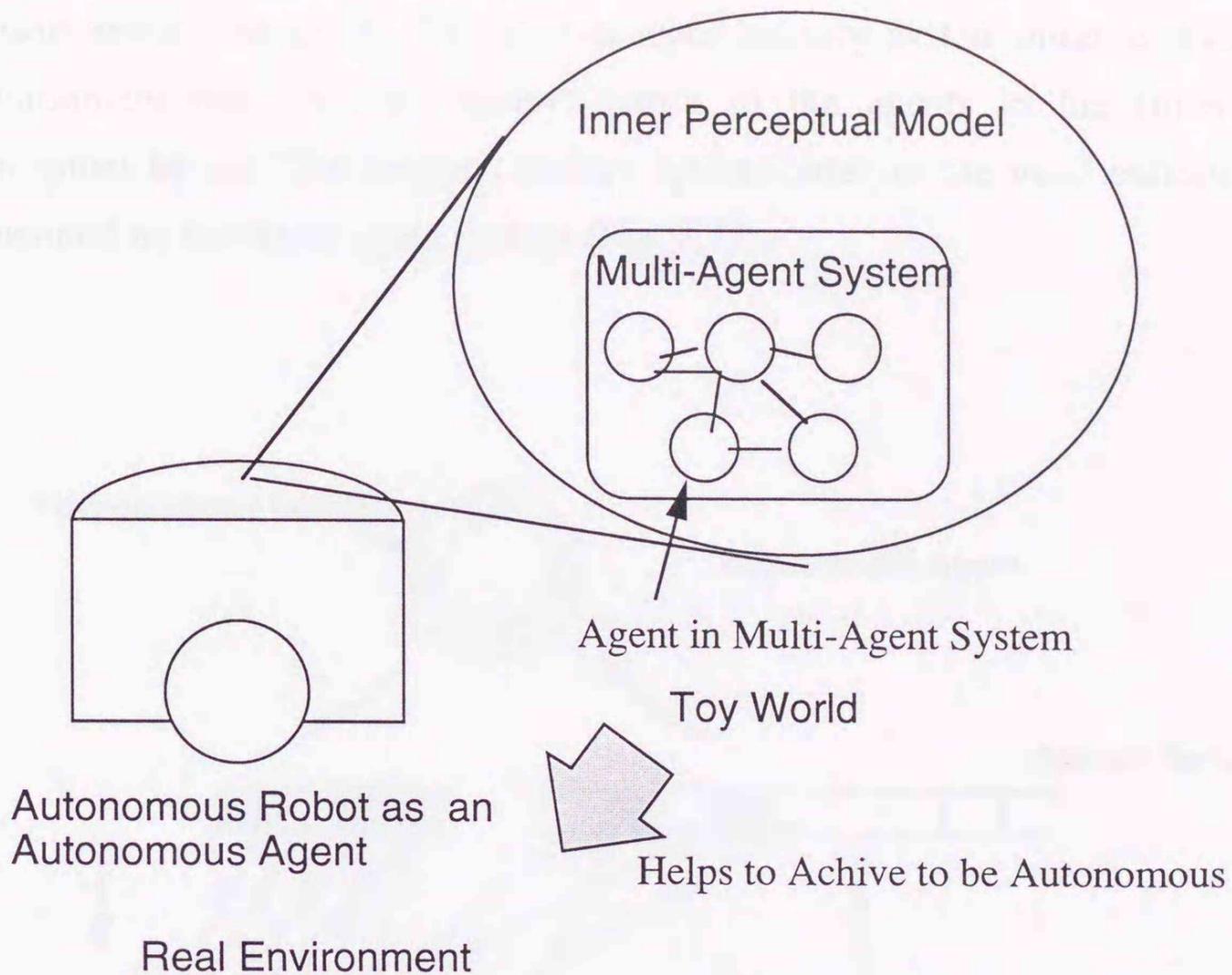
Fig.4. 10 Agents in Toy-World Helping Agent in Real World

The mechanism emerges the perceptibility as the rules of the agents in the Inner Perceptual Model with respect to the behaviors. Therefore, it is said that the Inner Perceptual Pattern in this case, represents the behavior itself but is also uninterpretable by the outside agent.

4.5.1 Sensory System

The sensory system of this mechanism consists of two kinds of sensory system, i.e., environmental sensory system and internal sensory system for action making. Any kinds of sensor will be available with this mechanism

for the environmental sensors, but within this thesis, they are assume as IR sensors around the agent. The environmental sensory system observes the environment and send the binary output to the agents in the Inner Perceptual Model. The internal sensory system observes the local pattern generated by the multi-agent system (Fig. 4.11).
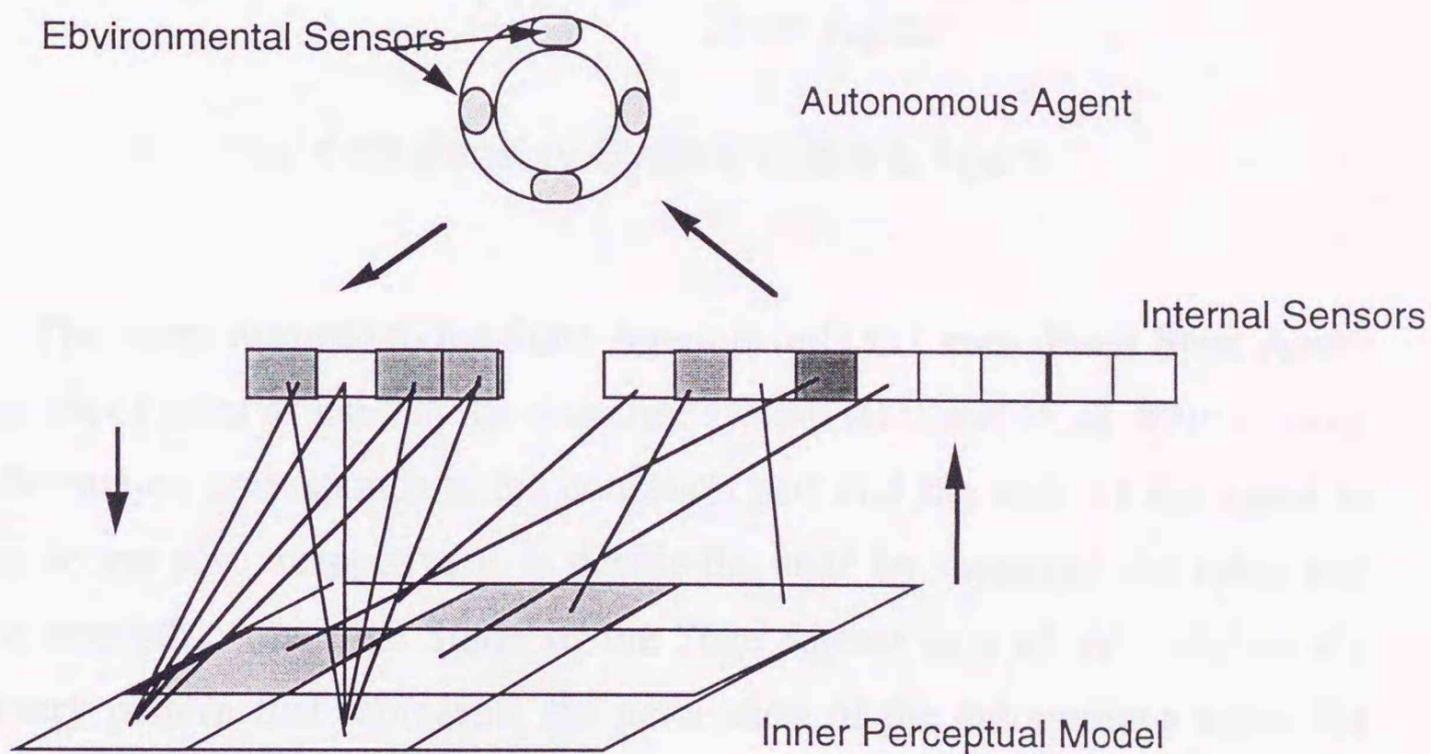

Fig. 4.11 Outline of the Mechanism with Sensory System

4.5.2 Inner Perceptual Model with Multi-Agent System

As shown in Fig. 4.11, the agents in the Inner Perceptual Model (I call it as State Agent hereafter) receives the inputs from environmental sensory system. They are arranged in the grid world. It decides the state of itself by using the environmental sensory inputs and the sensory system of its own. The sensory system of the State Agent observes the states of the agents in the Neumann neighborhood system as shown in Fig. 4.12.

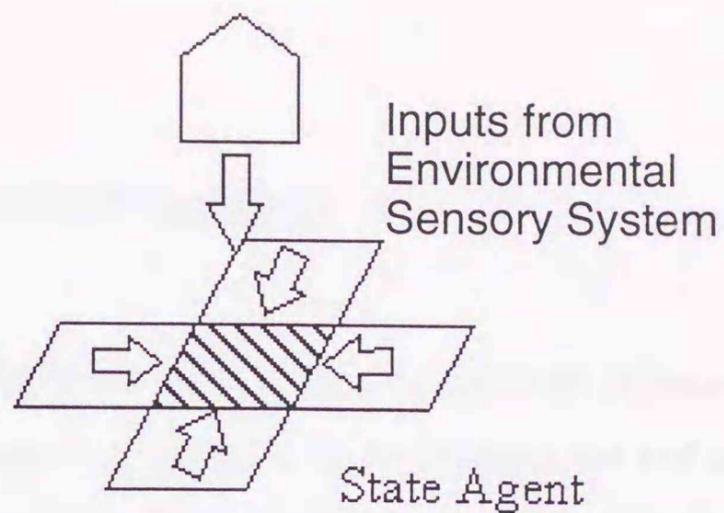Inputs from Environmental Sensory System

State Agent

Fig. 4.12 Sensory System of State Agent

The states allowed to the State Agent is only 0/1 now. Each State Agent has set of rules as used in the classifier system (Holland et. al. 89): sensory information corresponds to the condition part and the state of the agent to the action part, respectively. It decide the state by means of the rules and the strength of the rule. States of the State Agents as a whole, exhibits the binary pattern that represents the perception of the autonomous agent for the current environment.

4.5.3 Information Processing System

The mechanism have the information processing system as shown in Fig. 4.11. The behavior selection of the autonomous agent is also uses another set of rules with the strength. It observes the local area of the Inner Perceptual Pattern by the State Agents and decides its action according to the selected rule. With these information processing process, the autonomous agent is able to achieve the Inner Perceptual Model more

precisely as a rule set of the State Agents, and therefore, it is expected to behave appropriately in the complex environment such as the real world.

4.5.4 Learning Mechanisms

The learning mechanisms used in this mechanism is based on that of the classifier system. However, the rules to be learned are not allowed to have the "don't care" symbols. The learning phase have started when the autonomous agent achieves the task assigned by the user of the agent. In other word the agent is allowed to learn nothing if it never achieves the task.

The autonomous agent is assumed to receive certain amount of the reward from the user. The received reward is passed to the previous rule selected in the sequence of the success by means of the Bucket Brigade Algorithm (Holland et al. 89). Therefore the autonomous agent is considered to achieves the actions that is suitable for the environment as the rules those have higher strength.

The propagation of the reward is formalized as follows:

$$Strength = Strength - Bid + Reward, \tag{4.12}$$

$$Bid = a \cdot Strength, \tag{4.13}$$

where, Strength is the intensity of the rule that have selected at time t, Bid is the payoff for the rules selected at time t-1. a denotes the learning coefficient, and Reward is the reward from the user.

The State Agents refine their rule set the same way as that of the autonomous agent:

$$Strength - Strength - Bid + Bid\_Sum + Reward, \tag{4.14}$$

$$Bid = a \cdot Strength, \tag{4.15}$$

$$Bid\_Sum = \sum_t Bid(t+1) \qquad\qquad (4.16)$$

where, Strength is the intensity of the rule selected at time t. Bid is the payoff among the State Agent , a is the learning coefficient, Bid_Sum is the sum of the payoffs from the rules selected at time t+1 of the agent that affected at the input value. Reward in this case is from the autonomous agent.

With those four components, the autonomous agent is expected to emerge perceptibility of the environment.

4.6 Self-Perception

As a trial to achieve the perception mechanism based on the visual sensors, I introduce a trial to make the autonomous agent able to perceive on itself in this section. It is not more than a trial, but the concept is considered as very important for the realization of autonomous agent.

Can we perceive the movement of ourselves only from the visual inputs, namely the optical flow(Buelthoff 89, Dev 95)? We would say "yes" for this question.. For example, we sometimes have an optical illusion when we are getting on a car and waiting for the signal turns on and stared vacantly at the car next to us is going to stop. We are often startled to find ourselves going backward and to step the brake pedal more powerfully, then after a moment find that it was not our car that was moving.

While on the other hand, the agent seems not being allowed to have this startlingness. It must be because the designers of the agent did consider

that the agent is not required to have the property. The sensors to those agents are often used as only a feedback system for the motion (Kuipers 93). However, the consideration of the designer itself would result in the compulsion of the designer's model of the agent's movement. The agent's perspective on its movement is required for the adaptive agent in the noisy real world.

In this sub-section, the outline of out idea for the mechanism that would allow the agent to perceive its movement as its own style is described.

The mechanism consists of three parts: the optical flow, the Empirical Filters, and the processing system. The optical flow is the vector field formed by the projection of the 3D-motion of the environment on the image plane of the agent. At the same time, it projects the motion of the agent on the image plane. We consider it as the input to the agent. For our purpose, optical flow is defined as $o_r = <r, v>$, where r is a point at the image plane, and v is the flow vector at the point.

The Empirical Filters (denoted as $\mathcal{EF}$) those are act as the IPM in the previous sub-section, and are treated as the "grounded symbol" for the agent that represents the movement of the agent. The reconstruction method, i.e., algorithmic expression in this paper, of the Empirical Filter is as follows by means of the processing system:

$$
\begin{aligned}
&\mathcal{EF} = \left\{ \mathcal{F}_i \mid i \in I, 0 \le i < N, I \text{ is Integer} \right\}, \\
&\mathcal{F}_N = \left\{ f_x \mid f_x = \frac{1}{T} \sum_t^T P_x(o_r(t)) \right\}, \\
&P_x(o_r) = \begin{cases} 1 & \textit{iff } x \in o_r \\ 0 & \textit{elseware} \end{cases}.
\end{aligned}
\tag{4.17}
$$

where, x is a coordinate in the Filter, T is a flame numbers for the optical flow. The rule for the reconstruction of the new filter is,

$$\chi(C_i, \mathcal{F}_i) \le \mathrm{Th},$$

$$C_i = \mathcal{F}_i \bullet \sum_{t}^{T} \mathrm{P}_x(o_r(t)). \qquad (4.18)$$

where, χ is a correlation operator, and Th is the threshold.

The Empirical Frame is now representing the movement of the agent. By labeling each filters with the output for the motors, for example, the agent would acquire the perception of its movement with respect to the motors. Therefore, when they are carried by the other agents, i.e., corresponding to the real outputs for the motors are both zero, it can perceive its movement with the representation of its motor outputs.

