An Architecture of Behavior Selection Grounding Emotions

Tadashi Kitamura

Department of Mechanical System Engineering
College of Computer Science and System Engineering
Kyushu Institute of Technology
680 Kawatsu, Iizuka-city Fukuoka 820-8502 Japan
kita@mse.kyutech.ac.jp

Abstract

Emotion is part of consciousness. We gave "consciousness" a technical definition as a function of internal response which is aroused if an action being conducted is obstructed, and activates another action. We designed CCA (Consciousness-based Architecture), a six-layered hierarchy of consciousness linked to behaviors including reflex action, approach, detour, and ambush. While a level of behavior is chosen so that the magnitude of the emotional value, a function of perception and its memory is maximized, an action at the chosen level is selected to make the emotional value larger than the last step. Model design was tested using two small mobile robots, and a limited use of temporal and spatial information of environments was shown.

Introduction

It may not be possible to give a precise, quantitative definition of "emotion" to be embedded in a mobile robot. However, emotion is what subjectively activates behavior, is aroused by obstruction of behavior, and is objectively visible through behavior. This idea about emotion is included in the concept of consciousness by the Vietnamese philosopher, Tran (Tran, 1951). According to him, emotion is part of consciousness aroused if the behavior is inhibited. Tran proposed a conceptual model of the relationship between consciousness and behavior based on a currently accepted assumption that the mental process of an animal has developed in the phylogeny from single-celled animals to humans, just as human consciousness develops in its ontogeny.

According to his model based on the analysis of human consciousness, a level of consciousness activated selects and produces an action on the immediately higher level than the level of inhibited behavior. We define consciousness as what comprises perception and inhibited behaviors and activates an action. Based on this definition of consciousness, we have designed a software architecture, Consciousness-based Architecture (CCA), to integrate both adaptive animal-like behaviors and more symbolic behaviors. The feasibility of the architecture was tested by computer simulation and an experiment of the behaviors of two imaginary animals, to include sleep, reflex action, approach, and detour (Kitamura, 1995 and 1998). This study shows the model design for behavior selection in CCA and also demonstrates the results of the experiment using two criteria, functions of object-dependent emotion values.

Consciousness-based Architecture (CCA)

Hierarchy of the Architecture

According to Tran's model, the relationship between behavior and consciousness of mammals lower than apes, or that of an infant younger than two years, has a hierarchical structure of six levels. The word "consciousness" is used in a broad sense to mean awareness of an object externally and/or being internally capable of responding to it, where external response means behavior and the internal one consciousness of emotions, representations and symbols. Thus all living beings from a single cell to a human can be said to have "consciousness". To implement Tran's conceptual model of consciousness, we gave consciousness a technical definition as a function of internal response which is aroused if an action being conducted is obstructed, and triggers another action.

Based on this definition of consciousness, we designed Consciousness-Based Architecture (CCA). Its hierarchy, as shown in Fig.1, is efficient because a complex task is processed with elevation of the level: inhibition of behavior elevates the level of consciousness and behavior. In Fig.1, each arrow from behavior to consciousness indicates that the consciousness level thus indicated is chosen. A real-time image of the activation of consciousness is shown on the computer screen, and is used as a behavior design tool, as mentioned in the next section. An arrow from the consciousness field in the figure selects and activates behavior at the level the arrow indicates.

From levels of 1 to 4, emotion is partitioned into two values, pleasant and unpleasant, and correspondingly this level contains only two opposite actions, attraction and aversion, but the existence of emotional memory depends on the level. Symbolic representations belonging to animals at Level 5 include no emotion. Symbolic behaviors higher than Level 5, such as the use of tools, production of tools, and commanding language, are removed from Tran's original model because this study is limited to modeling