A example of implementation of the mechanism is shown in Fig. 4.13 and the examples of the Empirical Frame is shown in Fig. 4.14.
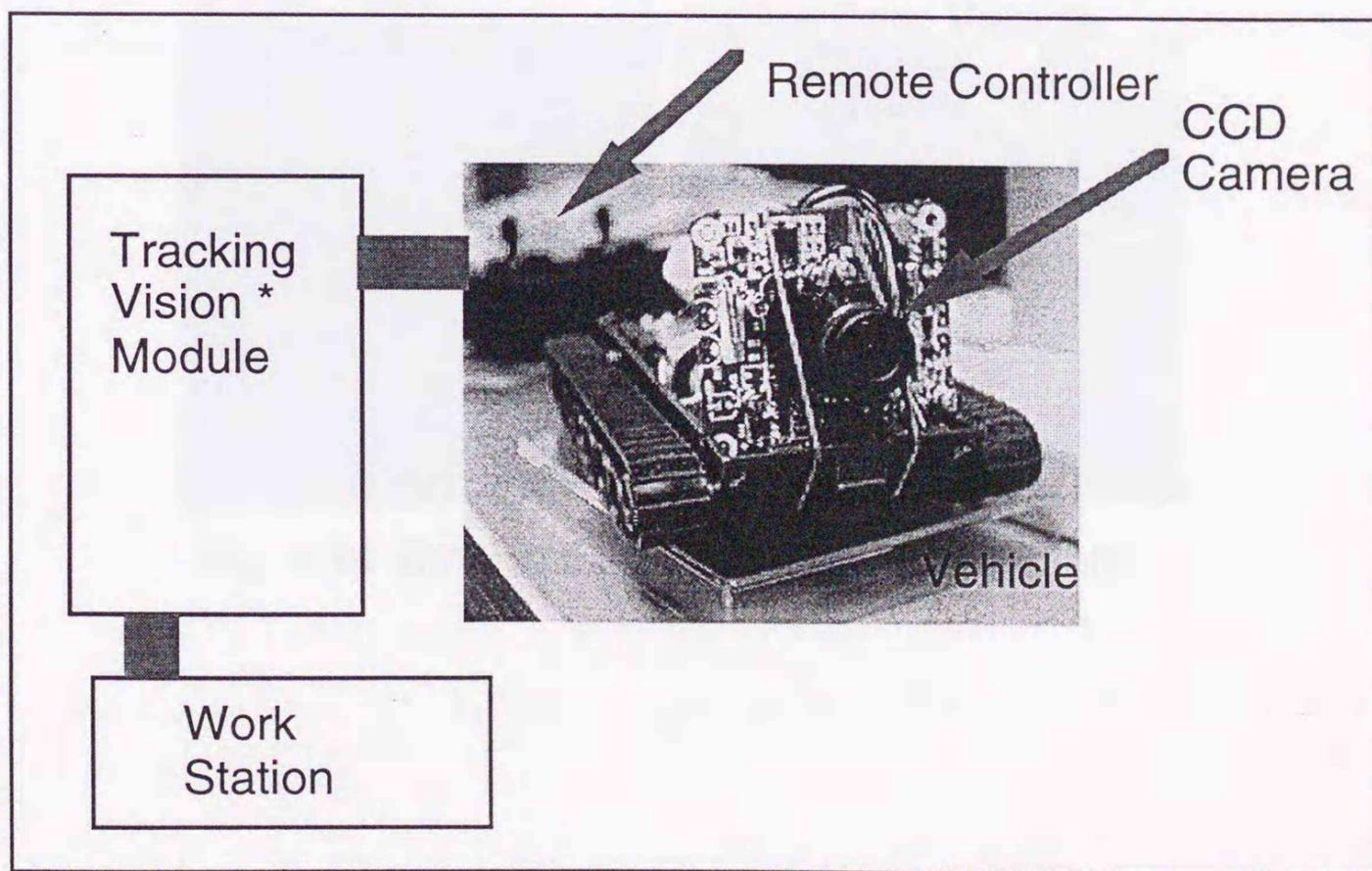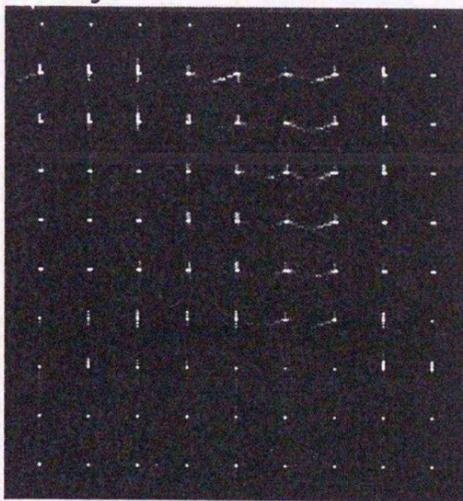

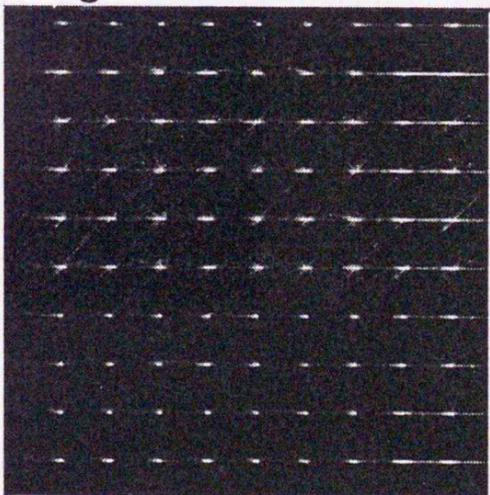Fig. 4.13 Outline of Vehicle for Self Perception.
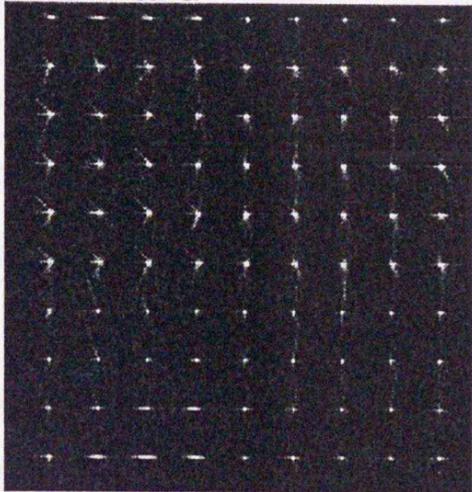
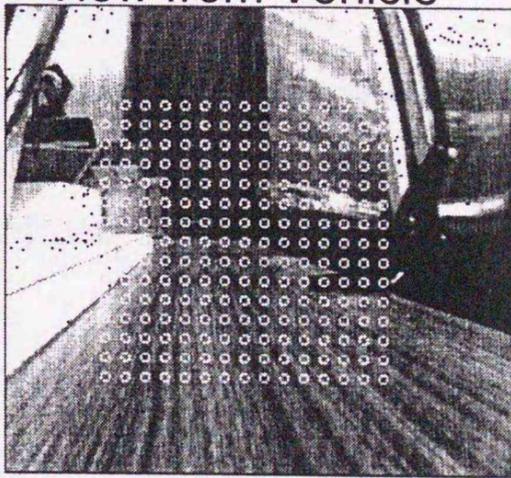Forward Stay

Right Turn View from Vehicle

Fig. 4.14 Empirical FIlters Acquired by Agents.

4.7 Conclusions

In this chapter two concrete mechanisms for the emergent perceptibility have introduced:

• The mechanism with internal simulator

The mechanism is designed especially for the realization of the autonomous agent that is able to perceive the Affordances of the environment, and therefore, the four components are select as:

Active Observation Systems

It generate pulse wave and observes the integral intensity of the reflection wave because the reflection wave is expected to contain the geometric relations among the objects those constitute the environment.

Inner Perceptual Model with Simulator

The simulator of the Active Observation System to reconstruct the Inner Perceptual Model is introduced in such way that the agent itself to be self-confident in the reconstruction.

Information Processing System

The mechanism have utilized several Artificial Neural Networks to make the connections among the components with certain robustness.

Learning Mechanism

Learning Mechanisms in each component are almost the same as that of ANN's.

• The mechanism with multi-agent system

The mechanism is utilizes the agents in the "Toy-world" for the Inner representation system of the environment. This mechanism is designed especially for the autonomous agent based on the

reinforcement learning to be able to achieve the action states to be its own. For this purpose, this thesis selects the components as follows.

IR Sensors

Agent is assigned the IR sensors around the agent to transform the local information surround it.

Inner Perceptual Model with multi-agent system

The multi-agent system is expected to works effectively, because the state space of the IPM is almost like a Toy World. The use of the multi-agent is the enlargement of the information on the environment is able to be achieved, at the same time it tries to learn the reconstruction.

Information Processing

The mechanism uses the rules as the information processing system for the State Agent is to be worked simply.

Learning Mechanism

The learning is achieved by means of the Bucket Brigade Algorithm to utilize the time sequence of the behaviors.

Both mechanisms are consisted of the metrologies used also in the conventional AI. However, they both have the four components carefully designed to emerge the empirical measure. Design of the autonomous agent requires us to combine the four components appropriately. Namely, the four component is the necessary conditions but not the sufficient condition.

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CHAPTER 5

Experiments

5.1 Introduction

So far, the thesis has discussed on the mechanisms that will realize the emergence of the perceptibility of the autonomous agents in the previous chapters. In this chapter, discussions on the perceptibility achieved by the proposed mechanisms by forcing them several kind of problems are made.

The results shows that the proposed mechanisms have possibilities to emerge the perceptibility of Affordance from the environment. This means that the realization of the agents that have more independent, and adaptive characteristics than the agents based on conventional AI, namely on Cartesian System. The autonomy of the agents will be developed by means of the mechanisms proposed in this thesis, because the independency and the adaptability of the agent are able to be developed.

In Section 5.2, the mechanism with the Inner Perceptual Model based on the simulators possibilities to emerge the perceptibility of the

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Affordance for passing through. Section 5.3 shows that the Inner Perceptual Model have been able to extended the range of the scope of information on the behaviors of the agent by introducing the multi-agent system for reconstruction of the Inner Perceptual Pattern.

5.2 Experiments for the Mechanism Based on Inner Perceptual Model with Internal Simulator

In this section, attempts to reveal the possibilities of the proposed mechanism based on the Inner Perceptual Model with Internal Simulator is made, mainly on the possibility to emerge the perceptibility of Affordance on passing through. For that purpose, the first four sections are assigned to confirm the possibility of the mechanism to satisfy the four necessary conditions described in Section 4.2:

1. **Distinction ability of the difference among the environment**.

    IPM corresponds to the environment itself for the agent. Therefore, it is expected to represent the difference among the environment more or less.

2. **Successiveness in accordance with action.**

    The move of the agent is expected to change the IPM. The change should be occurred in accordance with the degree of the movement.

3. Dependence on the environment.

The environment is consisted of a lot of parameters to be changed such as permeability of the air, noises in the environment, and so on. The environment to the agent should change in accordance with these parameters.

4. Successiveness on the experience.

IPM is based on the conviction of the agent because the reconstruction method of it is considered to be acquired through learning. Namely, what should be perceived is different in accordance with the experience.

Then, the agent's perceptibility on the multi-agent environment will be tested as the perceptibility of the kinds of objects in the environment. Namely, whether the agent is able to perceive the existence of the other agent have tested. In subsection 6, the agent is forced to acquire the Affordance for passing through by means of the proposed mechanism. Finally, a test to confirm that the agent have an ability to emerge the perceptibility of Affordance with respect to the characteristics of its physical properties.

5.2.1 Ability to Distinct Different Environments

This simulation attempts to illustrate the ability of the proposed mechanism to distinguish the different environments. This ability is indispensable for the perception of the agent not only with Affordance but those agents somehow reducing the amounts of information on the

environment. In this simulation, the number of objects is restricted to one, and the distance between the agent and the object is fixed for simplicity.

This is the most important and primitive conditions to be satisfied by the autonomous agents with the perception, because the perception doing nothing when this ability is lacking. In this simulation, the module is fixed to the rectangles as a shape, and 1 pixel times 1 pixel as a primitive size. The shape of the object in the real environment is settled as a circle and a rectangle respectively, and are wavered by random noise. The agent is assumed to penetrate the wave for simplicity.

Fig. 5.1 shows the result of the experiment. The left column corresponds to the real world, and the left-center is to the sensing patterns observed in the real world. The right column corresponds to the perceptual pattern reconstructed in the inner model, and the right-center is the sensing pattern in the inner model. The arrows in the figure show the direction of the agent. The small dots in the inner model are the modules satisfying the criteria. Although there are 14,400 candidate places the agent is allowed to put the modules, the simulation is stopped at 3,500 times trial for the sake of the computational time.

As shown in Fig. 5.1, the reconstructed Perceptual Pattern reflects the difference of the objects, even though the two environments are different only in their shapes. This simple experiment shows that the mechanism have a possibility to distinguish the difference of the different environment.
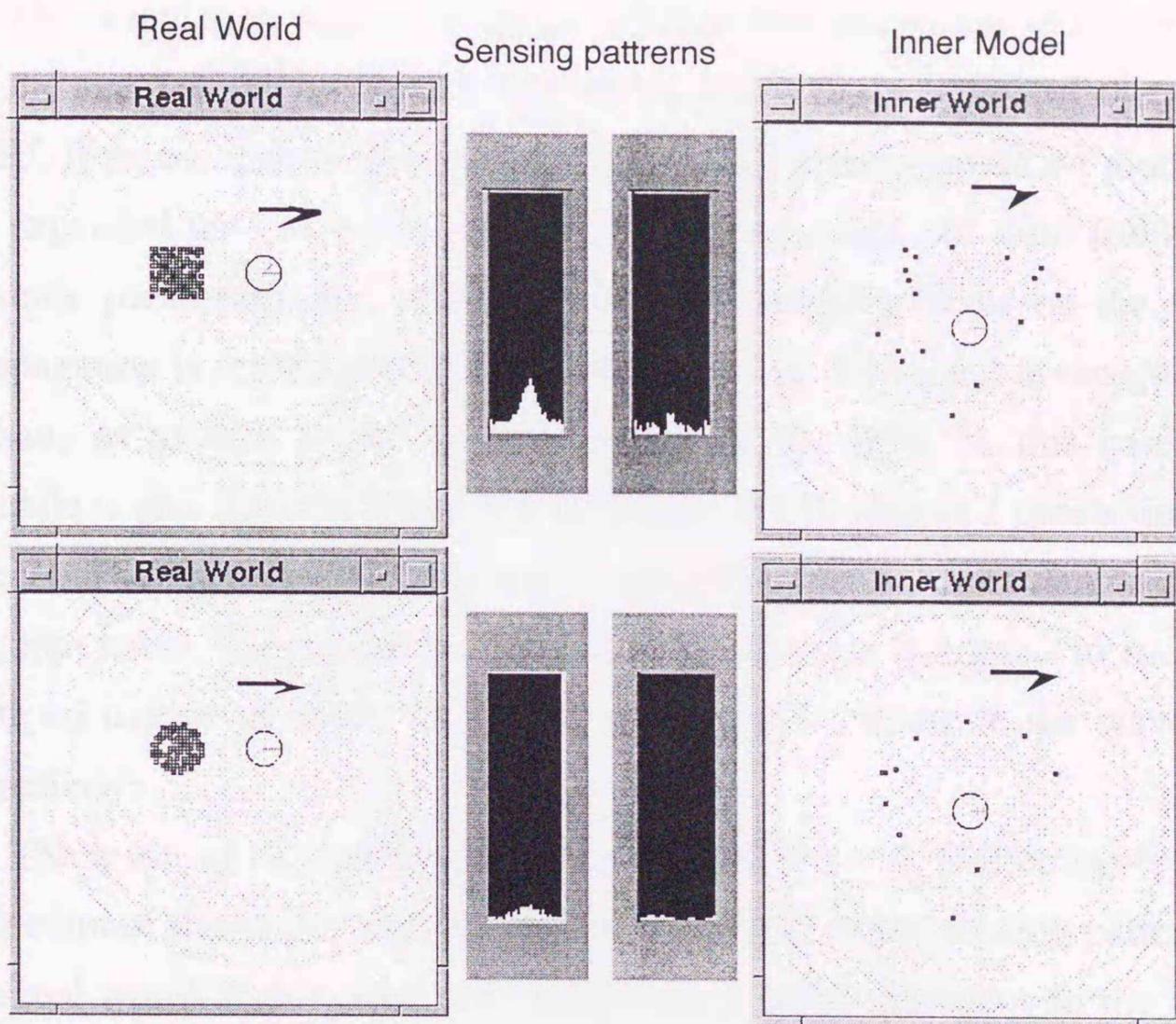
Fig. 5.1
Result of Simulation to Illustrate Ability of the Robot to Distinct
Different environments.

The left column corresponds to the real world, and the left-center is
to the sensing patterns observed in the real world. The right column
corresponds to the perceptual pattern reconstructed in the inner
model, and the right-center is the sensing pattern in the inner model.
The arrows in the figure show the direction of the robot. The small
dots in the inner model are the modules satisfying the criteria.
Although there are 14,400 candidate places the robot is allowed to
put the modules, the simulation is stopped at 3,500 times trial for the
sake of the computational time.

5.2.2 Successiveness in Accordance with Action

This simulation tries to illustrate whether the perception reconstructed by the agent would be expanded in accordance with the action of the agent itself. It means that the perception acquired at a glance should be modified or expanded with its move. The simulation is carried out with following specific parameters and rules. Namely, the damping factor on the wave propagation is settled to 0.95 in the both worlds. The agent is designed to behave as to turn to the nearest module in the IPM. In this case, the module is also fixed its shape as a rectangle, and its size as 2 pixels times 2 pixels. The shape of the object(s) is settled as circles or rectangles with random noise. The movement allowed to the agent is restricted to rotation with 45 degree in notch. The agent is assumed to penetrate the wave for simplicity.

The result of the simulation is illustrated in Fig. 5.2. Within (a)-(c), the left column shows the real worlds, the left-center is the sensing pattern of the real world, right-center is sensing pattern in the simulator in the inner model, and right column is the reconstructed perceptual pattern. The top row is the state after 1,000 trials to settle the modules. The robot is designed to do the trials until the both sensing patterns are equal. At (a), this criteria is not satisfied, and the robot turns randomly (at this time 180 degree). Then makes trials again . The second row corresponds to the states after another 1,000 times trial. The criteria did not satisfied again, and robot turns left by 45 degrees. At the first trial in the state represented in the third row, the distortion occurred in the sensing pattern, i.e., the inner sensing pattern exceeded that of the real world. So that the robot removed the nearest module in the inner perceptual pattern. (The agent turns 180 degree between a-(i) and b-(i) and turns 45 degree to the left through b-(i) to c-(i) according to the rule described in above.
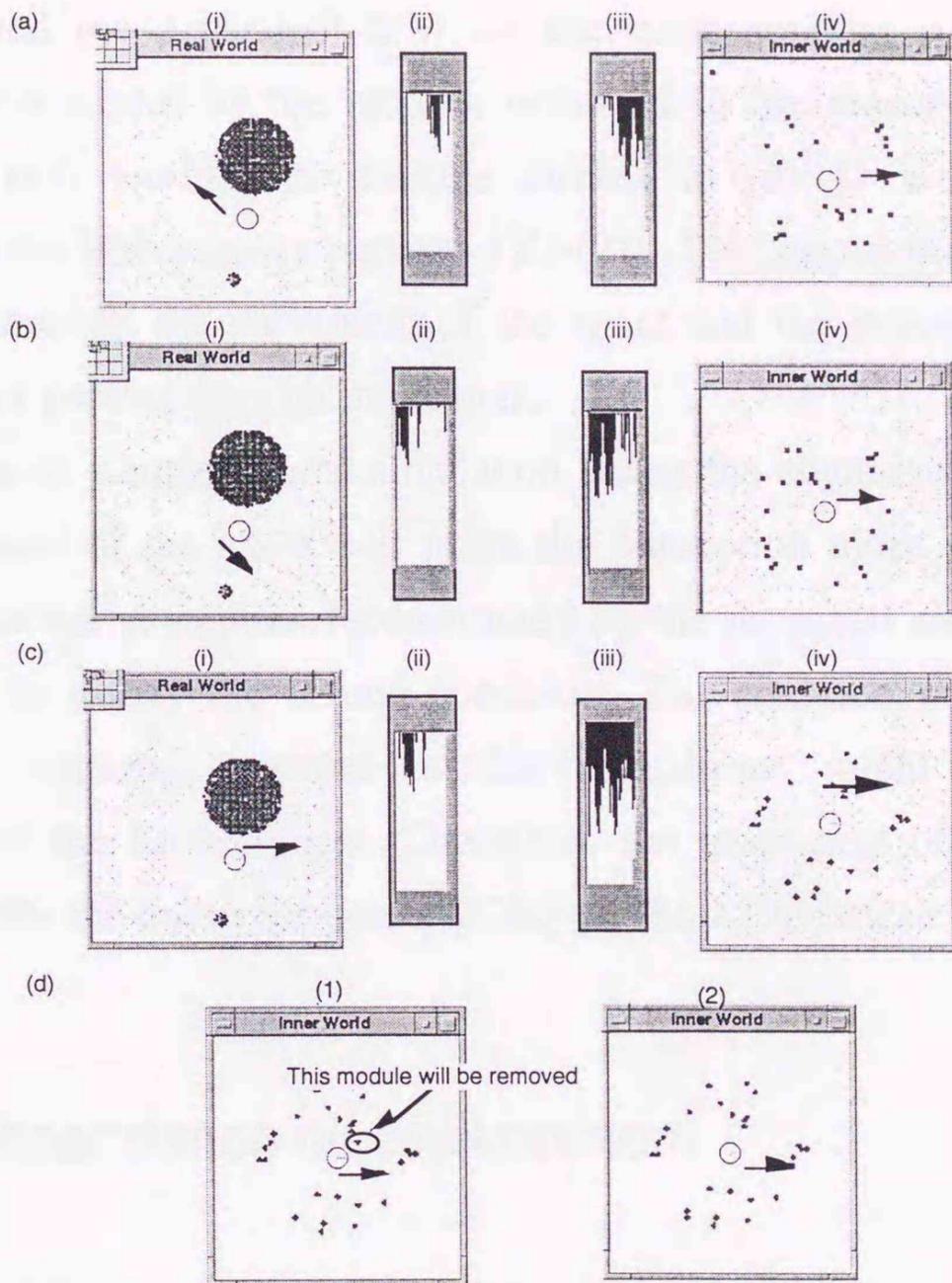
Fig. 5.2 Building Process of Inner Model in Accordance with Action.

Within (a)-(c), the left column shows the real worlds, the left-center is the sensing pattern of the real world, right-center is sensing pattern in the simulator in the inner model, and right column is the reconstructed perceptual pattern. The top row is the state after 1,000 trials to settle the modules. The robot is designed to do the trials until the both sensing patterns are equal. At (a), this criteria is not satisfied, and the robot turns randomly (at this time 180 degree). Then makes trials again . The second row corresponds to the states after another 1,000 times trial. The criteria did not satisfied again, and robot turns left by 45 degrees. At the first trial in the state represented in the third row, the distortion occured in the sensing pattern, i.e., the inner sensing pattern exceeded that of the real world. So that the robot removed the nearest module in the inner perceptual pattern.

(i)s in the figure illustrate the states of the agent against the environment. Among each step the agent repeats the put-and-remove process of the module in the IPM to built the IPM. (iv)s correspond to the reconstructed (or expanded) IPM for the corresponding (i)s. In (d), a contradiction caused by the rotation occurred in the sensory patterns of IPM and real world. The module circled in (d)-(1) is removed to coordinate the both sensory patterns ((d)-(2)). This means that the IPM is modified through the movement of the agent and the perception of the agent grows precise through movement.

As a result, computational simulation shows the cognitive process that the movement of the agent will make the perception more precise. This result shows the perception reconstructed by the proposed mechanism has an ability to satisfy the second condition. The common pattern in the perceptual patterns observed in this experiment might contain the Invariant of the Environment. Therefore, the movement of the agent is important for the emergent perceptibility of the Affordances.

5.2.3 Dependence on Environment

This simulation tries to illustrate the perception will change depending on the state of the environment. For the parameter that fixes the state of the environment, we select damping factor of the wave in the environment. This would be corresponding to the change of the state of the air in our world. Namely, our human perception changes in accordance with the diffusion of the ray. For example, our perception on a fine day is fairly different from that on a foggy day. Information perceived by us are different, even if we are exactly in the same place, when these environmental parameters are different.
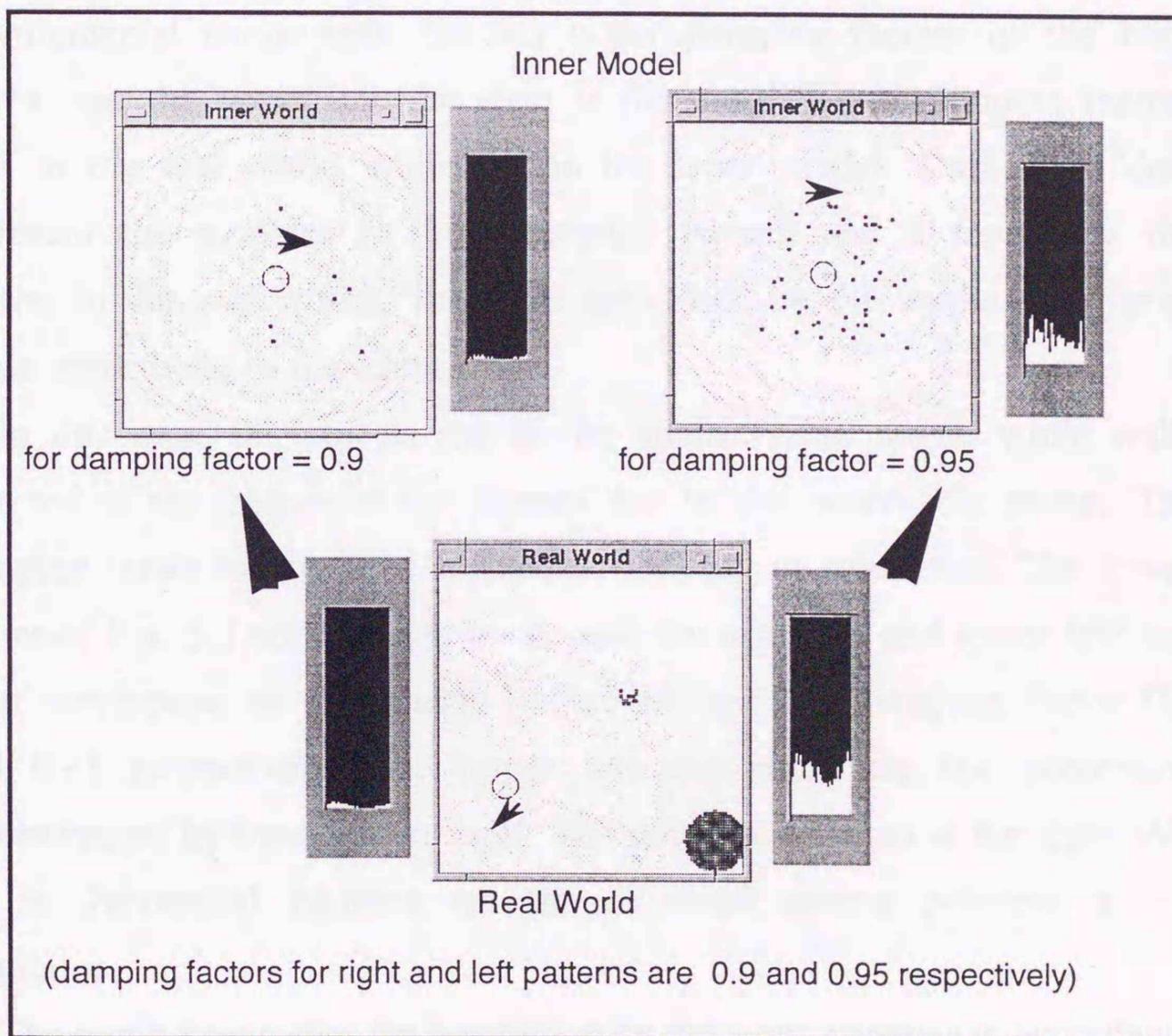
Fig. 5.3 Damping Factor's Effect on Perceptual Model

The top row corresponds to the reconstructed perceptual model on different environmental parameters: the left is for damping factors of the both world are the same: 0.9, the right is for the different damping factor: 0.95 in the real world while 0.9 in the inner model. Dark gray dots represent the modules and light grey dots are the waves.

The parameter for modules used in this simulation is fixed shape as a rectangle and 1 pixel time 1 pixel as a size.

The result of the simulation is represented in Fig. 5.3. The top row corresponds to the reconstructed perceptual pattern on different environmental parameters: the left is for damping factors of the both world are the same: 0.9, the right is for the different damping factor: 0.95 in the real world while 0.9 in the inner model. Dark gray dots represent the modules in the perceptual pattern and it represents the objects in the real world. The light gray dots are the waves. The large circle correspond to the agent.

In this case, the objects are in the unobservable range, while walls depicted as the frames of the figures are in the observable range. The damping factor for the IPM is fixed at 0.90 in this simulation. The lower center of Fig. 5.3 corresponds to the real environment and lower left and right correspond to the sensing pattern observed in damping factor 0.9 and 0.95 respectively. The upper left and right are the perception reconstructed by the agent in itself. The patterns depicted at the right side of the Perceptual Patterns are the observed sensing patterns in the simulator.

The result shows that the perception by the agent changes in accordance with the environmental parameter, i.e., damping factor in this case, and seems reasonable compared with our perception. It is also said in this simulation that the common perceptual pattern observed in both environmental parameter have illustrates the Invariant of the environment.

5.2.4 Successiveness on Experience

With above three experiments, the successiveness on the experience of the agent is obviously satisfied. It is because the order of placing the module affects deeply on the reconstructed inner perceptual pattern. The order is changed by the learning mechanism described in Section 4.4.5. Therefore, the reconstruction of the inner perceptual pattern for an moment will affect the successive reconstruction of the inner perceptual pattern. From this fact, it is also shown that the inner perceptual model have an ability to represent enormous amount of information.

The successiveness on the experience of the agent is important in that the agent is able to reconstruct the same perceptual pattern when it observes the same situation. It also allow agent to have the trends in reconstruction of the perception, namely, the way of perception.

5.2.5 Perceptibility in Multi-Agents Environment

The autonomous agents in the environment where they are expected to act cooperatively with the other agents, are at least required to perceive the existence of the others. To see the agent in our simulation have a possibility to perceive the other agents, we prepared two environment with three obstacles and three other agents in the same configuration. Although the obstacles are quiet in the environment, the agents give off the sonar wave of their own to observe the environment respectively. The environment with several agents is a kind of noisy environment. The agent in this noisy environment, therefore, would find itself very difficult to

observe the world. However, it turns out to be a clue for perceiving the existence of the other agents, if the Perceptual Pattern in the IPM shows some distinctive, i.e., invariant, caused by the existence of the others. This simulation is assigned to check the possibility that proposed mechanism would have an ability to perceive the existence of the other agents.

The result of the simulation is shown in Fig. 5.4. Throughout the figure, the left column corresponds to the real environment of the agent, and the right corresponds to the Perceptual Pattern created by the proposed mechanism, respectively. The agent perceives differently even though the configurations of the objects, i.e., obstacles or agents, are the same, but different in the characteristics (see (i) and (ii) in the figure.)