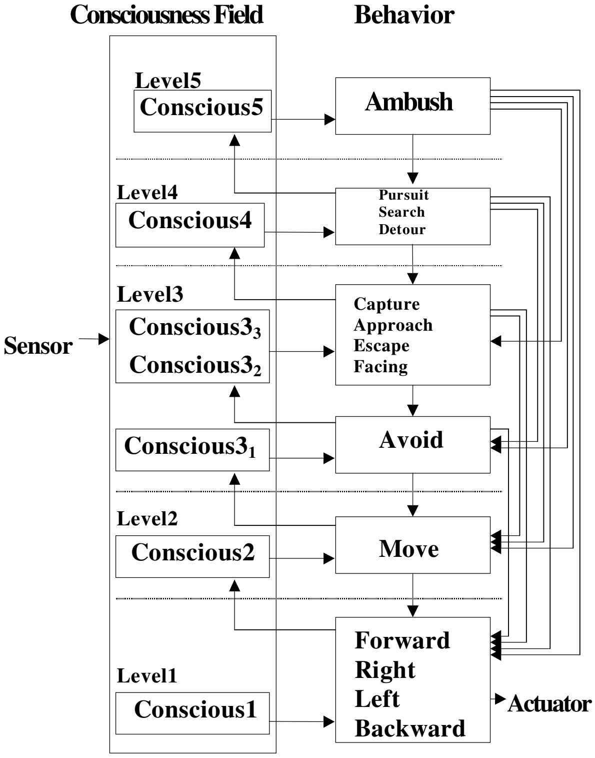

Fig.1 Block Diagram of CCA

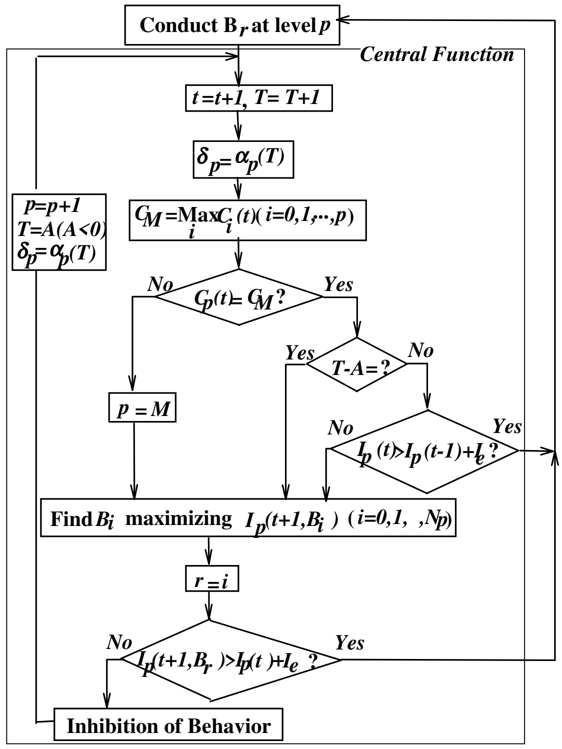

Fig.2 Flow Chart of Behavior Selection

less intelligent consciousness and behaviors than Level 6. Details of the function of each level will be described in Behavior Design.

CCA has a central processing for behavior selection described in the next section. This central function is linked to the "consciousness field" which dynamically changes depending on perception of environments as well as behavior. Perception by the sensors are linked to all levels of the consciousness field, but at which level a perception appears depends on the perception. The memory for this architecture is partitioned into all levels of the consciousness field, and is used according to behavior function. The behavior function B_{ij} for jth behavior at the level i is defined as an appropriate combination of lower behaviors: $\{B_{1j}\}$={Move Forward, Right Turn, Left Turn, Move Backward}, $\{B_{2j}\}$={Move}, $\{B_{3j}\}$={Avoid, Face, Escape, Approach, Capture}, $\{B_{4j}\}$= {Search, Pursue, Detour}, $\{B_{5j}\}$={Ambush}. Each function combining lower actions is fixed for simplicity.

Behavior Selection

A flow chart of the whole process of the central function for behavior selection is shown in Fig.2. Change of behavior depends on the two criteria as defined below, $C_k(t)$ for level selection and $I_i(t)$ representing an emotion value for action selection at a selected level. Suppose that the animal is conducting behavior B_r at level p. If there is a level M maximizing the criterion $C_i(t)$ representing the intensity of consciousness at level i ($0<i<p$) at a discrete time t, then the animal determines an action B_{Mq} based on the behavior set $\{B_{Mj}(j=1,..,N_M)\}$ such that $I_M(t+1,B_{Mq}) > I_M(t)+I_e$ using the action selection index $I_i(t)$ with an appropriate threshold I_e. But if $I_M(t+1,B_{Mq}) \le I_M(t)+I_e$ for any j, then the last behavior B_r is called to be "inhibited", and the level of consciousness elevates from p to p+1. In this case α_{p+1}, absorption in behavior, in the following equation (2) plays an important role in securing the continuous selection of level p+1 after the behavior inhibition at level p for a given time A before a different level than p+1 is selected.