When the configurations of the other agents are different, the agent perceives differently (see, (ii) and (iii) in the figure.) However, the agent should somehow perceive the same spatial topology between (i) and (ii). To check this point, correlation value c_i by the equation (5.1) is introduced:
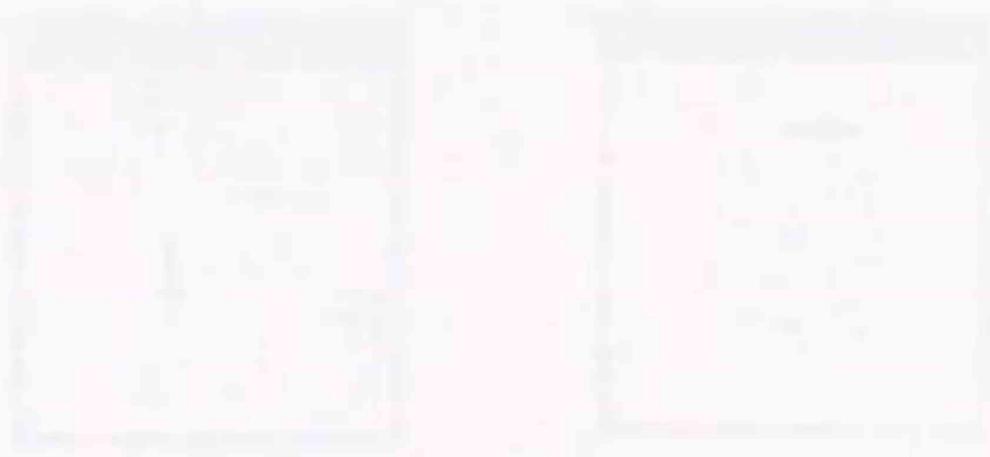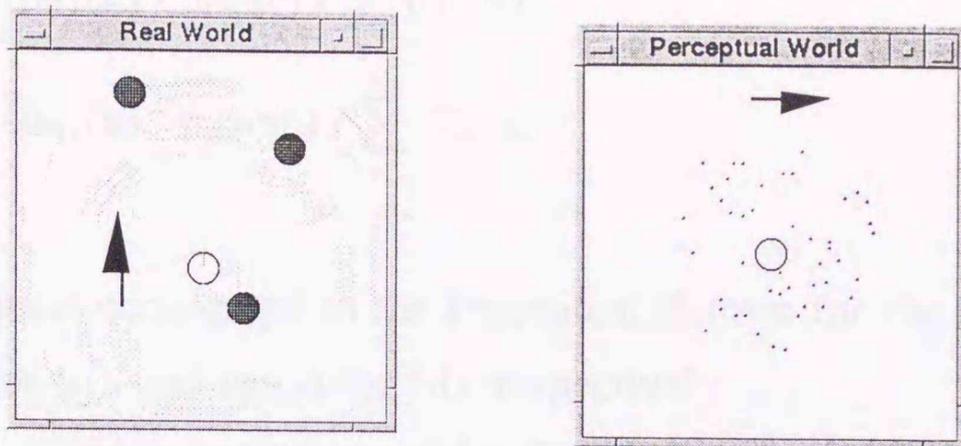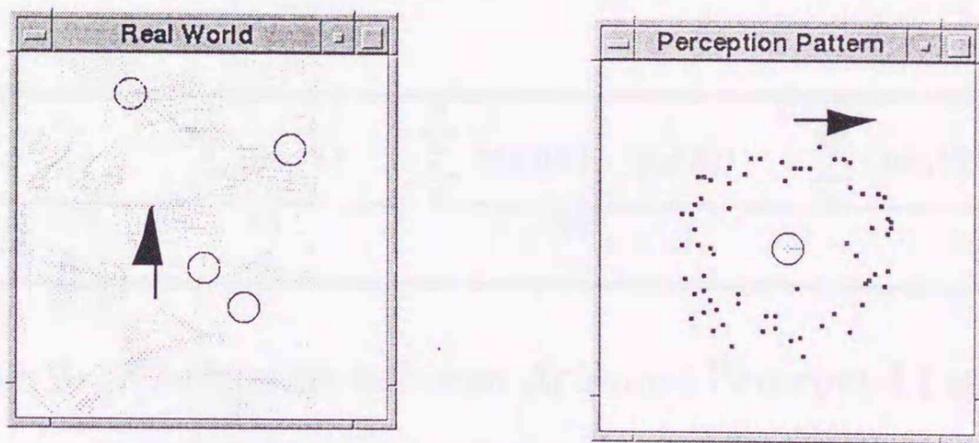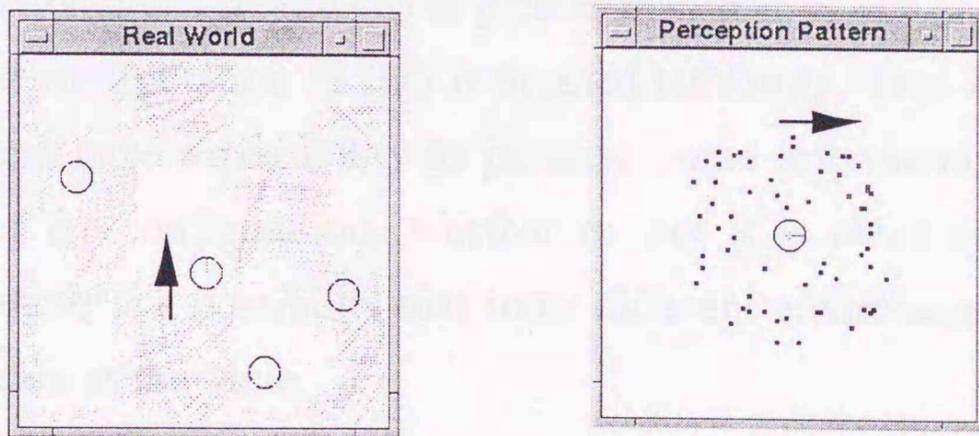
Fig. 5.4
Differnce of Perceptual Pattern with Respect to Existence of Other Robots

From (i) and (ii), robot is able to distinguish the environment consist of obstacles and robots. From(ii) and (ii), robot can distinguish the difference caused by the configuration.

$$c_1 = \sum_x^N (p_{R1}(x) \cdot p_O(x)) / \sum_x^N p_{R1}(x),$$

$$c_2 = \sum_x^N (p_{R1}(x) \cdot p_{R2}(x)) / \sum_x^N p_{R1}(x). \tag{5.1}$$

where, $p_O(x)$ correspond to the Perceptual Pattern for the environment (i), $p_{R1}(x)$ for (ii), and $p_{R2}(x)$ for (ii), respectively.

$p_i(x) = 1$, iff module is existing on glid x. The result is illustrated in Table 5.1.

c		$\sum_x^N p_{R1}(x)$	$\sum_x^N (p_{R1}(x) \cdot p_O(x))$	$\sum_x^N (p_{R1}(x) \cdot p_{R2}(x))$
1	0.478	46	22	-
2	0.065	46	-	3

Table 5-1 Correlation between Acquired Perceptual Patterns

As shown in the table, correlation between the *Perceptual Patterns* for the Environments (i) and (ii) is greater than that of (ii) and (iii), even through the configuration of (iii) is decided randomly. This result shows that the agent have a possibility to perceive some information on spatial topology of the configuration, whether or not it is noisy environment. However, there is a possibility that some different environment make the agent perceive as the same.

5.2.6 Acquisition of the Perceptibility of the Affordance on Behaviors

This subsection is assigned for confirming the proposed mechanism has possibilities to emerge the perceptibility of the Affordance. As a task for the agent in this experiment, I have selected the same problem as that is

discussed by Warren (Warren 87), i.e., on Affordance for "passing through" for explanation on human perception. As shown in Fig. 5.5, I have prepared a wall with two different size of openings in the environment. The one opening is physically able to be passed through by the agent, while the another is not. The width and the position of the openings change randomly so that the agent is not able to make appropriate decision unless it emerges the perceptibility of the Affordance for passing through. Namely, the environment is dynamically changes and the agent is expected to behave appropriately in the unknown environment.
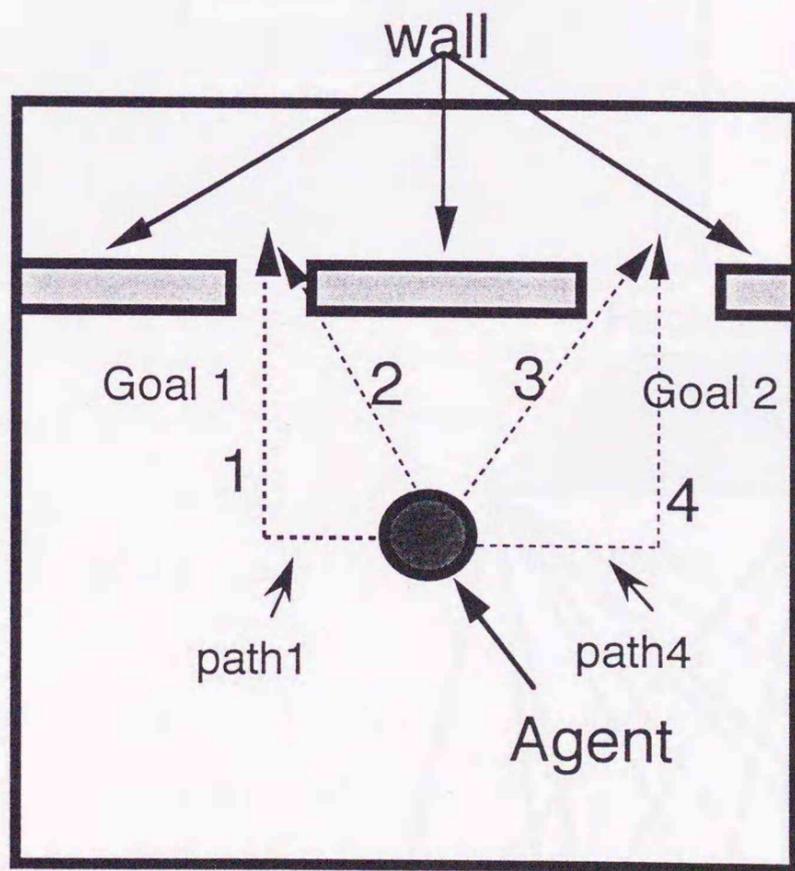
Fig. 5.5 The Environment for the Problem
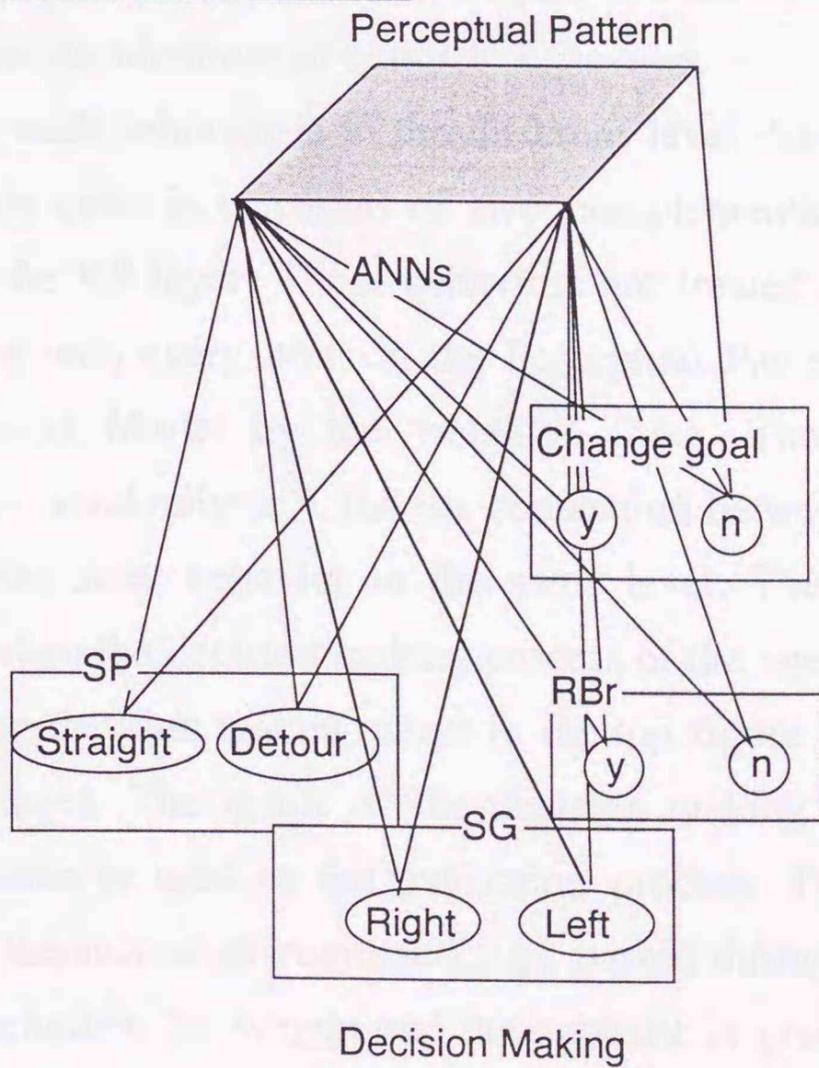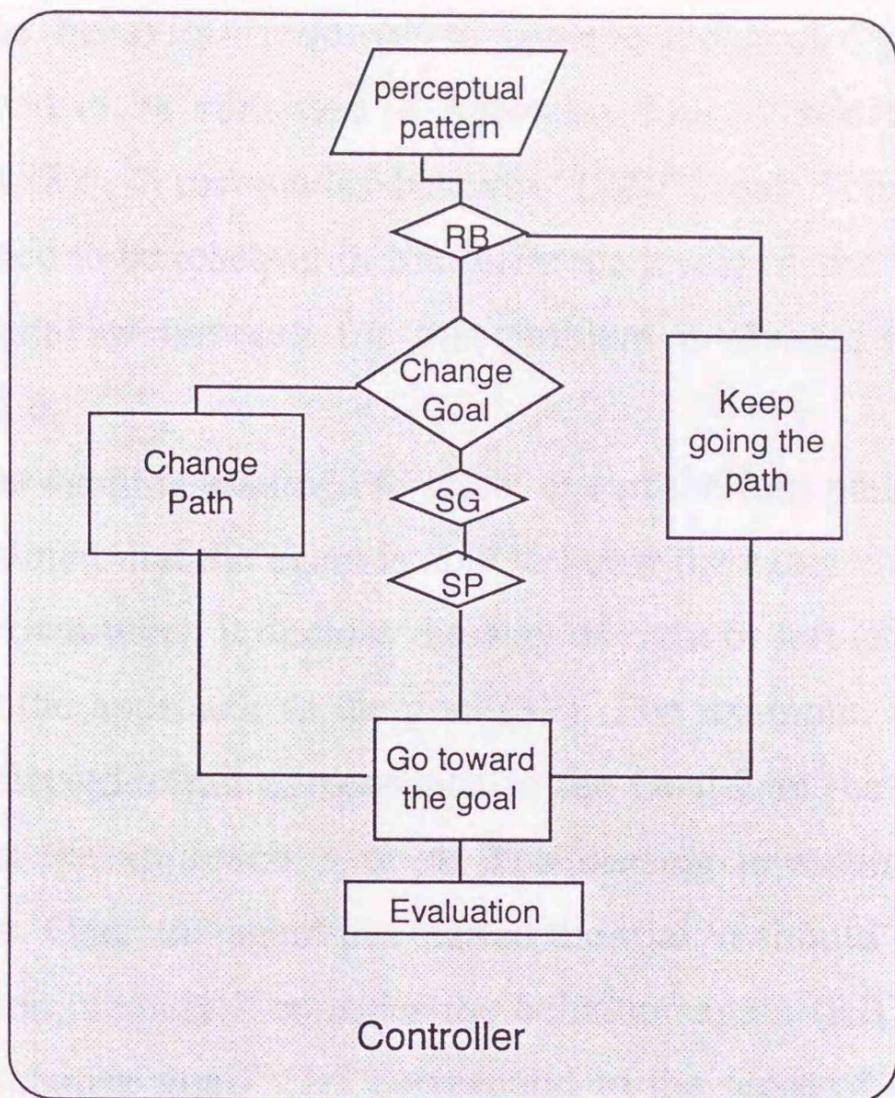
Fig. 5. 6. Behavior Flow and Behavior Network for the Problem

The behaviors required to achieve the goal ("passing through") are assumed to be consisted of following four: " select goal (SG)", " select path (SP)", " reconsider behavior (RB)", and " change goal". They are assumed to be existing in the different levels of the behaviors. Therefore, the behavior network for this problem is divided into five as shown in Fig. 5.6.

The agent is assumed to select one of the four paths at the beginning. It is assumed that the agent is able to know the exact coordination of the goal of its own when it decides the way of right or left (SG). It also required to select the approach to the goal (SP). For example, assume that the agent has selected left, it corresponds to the Goal 2 in the figure, then it should decide the approach 3 or 4. The sensing is assumed to occur when it moves. Once the agent has started the trial, it should make three additional decision, namely " consider the behavior again (RB)", " decide to change goal (change goal)". B3 correspond to the sense of danger, and the other behavior corresponds to the reconsideration of concrete behaviors.

As illustrated in Fig. 5.6, each behavior is in the different level. Each level of the behavior, in this case, is consisted of two complementary behaviors, e.g., yes or no in the RB layer. Those behaviors are treated as units in the ANNs, and linked with every units in the Perceptual Pattern Layer in the Inner Perceptual Model by the weighted links. Those networks are initially weighted randomly or 1 for the connection between certain behavior and 0 for the other behavior in the same level. These networks are become active when the decision making process of the agent come across the corresponding decision making phase in the top figure in Fig 5.6 (depicted as a lozenge). The result of the decision making is stored and those stored decision is used in the evaluation process. The decision makings that lead to the success of command, i.e., passed through the wall, are evaluated as strengthen the weight and the opposite is given penalties as weaken the weights to the behaviors.

These trial and error style learning is expected to enable the agents to capture the inner perceptual pattern for certain behavior. This leads the agent to be able to perceive the Affordance.

With these settings, the results of the experiment on the growth of the emergent perceptibility of the agent is depicted in Fig. 5.7. The pictures illustrate that the agent improve its behaviors as time goes by. This improvement is considered as the result of the emergence of the perceptibility of the each behaviors described above, and as a whole behaviors, it emerges the perceptibility on the Affordance of "passing through".

The Invariants for each behavior are shown in Fig. 5.8, and these shows the tendency of the behavior selection when the combination of the modules consisting the pattern are observed. These Invariants together with the behavior selection mechanism, realizes the Affordance for "passing through" for the agent. Again, the patterns constituting the Invariants are unpredictable from the outside the agent. In other word, the agent is an autonomous robot and have emerged the perceptibility of the Affordance.

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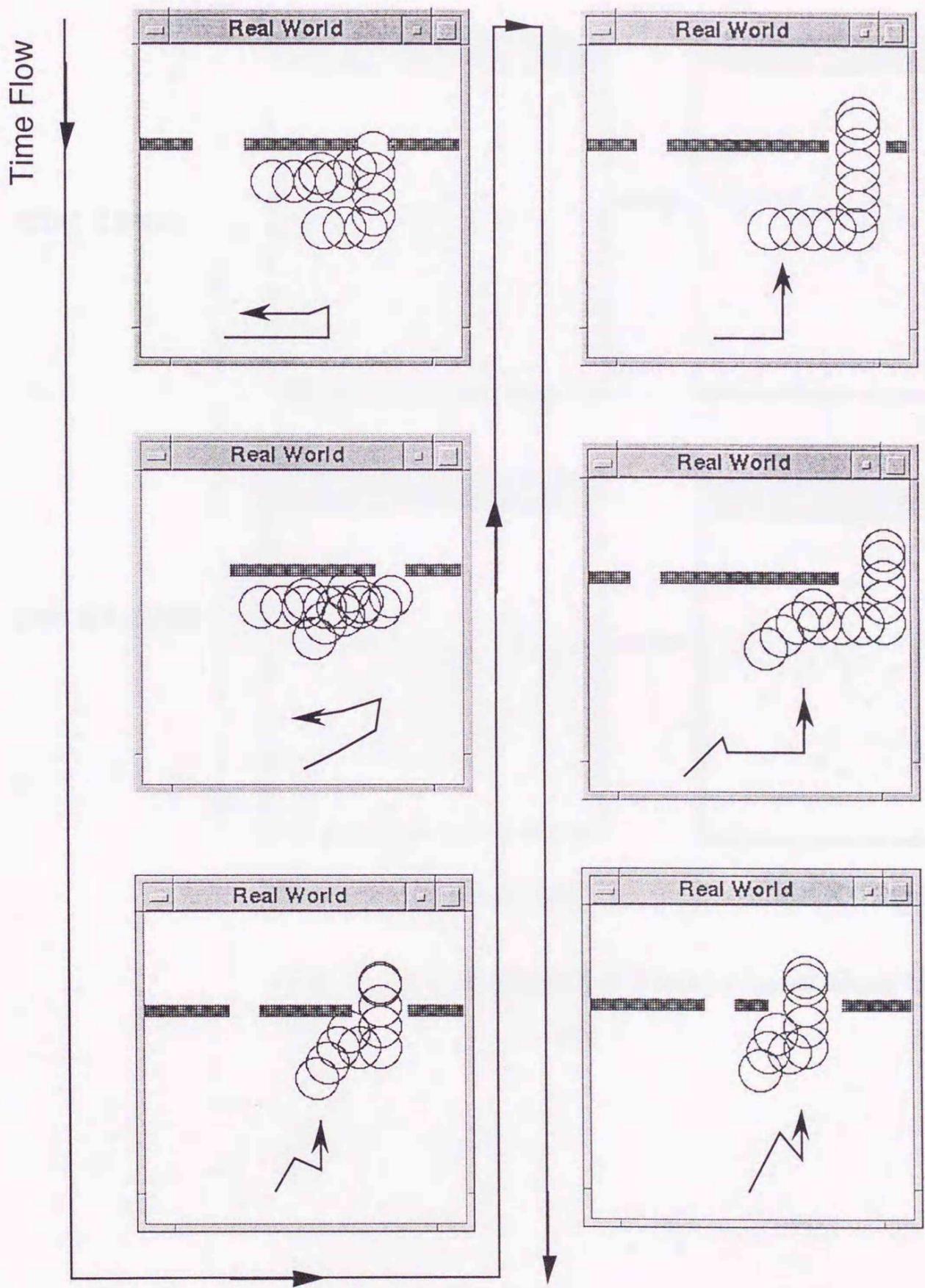
Fig. 5.7 Improvement of Behavior as a Result of Emergent Peceptibility

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Leaning

after 6 trials

afer 24 trials

Invariant for select left   Invariant for select right

Fig. 5. 8a Candidates of Invariants for Goal Selection

Leaning

after 6 trials

afer 24 trials

Invariant for go straight   Invariant for go detour
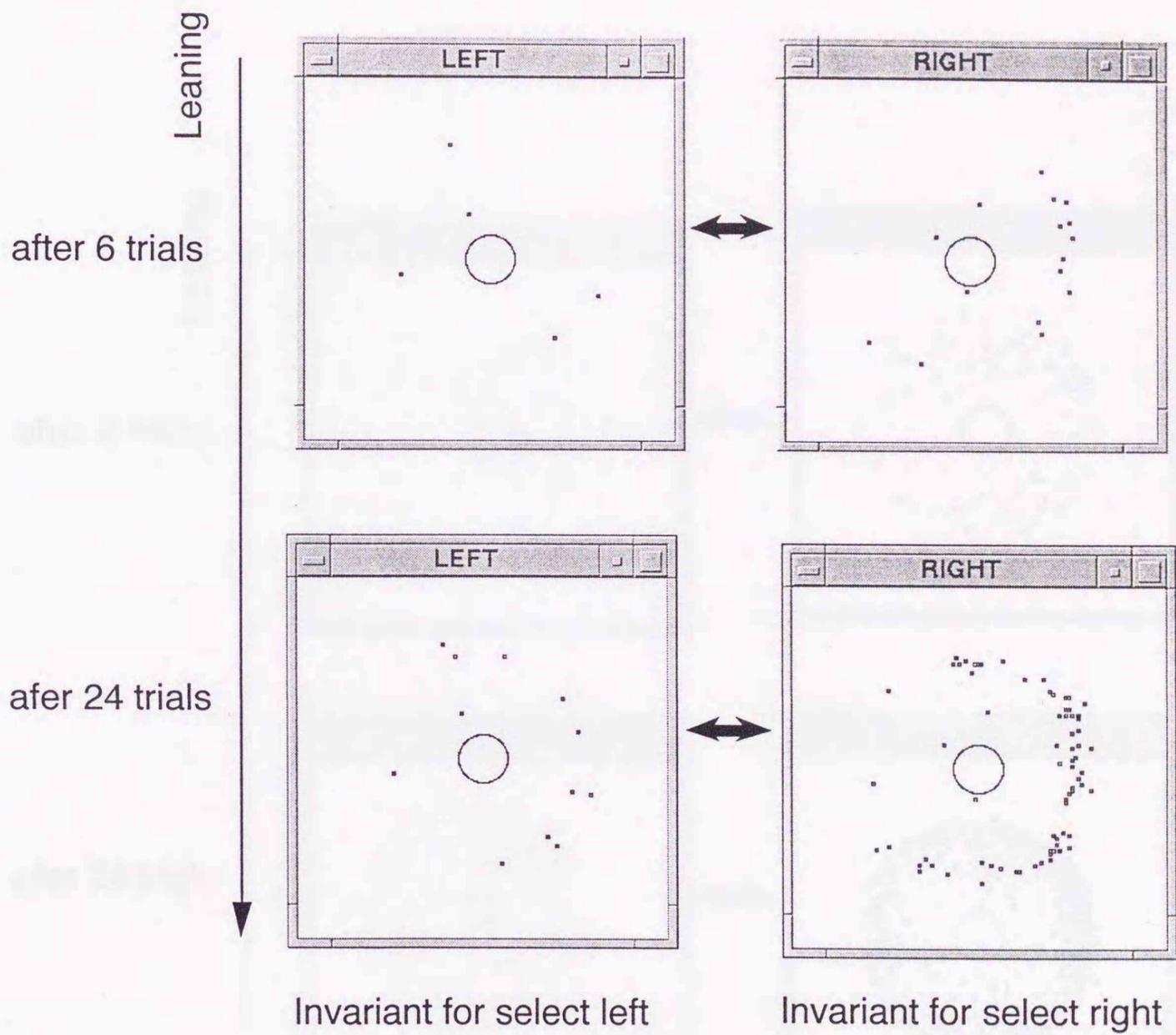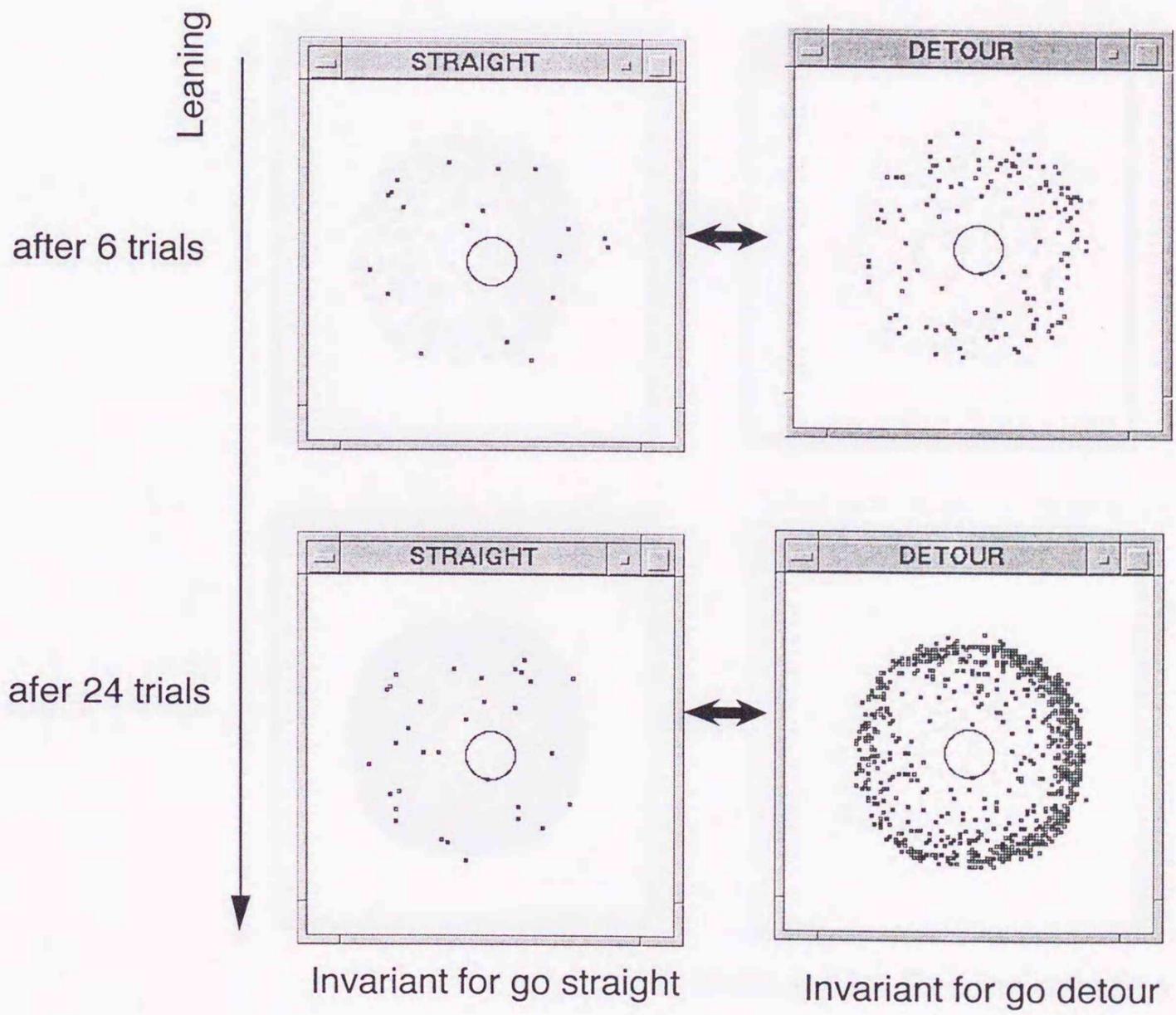
Fig. 5. 8b Candidates of Invariants for Path Selection
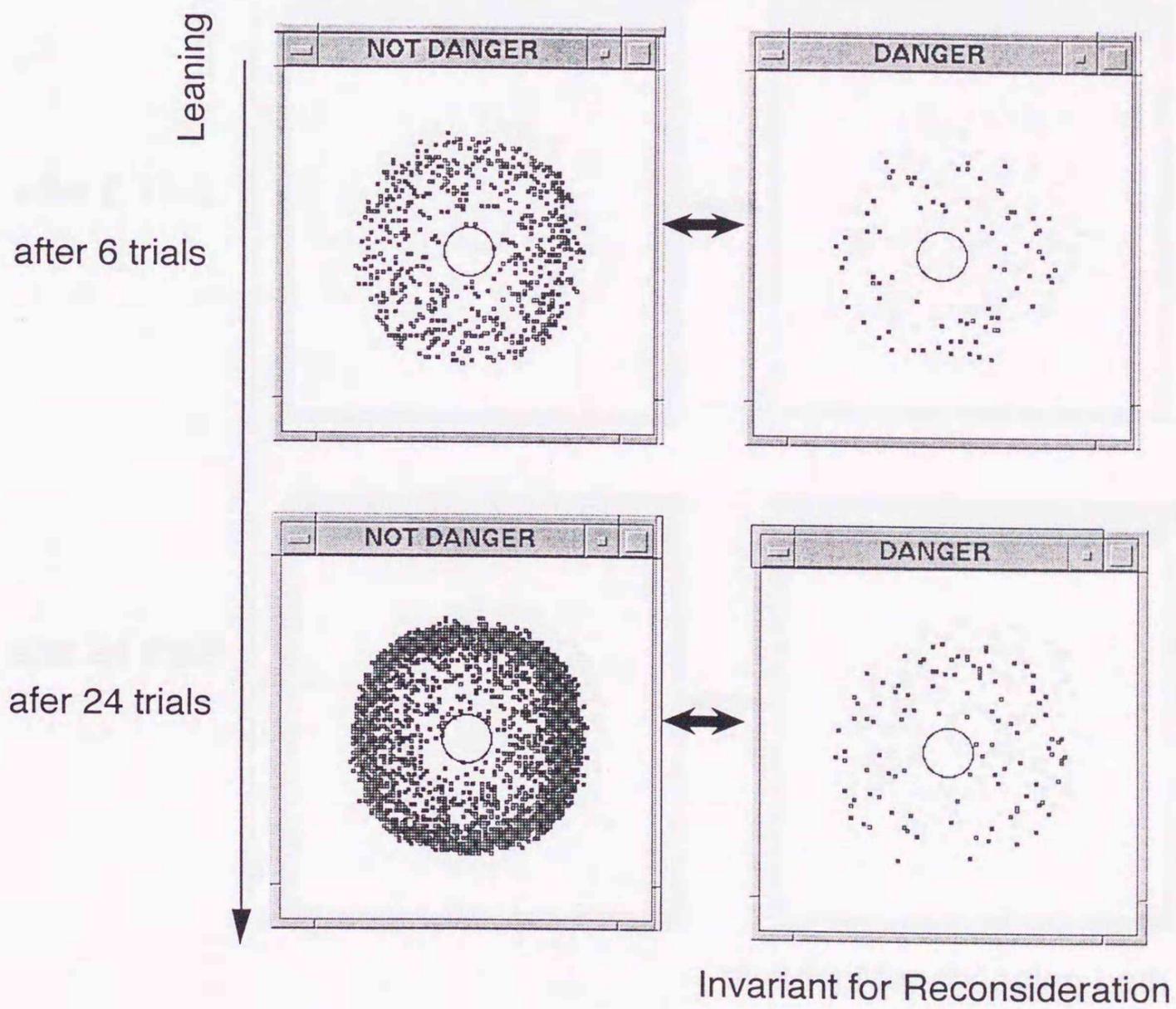
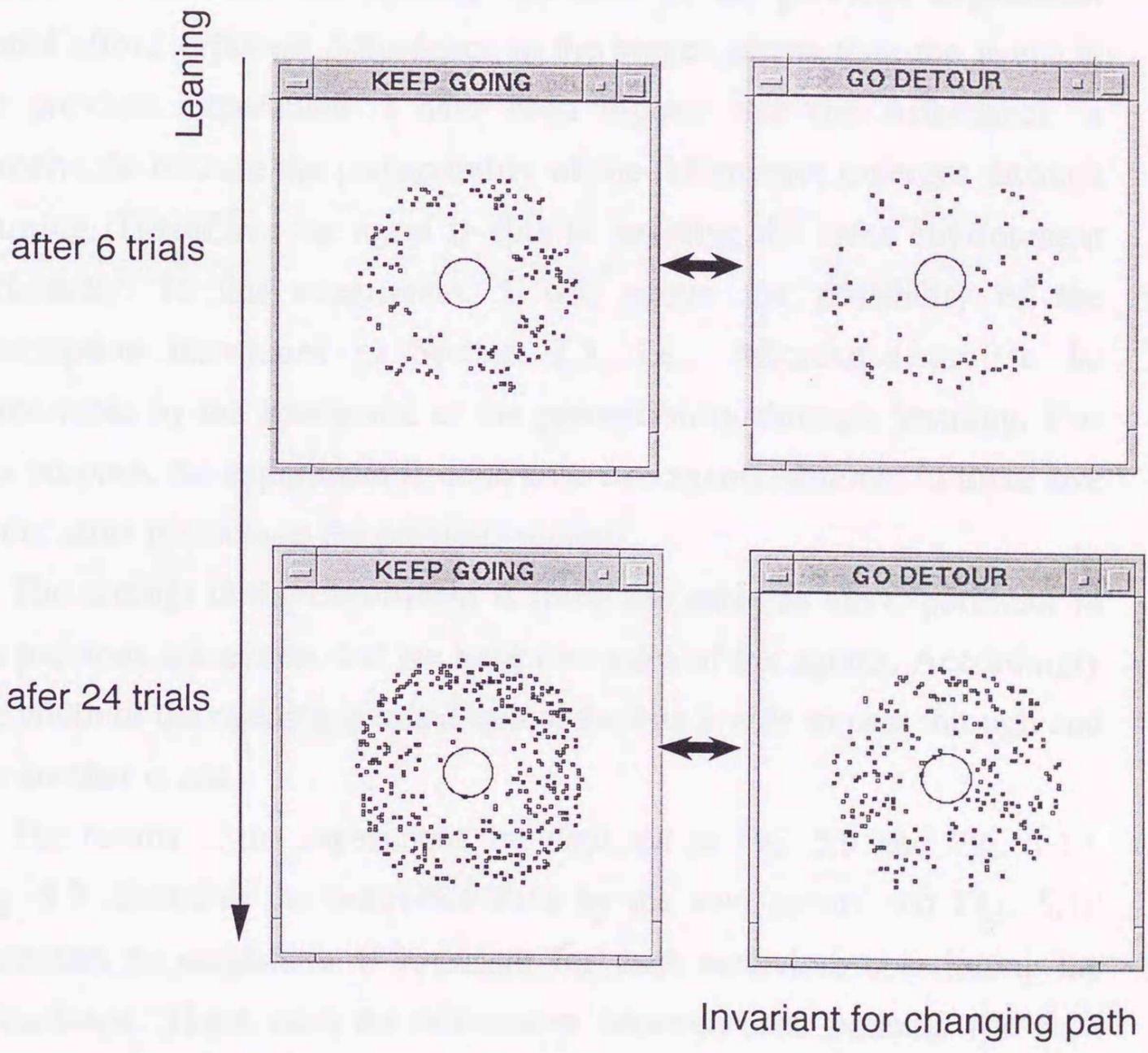Fig. 5. 8c Candidates of Invariants for Reconsideration of Behavior