$$C_i(t) = \begin{cases} \sum_{j=1}^{N_E} |\beta_{ij}| + \sum_{j=1}^{N_I} |\gamma_{ij}|, & (i \neq p) \quad (1) \\ \delta_p(t) + \sum_{j=1}^{N_E} |\beta_{pj}| + \sum_{j=1}^{N_I} |\gamma_{pj}|, & (i=p) \quad (2) \end{cases}$$

$$\text{for } \delta_p(t) = \begin{cases} \alpha_p(t), & \text{only while the level is staying at p after changing from } p-1 \text{ to } p, \\ 0, & \text{else;} \end{cases}$$

$$I_i(t) = \sum_{j=1}^{N_E} \beta_{ij} + \sum_{j=1}^{N_I} \gamma_{ij} \quad (3)$$

where $\alpha_p(t)$ ($1>\alpha_p>0$) is absorption in a selected behavior at level p. β_{ij} and γ_{ij} are the intensity of the external stimulus at level i and that of jth internal perception such as hunger, respectively, and β_{ij} depends on the position of the object measured by the four distances of zero ($0<d<20$), near ($20<d<100$), medium ($100<d<400$), and far ($400<d$) for d in mm. β_{ij} and γ_{ij} are valued between -1 and 1, positive for a positive emotion and negative for a negative emotion. N_E and N_I are the number of external objects and internal perceptions respectively. The values of α_i, β_{ij} and γ_{ij} should be identified depending on the modeled animal, but are assumed to be explicitly time-invariant for simplicity in the present study.

The animal continues the same action B_r at level p if $C_p(t)$ is maximal in $C_j(t)$ for $0<j<p+1$ and $I_i(t)>I_i(t-1)+I_e$. But if $C_p(t)$ is maximal but $I_i(t)<I_i(t-1)+I_e$, then the animal chooses B_i such that $I_p(t+1,B_i)>I_p(t)$. If there is no such behavior, then the behavior is inhibited, and the animal starts to find a behavior at level p+1. Then the animal, whose highest level of behavior is p, would remain at p. In addition, if a maximal $C_i(t)<C_0$ for a fixed positive real number C_0, the animal does not move at level 0, resting or sleeping.

Absorption α_p represents a nature that an animal tries to continue to conduct a purposive behavior at level p. In this study, it is assumed that absorption occurs only while the animal stays at level p right after behavior at level p-1 is inhibited. The index I_i, by which an action is selected from a set of actions at level i, represents a summation of emotional values, i.e., grade of comfort, which is defined by removing the symbols of absolute value out of C_i without the absorption term. The physical meaning of maximal $C_i(t)$ at each moment represents a summation of all the magnitudes of perception, i.e., activity of the consciousness at level i, while $I_i(t)$ is the positive value for survival at level i. It is assumed for simplicity that both $C_j(t)$ and $I_i(t)$ are a linear combination of their components. In the definitions of these criteria, psycho-physiological interactions between internal and external perceptions, β_{ij} and γ_{ij}, e.g., hunger producing a chill, and sensation of fullness producing drowsiness, are neglected.

Interface Screen

The interface screen depends on both user's inputs and robot's state (Kitamura, 1998). A user can input virtual obstacles and objects in the robot's field of view called consciousness field, on the interface screen using a mouse, while the screen image also depends on robot's perceptions and conditions at each level of the consciousness field of CCA. Parameters included in $C_i(t)$ in (1) and (2) such as β_{ij},and γ_{ij} correspond to independent variables of functions which graphically display the robot's field of view on the screen. The screen was designed on a host computer, SunSparc10, in accordance with the sensors and the actuator of a small Swiss mobile robot, Khepera with proximity sensors for eight directions and an image sensor for a longer distance.

The windows in the robot's field of view show the front and rear views experienced by the robot, respectively. A circle in each window turns on when an object is sensed by the image sensor, and its size changes within four degrees depending on the distance of the object from the robot. The circles in each window turn on when the obstacle-avoid sensor in the corresponding direction perceives an object. An image of a spatial coordinate system representing four distances and eight directions from the robot's view is also displayed. A direction of a virtual object is selected by clicking the circle in the required frame, and its type and distance can be chosen from the menu on the consciousness field.