Fig. 5. 8d Candidates of Invariants for Changing Path

Leaning

after 6 trials

afer 24 trials

KEEP GOING   GO DETOUR

KEEP GOING   GO DETOUR

Invariant for changing path

5.2.7 Differences of the Affordance among Agents

The same situation of the environment for the different agents provides different Affordances for each agent according to the characteristics of the agent. For example, the opening appeared in the previous experiment would afford different Affordance to the bigger agents than the agent in the previous experiment. I have been insisted that the Affordance is perceivable because the perceptibility of the Affordance emerges through learning. Therefore, the agent is able to perceive the same environment differently. In this experiment, I will prove the possibility of the Assumption introduced in Section 3.3, i.e., Affordance are to be perceivable by the emergence of the perceptibility through learning. For this purpose, the experiment is done with two agents different in there size in the same problem as the previous section.

The settings of the experiment is quite the same as the experiment in the previous subsection, but we have two sizes of the agents. Accordingly the width of the opening is tuned as that the one is able to pass through and the another is not.

The results of the experiment are depicted in Fig. 5.9 and Fig. 5.10. Fig. 5.9 illustrates the behaviors done by the two agents and Fig. 5.10 illustrates the candidates of Invariant for each behaviors constituting the Affordance. There exist the differences between each patterns for each behaviors. These differences reveals the fairness of my assumption, because it will lead the differences of the Affordances between the two agents.

From this experiment, it is apparent that the proposed mechanism is able to provide the agent to have its own measurement of the environment.

Namely, it enables the agent to have the emergent perceptibility of Affordances.

Fig. 5.9a Behaviors Achieved by the Smaller Agent

Fig. 5.9b Behaviors Achieved by the Larger Agent

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Smaller Agent

Invariants for Selecting Left Goal   Invariants for Selecting Right Goal

Latger Agent
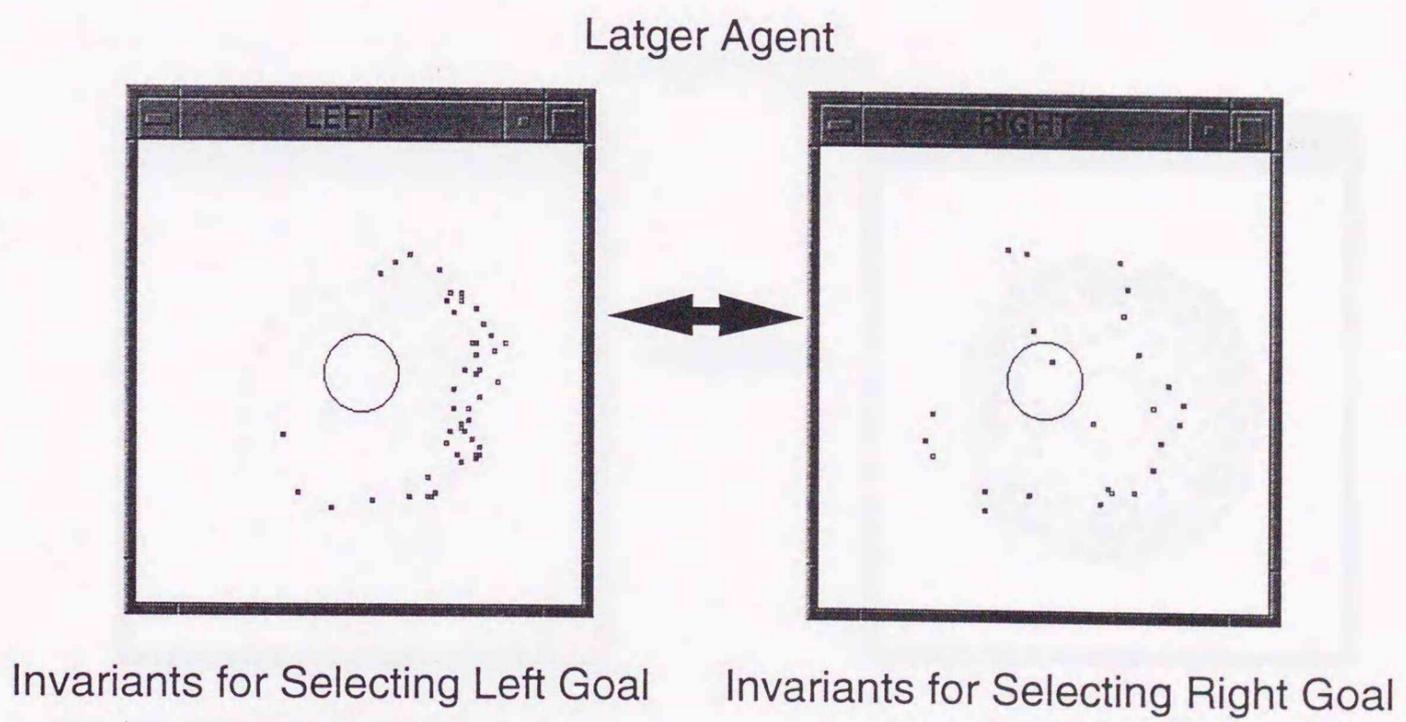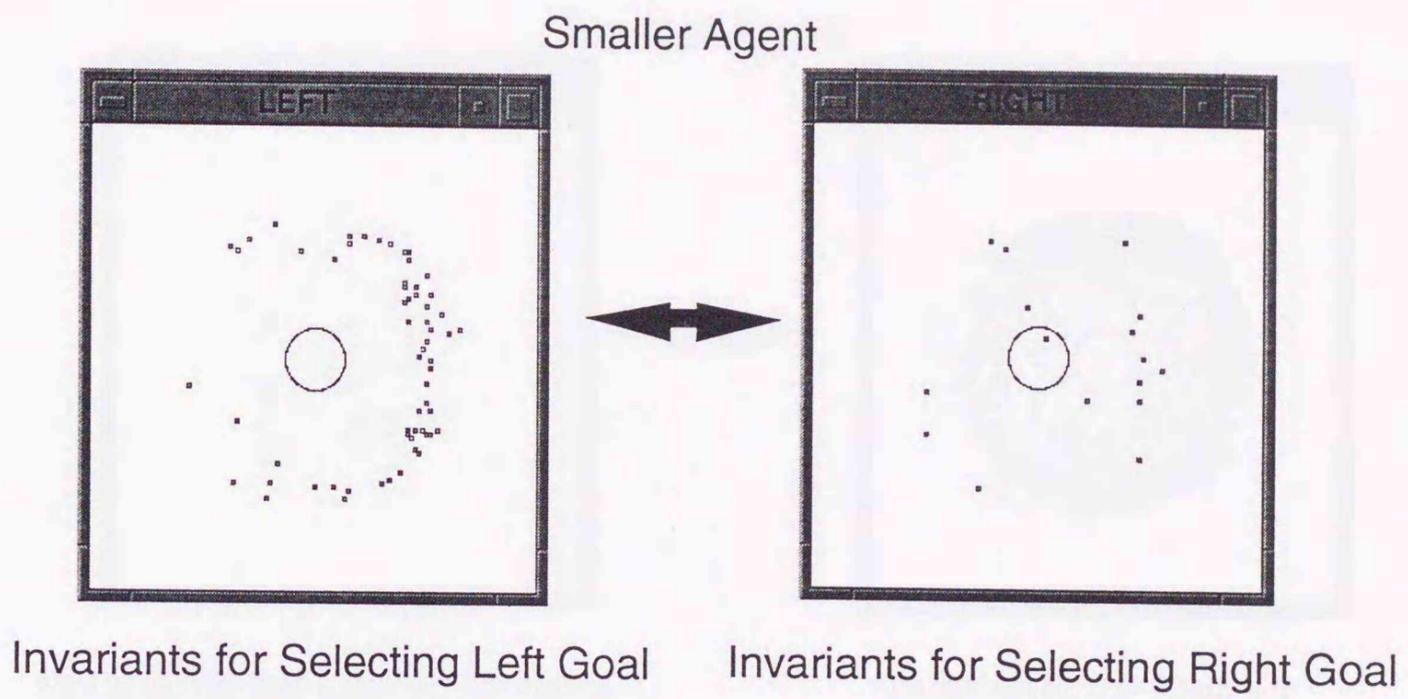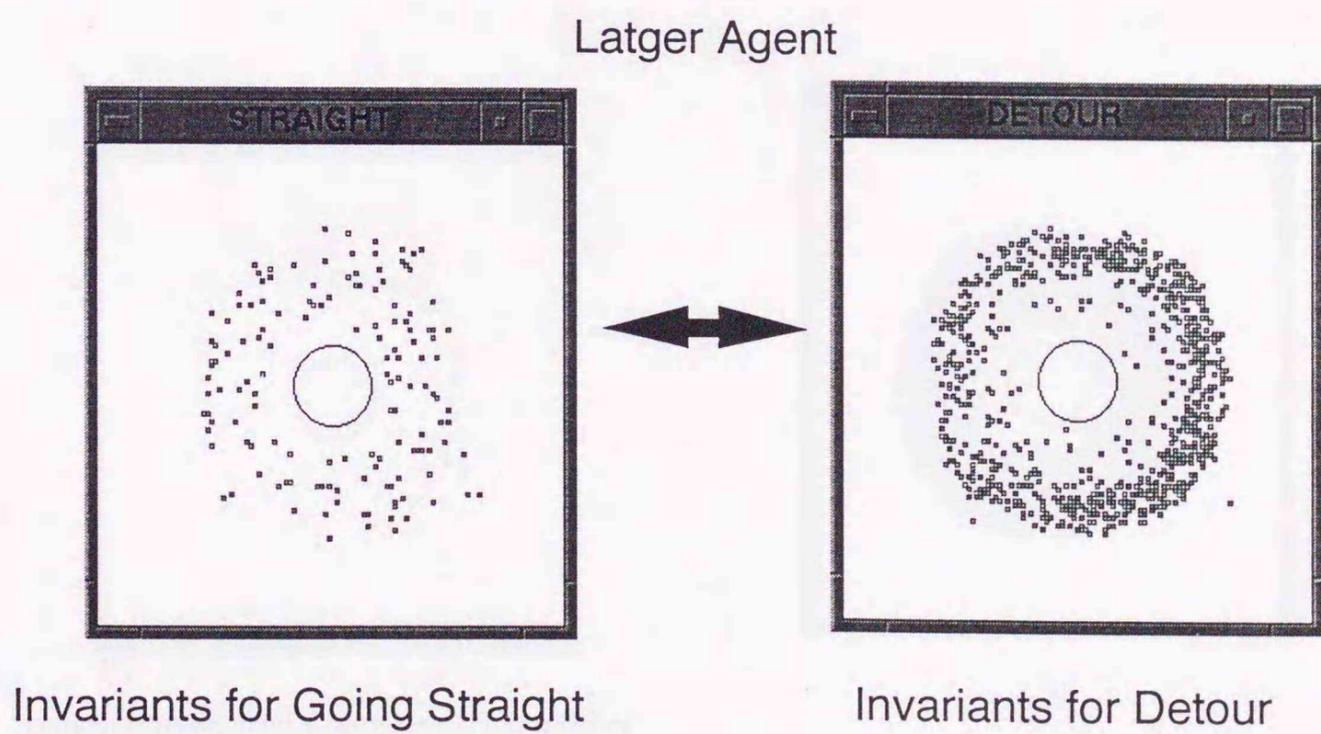

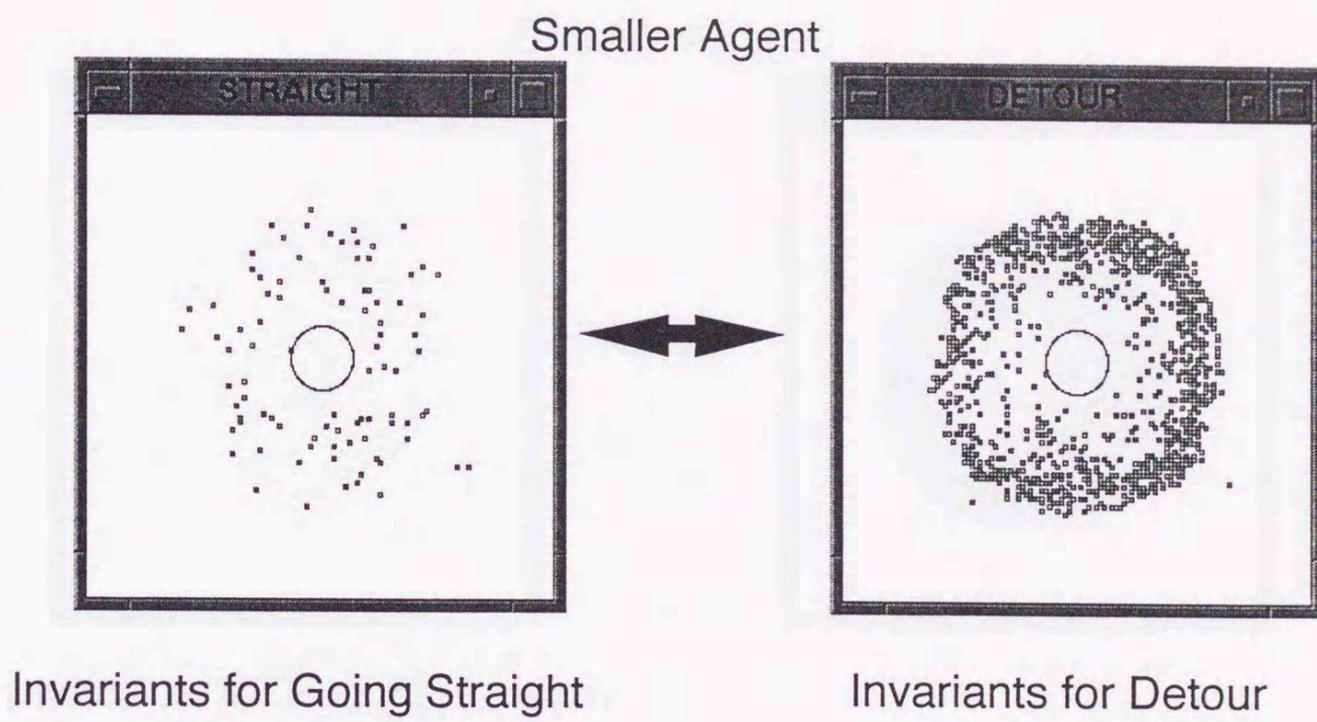Invariants for Selecting Left Goal   Invariants for Selecting Right Goal

Fig. 5.10a Candidates of Invariants for Goal Selection

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Smaller Agent

Invariants for Going Straight   Invariants for Detour

Latger Agent

Invariants for Going Straight   Invariants for Detour

Fig. 5.10b Candidates of Invariants for Path Selection

Smaller Agent
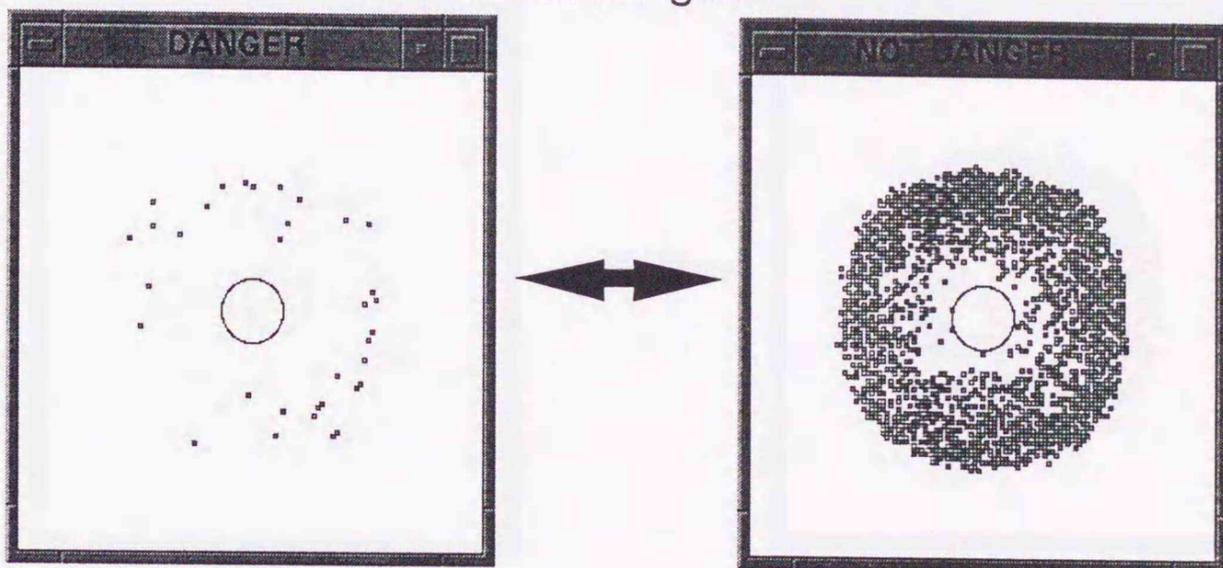
Invariants for Reconsideration

Latger Agent
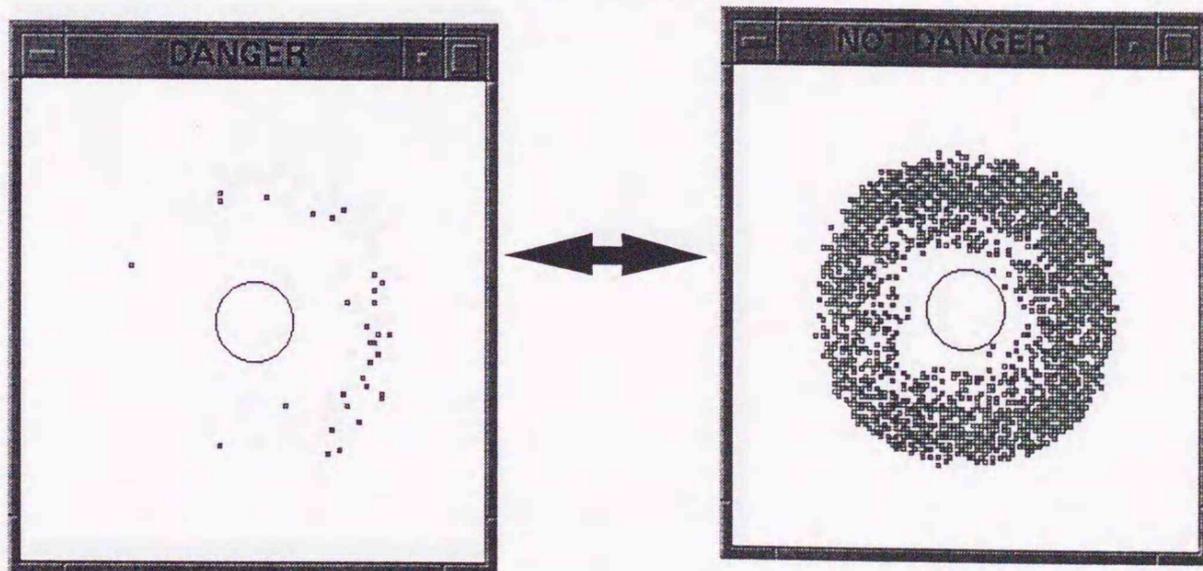
Invariants for Reconsideration

Fig. 5.10c Candidates of Invariants for Reconsideration of Behaviors

Smaller Agent
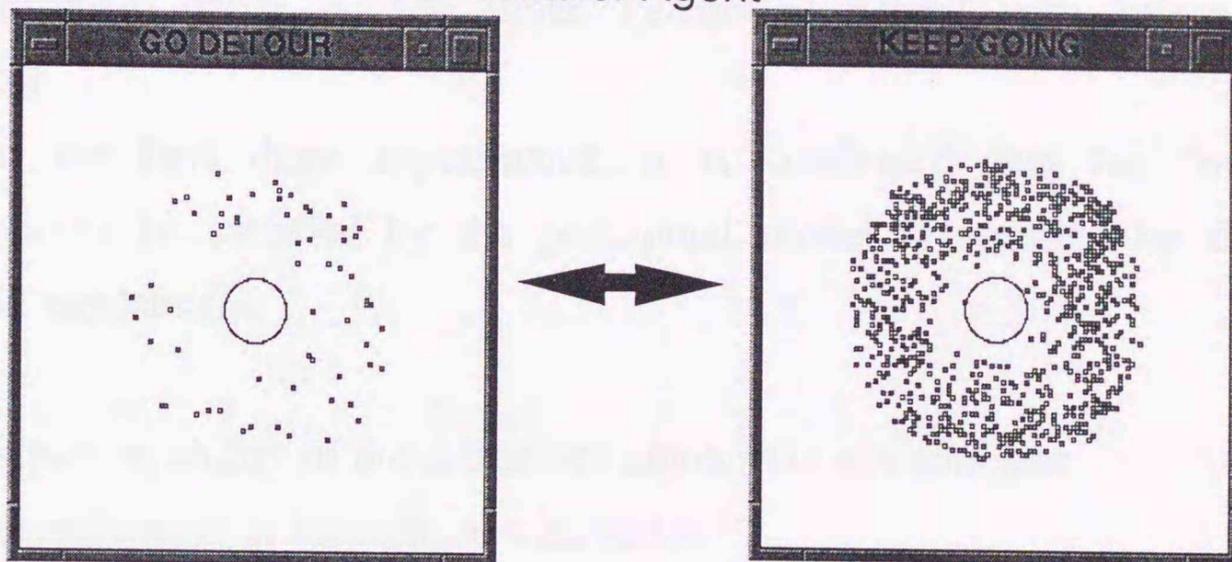
Invariants for Changing Path

Latger Agent
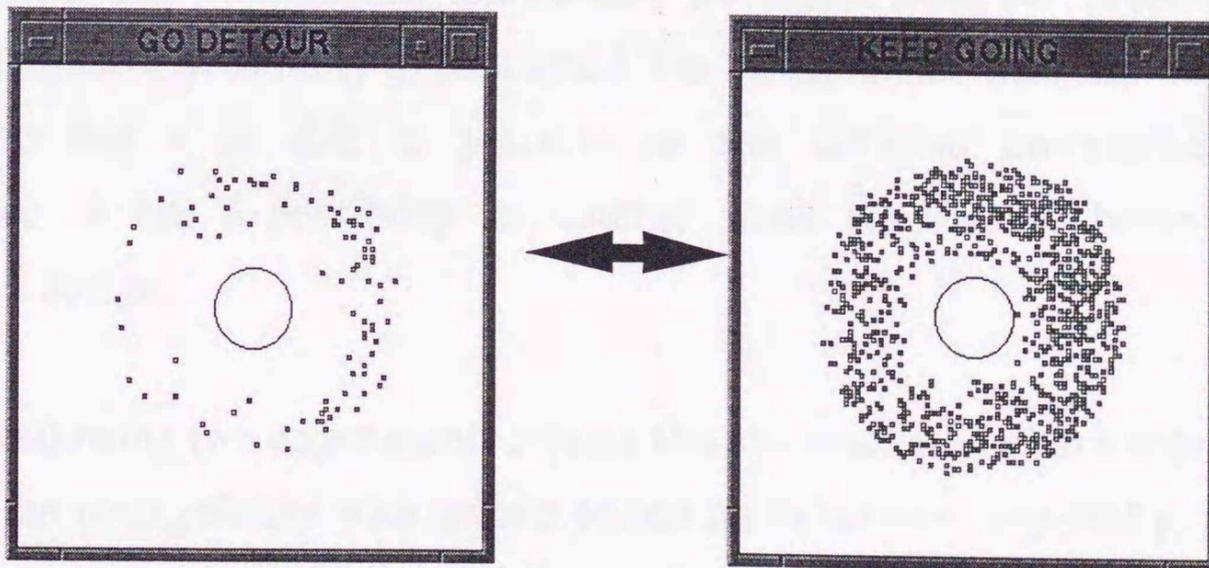
Invariants for Changing Path

Fig. 5.10d Candidates of Invariants for Changing Path

5.2.8 Summery on Mechanism

In this subsection, I will make a brief summery on the experiments for the mechanism based on the Inner Perceptual Model with Internal Simulator.

From the first three experiments, it is confirmed that the four conditions to be satisfied by the perceptual model is satisfied by the proposed mechanism:

- Distinction ability of the difference among the environment.
- Successiveness in accordance with action.
- Dependence on the environment.
- Successiveness on the experience.

The next one experiments shows that the agent with the proposed mechanism have possibility to distinguish the environment with the other agents so that it is able to perceive as the different environment. Therefore, it has a possibility to emerge some cooperative behavior without a design.

The following two experiments reveals that the mechanism have able to emerge the perceptibility with respect to certain behaviors. Especially, the last experiment supports more clearly the discussion, because it shows the agent have acquired the different perception with respect to the characteristics of its own without the designer's intention.

As a future work, it should be applied to the different problems to confirm the justification of the mechanism. As a further future work, I am planning to introduce the sensory systems for the inner states of the

agents. The mechanism for that case should still be the same in most part but will be different in that they should uniformly treat the information from the both sensory systems, i.e., for inside and outside the agent. I am expecting that the agents with the mechanism will emerge the motivation so that the behavior generation of the agent will be available.

5.3 Experiments for the Mechanism Based on Inner Perceptual Model with Multi-Agent System

The experiments for this mechanism is still in the preliminary ones. Therefore they are mainly on the abilities of the Inner Perceptual Model. Through the experiments, the sensors of the autonomous agent is omitted and the goal of the reconstruction of the Inner Perceptual Model is settled as to create the map of the real environment. Therefore, the autonomous agents is forced to move in the Inner Perceptual Model itself and the State Agent is assumed to have the input from the autonomous agent when it is on the State Agent.

5.3.1 Environment with No-Obstacle

Fig. 5.11 illustrate the problem space of the autonomous agent. The task required for the agent is to reach the reward area. The size of the reward area is settled as 30X30, while the size of the whole environment

is settled as 300X300. This experiment is assigned to confirm the ability of the Inner Perceptual Model to represent the world.
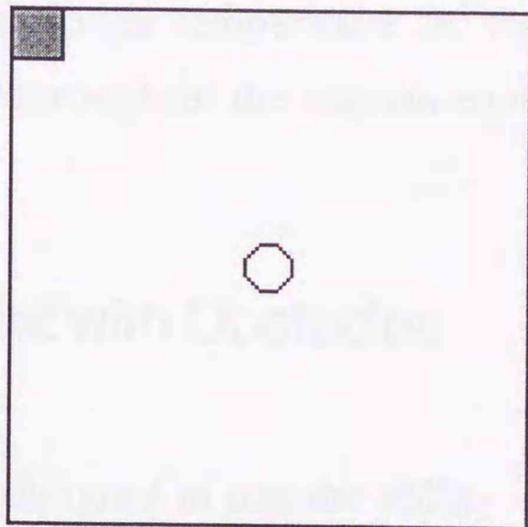
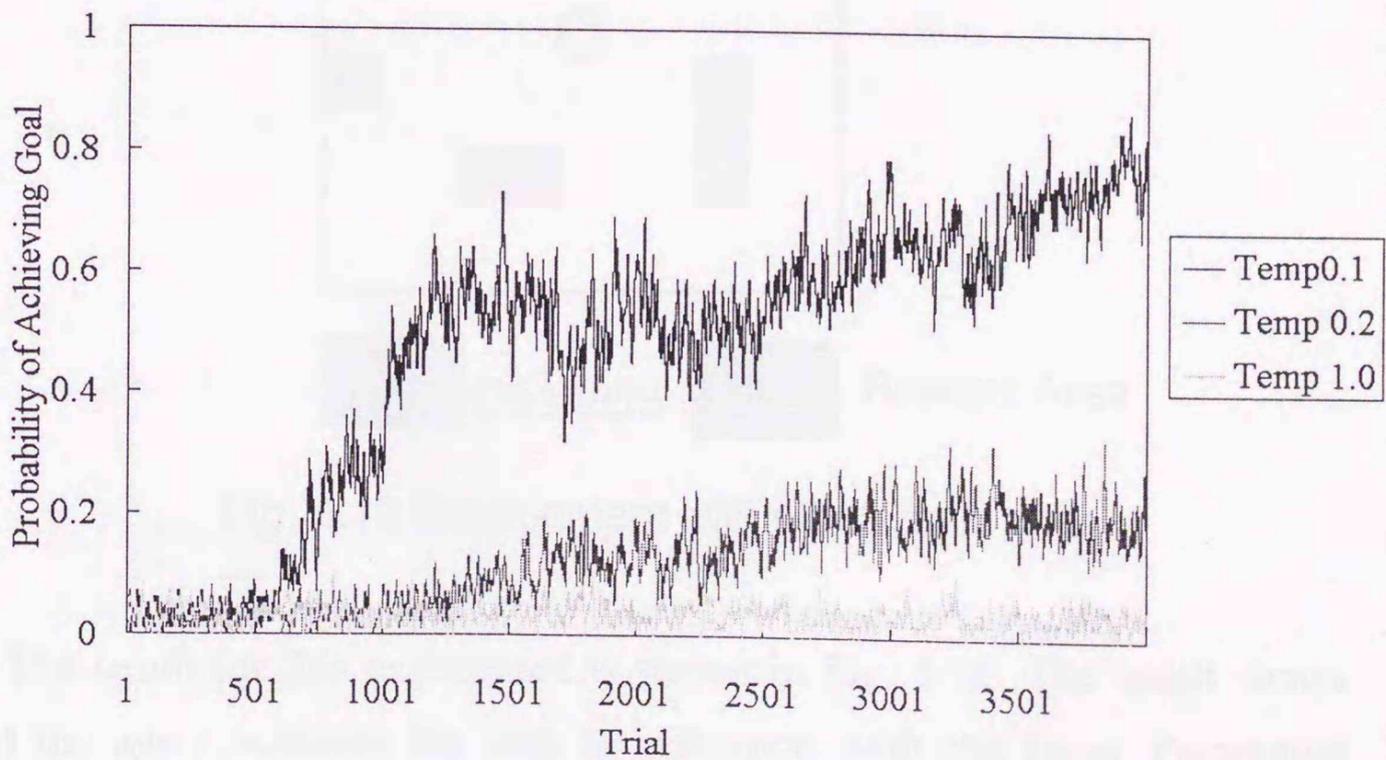Fig 5.11 Environment with Only Local Reward Area

Fig. 5.12 Result of Experiment 1

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The result of the experiment is shown in Fig. 5.11. The result shows that the temperature in the rule selection affects the achievement of the task. The lower temperature apt to provides the autonomous agent achieving the task. The lower temperature is, therefore, selected as the temperature parameter throughout the experiments in this thesis.