Behavior Design

Actions at each level have been carefully tested using the interface tool with the Khepera robot hooked up with the host computer SunSparc10. The robot has eight infrared proximity sensors evenly spaced around the robot's body that enable Kheperas to sense distance to an obstacle within 2 cm. The robot also has a vision sensor on the top, which detects real-time distance to a striped object up to 40cm ahead. Distance is measured by built-in encoders in error of less than 2%. Virtual objects can be set up to a real robot by a mouse in virtual environments on the screen image that is also linked with an actual environment, where the robot is situated among real objects and obstacles. The robot can recognize both virtual and real environments at the same time. Behavior level design was achieved with level 1 first, level 2 piled up on top of it, and up through the whole hierarchy from 1 to 5. Then all parameters in (1) to (3) were appropriately tuned, as mentioned below.

Level 1

An external stimulus results in a reflex action, i.e., attraction with $\beta_{1j}>0$ or aversion with $\beta_{1j}<0$, and a simultaneous sense, which appears in the consciousness field without memory. Actions, such as changing of body direction and feeding, as far as they reflexly occur, belong to the category of action at this level. In this study, four behaviors are defined at this level: turning to the right or left, or going forward or backward. What the robot likes is defined as a black object and dislikes is defined as a striped one.

Level 2

The consciousness field at this level values a stimulus as either pleasure for $\beta_{2j}>0$ or displeasure for $\beta_{2j}<0$, depending on the memory of stimuli. If a jth stimulus which causes a reflex action at level 1 goes over the threshold at both level 1 and 2, i.e., $|\beta_{1j}|=|\beta_{2j}|=1$, then the emotional value and position from the robot's view are memorized in the consciousness field at this level for a long time. This field, therefore, can be seen as a coordinate system with emotional values. The temporal lengths of memory are set long enough to finish achieving a single task such as capture or escape at level 3 based on the memory at this level. Stored information at this level, therefore, determines survival behaviors in the near future. In this study, there is only one action named 'move', which orientates and moves the body toward a goal organizing the four behaviors at level 1.

In one experiment, when a virtual disliked object was placed in front of the robot, it jumped backward due to the function of level 1, and then escaped after turning round. In this experiment, the velocity of escape depended on $\beta_{21}<0$ for the magnitude of displeasure. Then, the distance of jumping backward may be determined by the velocity of the disliked object and $\beta_{11}<0$ for the intensity of displeasure. The color of the whole consciousness field on the screen changes to purple if $\beta_{2j}=1$.

Level 3

The consciousness field at this level is memoryless emotion which should be partitioned into more than two values, such as desire, pleasure, comfort with $\beta_{3j}>0$, and hatred, anger, pain and fear with $\beta_{3j}<0$, depending on the external object. These emotions of a real animal would produce different actions. But in this study, these different emotions are not differentiated for action selection for simplicity, but are reduced into two opposite values, positive and negative in the criterion $I_i(t)$ in (3).

Immediately when an object goes out of sight, the emotion induced by that object disappears from the consciousness field, i.e., β_{3j} becomes zero for the object, the robot stops the behavior at this level. An experiment verified that when the robot approaching a real favorite object was disturbed by a virtual obstacle placed in the way, thus losing sight of the desired object, it can no longer search for the object. But an animal, designed with level 3 piled up at level 1 and 2, never forgets an object, if an object is memorized at level 2.

Four behaviors are defined at this level: avoid, face, approach, and escape, each of which is a function appropriately organizing 'move' at level 2 and the reflex motions of the four behaviors at level 1. We simulated hesitation of a hungry animal with the highest level 3 before a real prey and a virtual hateful object located at the same place. Suppose: (i) $C_1(t)=2$, $I_1(t)=1$ with $\beta_{11}=0.5$ for the prey and $\beta_{12}=-0.5$ for the hateful object, and $\gamma_{11}=1$ for hunger at level 1, (ii) nothing happened in the memory at level 2 assuming that $C_2(t)=2$, $I_2(t)=1$ for $\beta_{21}=0.5$, $\beta_{22}=-0.5$ and $\gamma_{21}=1$ and (iii) at level 3, the animal has $C_3(t)$ and $I_3(t)$ with a hunger intensity $\gamma_{31}(t)=-\gamma_0/(t+\gamma_0)+1$ for $\gamma_0>0$ as follows:

$$C_3(t) = \alpha_3 + \beta_{31}(d) + |\beta_{32}(d)| + \gamma_{31}(t) \tag{4}$$

$$I_3(t) = \beta_{31}(d) + \beta_{32}(d) + \gamma_{31}(t) \tag{5}$$

where $\alpha_3=0.4$, and $\beta_{31}(d)=(300-d)/900+0.5$ and $\beta_{32}(d)=-100/(d+200)-0.5$ are chosen so that $\beta_{31}(d)+\beta_{32}(d)$ is a single-peaked function of the distance to the objects, d in cm ($300\geq d\geq 0$). It is assumed that the distance d=300 at t=0. According to the behavior selection algorithms mentioned in Behavior Selection, level 3 is always chosen since $C_3(t)>C_1(t)=C_2(t)=2$. Therefore, as long as the robot moves toward the two objects for d>100 and then backward for d<100, $I_3(t)>I_3(t-1)$ is always true due to the single-peakness of I_3 as a function of d. As a result, the animal shows hesitation such as moving back and forth around d=100 maximizing $\beta_{31}(d)+\beta_{32}(d)$, and finally arrives at the prey as increasing hunger $\gamma_{31}(t)$ becomes dominant in $I_3(t)$ (Kitamura, 1998).

A behavior at a lower level than 3 can also be selected through the central function. Such behavior was easily designed in an animal of level 3 which was running after a real prey at level 3. When a prey was placed closer to the animal than the original prey, the animal changes to level 2 because the parameters of $C_i(t)$ (i=1,2,3) had been set beforehand such that $C_2(t)<C_i(t)$ (i=1,3). Here, it is also supposed that $\beta_{i1}(d)$ and $\beta_{i2}(d)$, both decreasing functions of d, for the original and second preys, respectively, satisfy $0<\beta_{i1}(x)<\beta_{22}(y)$ (i=1,3) for any x and y such that x>y>0. Then, the animal began to move toward the closer prey in order that $I_2(t+1)>I_2(t)$ increasing $\beta_{22}(d)$.

Level 4

To take an action at level 4, such as search, pursuit, and detour, an animal must have a stable and lasting emotion for the object. If a prey disappears behind an obstacle, stability of desire enables the animal to continue to search and pursue. Detour and pursuit were successfully tested by adding level 4 simply to all the lower levels with use of a virtual favorite object and real obstacle. Thanks to the function of level 4, the same object's image still continues to appear on the same circle as is originally located in the same upper frame of the screen after the object went behind the obstacle and disappeared. Then, $C_i(t)$ and $I_i(t)$ (i=3,4) are organized as follows.

$$C_i(t) = \alpha_i + \beta_{i1}(d) \tag{6}$$

$$I_i(t) = \beta_{i1}(d) \tag{7}$$

where $\alpha_3==\alpha_4=0.4$, and $\beta_{i1}(d)$ is the stimulus of the favorite object, a decreasing function of d. Suppose the animal is moving toward the virtual object at level 3 for $C_3(t)$ and $I_3(t)$ with $\beta_{31}(d)>0$. If a real obstacle is placed in front of the robot to hide the object, $\beta_{31}(d)$ becomes 0. Then, since $C_4(t)=\alpha_4+\beta_{41}(d)>C_3(t)=\alpha_3$, and there is no choice of behavior at level 3 so that $I_3(t+1)>I_3(t)$, moving toward the object at level 3 is inhibited, and therefore, the robot changes to level 4. The robot then detours the obstacle aiming at the virtual object in order that $I_4(t+1)>I_4(t)$, and thereafter continues to move around one point where the virtual object should be.

Level 5

Capabilities at this level should involve the recognition of events in time and space, and the acknowledgment of objects as temporal and spatial symbols: behaviors are ambushing, driving a prey into a corner with use of temporal and spatial information and geographical features of environments. Animals at this level should have information of much more partitioned time and space about environments than the consciousness field at level 2, and behavior selection at this level should be more symbolic than at lower levels. However, only one choice of behavior, ambush, is assumed in this study for testing a fundamental and limited use of spatial and temporal information.