5.3.2 Environment with Obstacles

This experiment is assigned to test the ability of representation of the proposed mechanism. In this case, the task for the agent is to avoid obstacles and go to the reward area (Fig. 5.13).
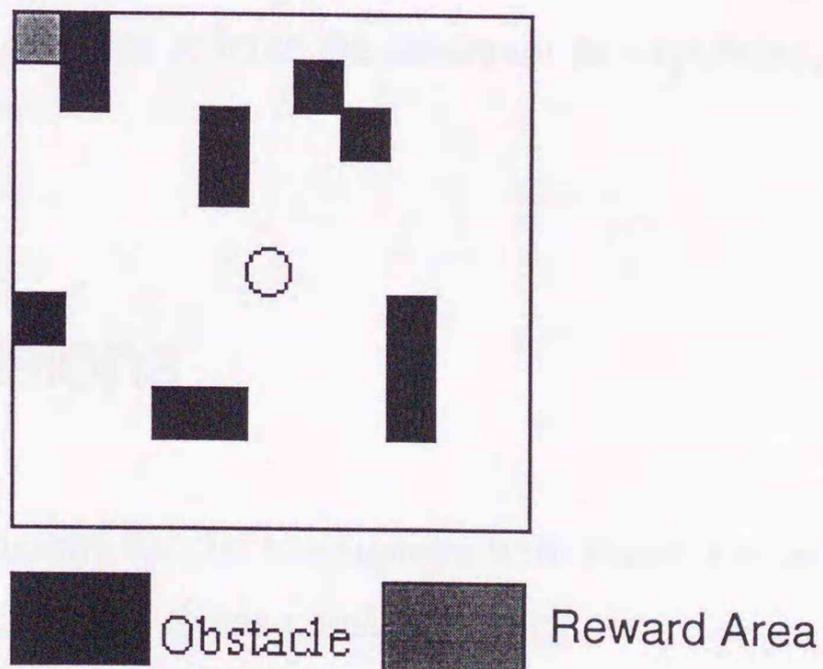
Fig. 5.13 Environment with Obstacles

The result for this experiment is shown in Fig. 5.14. The result shows that the agent achieves the task in reference with the Inner Perceptual Model that is not represent the environment as interpretable one to us. This means that the Inner Perceptual Model is somehow able to represent the existence of the obstacles.
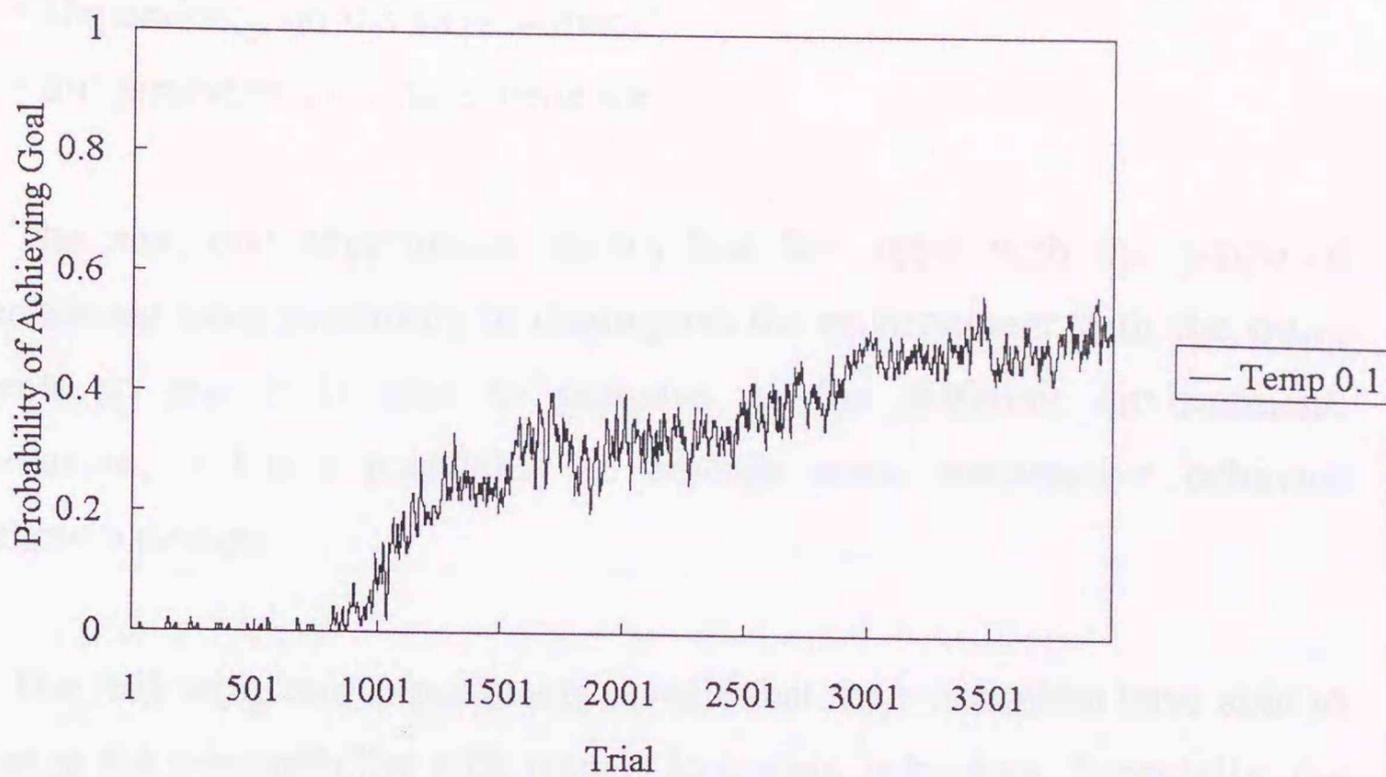
Fig. 5.14 Result of Experiment2

From above two experiments, it is considered that the proposed mechanism has possibilities to have the emergent perceptibility.

5.6 Conclusions

From the experiments for the mechanism with Inner Perceptual Model with Internal Simulator, the thesis considers that:

From the first three experiments, it is confirmed that the four conditions to be satisfied by the perceptual model is satisfied by the proposed mechanism:

- Distinction ability of the difference among the environment.
- Successiveness in accordance with action.

- Dependence on the environment.
- Successiveness on the experience.

The next one experiments shows that the agent with the proposed mechanism have possibility to distinguish the environment with the other agents so that it is able to perceive as the different environment. Therefore, it has a possibility to emerge some cooperative behavior without a design.

The following two experiments reveals that the mechanism have able to emerge the perceptibility with respect to certain behaviors. Especially, the last experiment supports more clearly the discussion, because it shows the agent have acquired the different perception with respect to the characteristics of its own without the designer's intention.

As a future work, it should be applied to the different problems to confirm the justification of the mechanism. As a further future work, I am planning to introduce the sensory systems for the inner states of the agents. The mechanism for that case should still be the same in most part but will be different in that they should uniformly treat the information from the both sensory systems, i.e., for inside and outside the agent. I am expecting that the agents with the mechanism will emerge the motivation so that the behavior generation of the agent will be available.

From the experiments for the mechanism with the Inner Perceptual Model with Multi-Agent System, it is considered that the mechanism has enough possibility to be the mechanism for emergent perceptibility of the autonomous agent. The much more experiments should made to confirm the possibilities.

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Summary

This thesis is summarized as follows:

In Chapter 1, the background of thesis is discussed and agents, environment and world is defined.

In Chapter 2, a limitation of the conventional AI has been revealed mathematically. Moreover, a overview of the problems pointed out for the agents with the Cartesian Style perception, and the four problems, i.e., Frame Problem, Symbol Grounding Problems, Lack of Situatedness, and Embodiment Problems, are described and discussed in detail.

The basis of the problems are considered as:

• It requires the agent to have the perception interpretable by the designer or the others.

• The object of perception is settled to enrich the reconstruction of the interpretable view of the environment.

The methodologies introduced in the Cartesian System will not limit the abilities of the agent but the view of the world limits the range of the agent's activity space(e.g., toy world). Therefore, changing the view of the world will enlarge the activity space of the agent (e.g., real world).

In Chapter 3, Affordance is regarded as the explanation on the non-Cartesian Perception in that

• It denies the importance of the retinal image as a stimuli but makes much of the information in the environment.

• It makes importance on the functional properties of the environment while the Cartesian System makes much of the physical properties of the environment.

Then, the use of Affordance as a perceptual object of the autonomous agent is discussed. For the realization of the emergent perceptibility of the Affordances, I have discussed that the mechanism for the autonomous agent should have the following components in the way that:

Sensors

A set of devices that is able to translate the environmental information in some way into the inputs of the agent.

The mechanism should sense the world not by means of the appropriate sensors suitable for the information to be extracted, but by means of only the innate sensors to the agent. Therefore the kinds and the number of innate sensors are not to be fatal for the agent.

Learning Mechanism

The object of the learning with in the aimed perception mechanism should be on acquiring the meanings of the sensors to the agent. This means that the row sensor data gives no information without the experience of the agents, but would give more than just sensed when the learning proceed.

Information Processing

Although Gibson had make less of the importance of the information processing, and nor Brooks. However, the information processing should not be omitted to achieve the learning described above.

Inner Perceptual Model

An inner representation system of the agent. The reconstruction of the Inner Perceptual Model is to be intrinsic to the agent. The agent,

therefore, should learn the reconstruction of the Inner Perceptual Model. The outside the agent unable to interpret the representation reconstructed in the Inner Perceptual Model.

The inner perceptual model is fatal for realizing the agent to make the deliberate think not just stimulus-response system. The inner perception allow the agent to have the grounded symbols that is intrinsic to the agents.

These four are indispensable when designing the autonomous agent because of the discussions above.

In Chapter 4, two concrete mechanisms for the emergent perceptibility have introduced those satisfy the requirement for the mechanisms as:

The mechanism with internal simulator

The mechanism is designed especially for the realization of the autonomous agent that is able to perceive the Affordances of the environment, and therefore, the four components are listed as:

Active Observation Systems

It generate pulse wave and observes the integral intensity of the reflection wave because the reflection wave is expected to contain the geometric relations among the objects those constitute the environment.

Inner Perceptual Model with Simulator

This thesis introduced the simulator of the Active Observation System to reconstruct the Inner Perceptual Model in such way that the agent itself to be self-confident in the reconstruction.

Information Processing System

The Mechanism introduced ANNs to make the connections among the components in certain robustness.

Learning Mechanism

Learning Mechanisms in each component are almost the same as that of ANN's.

The mechanism with multi-agent system

The mechanism is utilizes the agents in the "Toy-world" for the Inner representation system of the environment. This mechanism is designed especially for the autonomous agent based on the reinforcement learning to be able to achieve the action states to be its own. For this purpose I select the components as follows.

IR Sensors

Agent is assigned the IR sensors around the agent to transform the local information surround it.

Inner Perceptual Model with multi-agent system

The multi-agent system is expected to works effectively, because the state space of the IPM is almost like a Toy World. The use of the multi-agent is the enlargement of the information on the environment is able to be achieved, at the same time it tries to learn the reconstruction.

Information Processing

The mechanism uses the rules as the information processing system for the State Agent is to be worked simply.

Learning Mechanism

The learning is achieved by means of the Bucket Brigade Algorithm to utilize the time sequence of the behaviors.

Both mechanisms are consisted of the metrologies used also in the conventional AI. However, they both have the four components carefully designed to emerge the empirical measure. Design of the autonomous agent requires us to combine the four components appropriately. Namely,

the four component is the necessary conditions but not the sufficient condition.

In Chapter 5, several experiments to confirm the reliability of the discussions have made. The experiments reveals that the mechanism have able to acquire the empirical measurement with respect to its behaviors. Especially, the last experiment supports more clearly the discussion, because it shows the agent have acquired the different perception with respect to the characteristics of its own without the designer's intention. From these facts, the proposed mechanism is considered to have an emergent perceptibility for the autonomous agents.

From the experiments for the mechanism with the Inner Perceptual Model with Multi-Agent System, it is considered that the mechanism has enough possibility to be the mechanism for emergent perceptibility of the autonomous agent. The much more experiments should made to confirm the possibilities.

The discussions and the results of the experiments show that the autonomous agent is realized by means of the proposed mechanism. The fact that the agent is able to acquire the empirical measurement with respect to its behavior, allow me to induce that the autonomous agent achieved in this thesis will not come across the four problems listed in Section 2.5, i.e., Frame Problem, Symbol Grounding Problem, Lack of Situatedness, and Embodiment Problem. The reasons of this induction are,

It never forced to have designers' objective and physical measurement (Frame Problem).

It has its representation of the environment as grounded on the sensory system of itself (Symbol Grounding Problem).

It is apparent that the agent with empirical measurement have enough situatedness (Lack of Situatedness), and

It is acquired through trial and error style learning (Embodiment Problem).

From above fact, It is considered that Four component, i.e., Sensory System, Inner Perceptual Model, Information Processing System, and Learning Mechanism, are to be required in the design of the mechanism for the emergent perceptibility of the autonomous agents.

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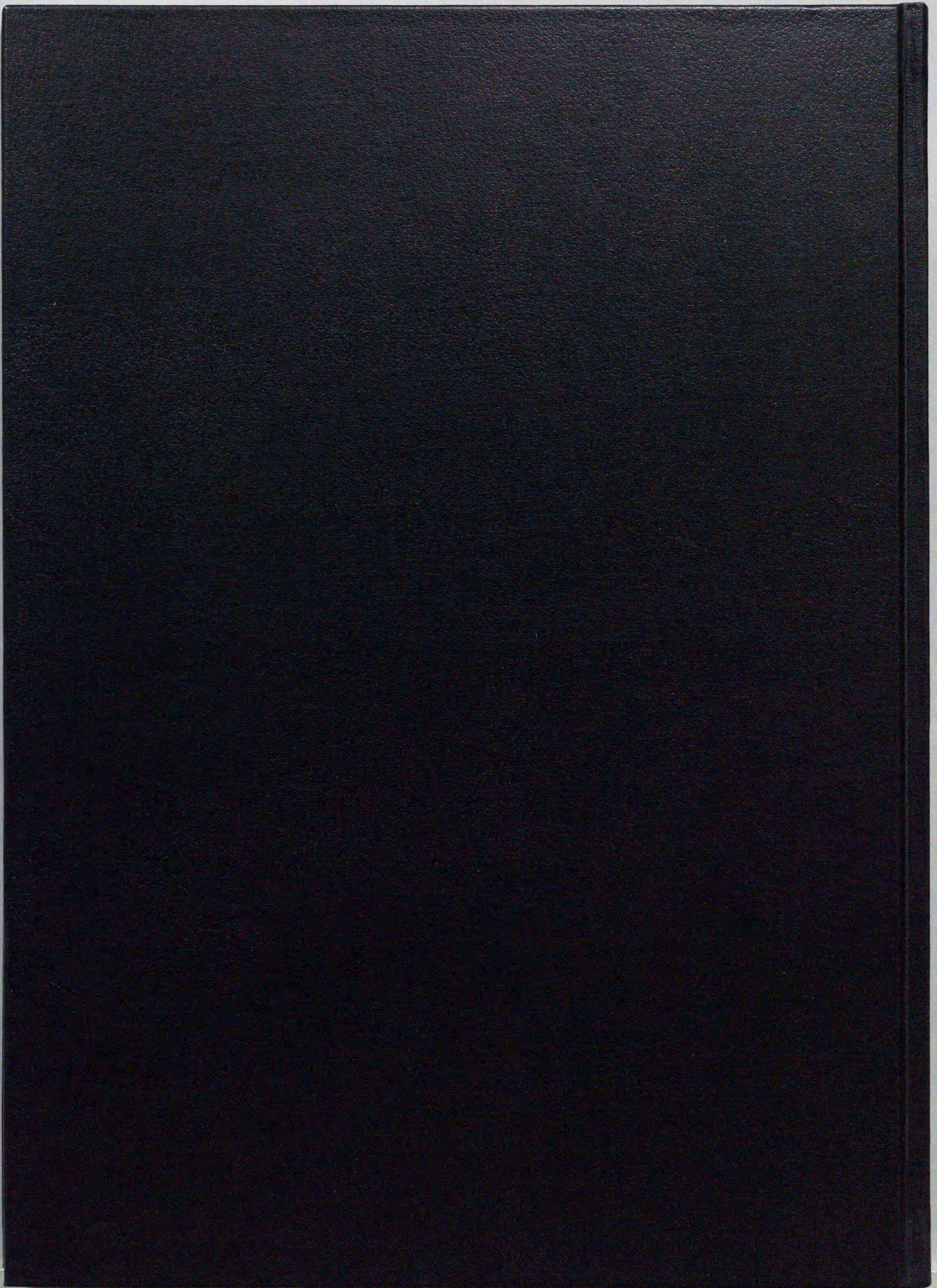
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