The experiment using the whole hierarchy was carried out using two real robots, Himiko with the levels of 0 to 5 and Takeru, Himiko's prey, with the levels of 0 to 3. Himiko and Takeru have the identical internal perceptions $\gamma_H(\tau)$ and $\gamma_T(\tau)$ representing hungry for all the levels respectively. Himiko has a threshold $I_e>0$ as a decreasing function of γ_H, at level 4 to pass level 4 to level 5 due to less hunger. The behavior tracks of both animals are shown in Fig.3. Himiko found Takeru at their initial positions. While pursuing Takeru at level 3, hungry Himiko lost sight of him near the striped obstacle. Then, Himiko entered level 4 at t=t, but immediately went out of level 4 because $I_4(t)<I_4(t-1)+I_e$ and $I_4(t+1,B_r)<I_4(t)+I_e$ for any B_r due to the hunger-dependent I_e, and then entered level 5. Thereafter, the animal continues to ambush at level 5 as long as the condition $C_5(t)>C_i(t)$ (i=0,1,...,4) is true. The time courses of variables of Himiko is summarized in Fig.4. If Himiko is more hungry at t=t, then she stays at level 4, detours the obstacle and pursues Takeru due to smaller I_e. Another use of ambush was also successfully tested where Himiko found an obstacle as a hiding place and waited for Takeru behind it (Kitamura, 1998).

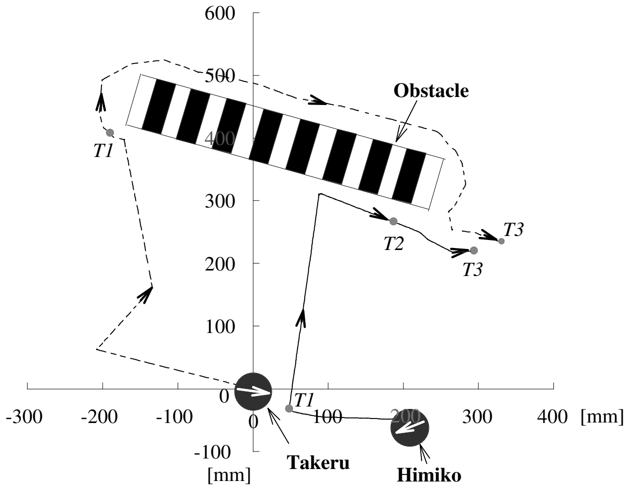

Fig.3 Behavior Tracks of Two Robots

Discussion

The advantage to applying CCA to action selection is that it takes an efficient action-selection strategy in that obstruction of behavior at one level activates an internal state for choosing a higher level of behavior in the evolutionary

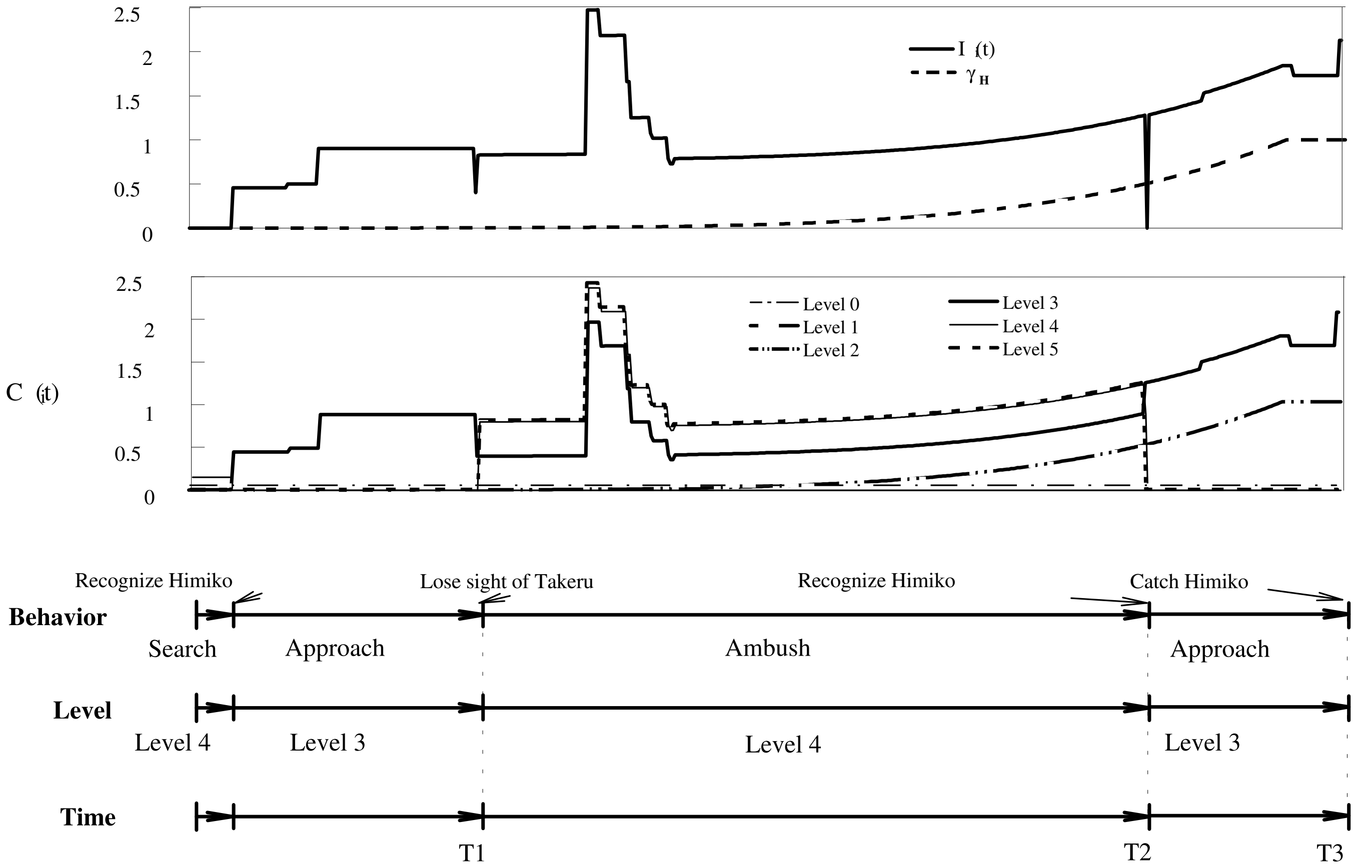

Fig.4 Time Courses of Himiko's Behavior

hierarchy. This architecture makes it possible to combine reactive actions and symbolic one such as ambush. Similar efforts have been made (Connel, 1992), but little attention was paid to make a robot have emotion and representation of its internal process available for behavior design.

The linkage of the reactive and symbolic behaviors is successful in a limited sense in the experiment. First, the inhibition of a behavior activates the consciousness level to select the next higher behavior, and second, behavior can be designed by visualizing consciousness and behavior transitions on a screen. A finding that performing a symbolic behavior of primates seems to require independence of physical needs leads us to design a symbolic criterion for action selection from more than two symbolic behaviors at level 5 rather than using an emotional one representing a physical need such as $I_i(t)$. Further investigation is also necessary to determine how more than two symbolic behaviors at level 5 should be linked to emotions at lower levels.

The consciousness of the levels 1 to 4 has the memory of emotions to past behaviors failing to reach given goals, and a behavior is outputted by the emotional memory of the consciousness field. Cognitive scientists have a similar argument that emotion is associated with disparity of behavioral output from expectation, and that the disparity triggers cognitive control (Totes, 1994). Our model analyzes disparity of behavioral output from expectation into the five layers 1 to 5 of the consciousness field, and organizes them in the hierarchy.

Our approach is advantageous over behavior-based approaches (Brooks, 1991) in the sense that our architecture has the central processing function for behavior selection by which a user can follow reasons of behavior selection. Brooks assumed intelligence without representation in robots and animals (Brooks, 1991), and all behaviors are always activated without representation, whereas the central function of CCA is linked to the representation named “consciousness field”. In our experiments, emergent behaviors never appeared, nor did we expected them. Himiko might have shown hesitation in an emergency as we designed in 3.2 by appropriately tuning her parameters for Takeru and his nest at level 3. But such emergency, which the behavior-based approach usually expects, is not important in this study because the goal of this study was to design the same behaviors as we expected.

Conclusion

In CCA of a six-layered hierarchy, while a level of behavior is chosen so that the magnitude of the emotional value, a function of perception and its memory is maximized, an action at the chosen level is selected to make the emotional value of the level larger than the last step. A level of consciousness in CCA is activated if a behavior is inhibited, then the activated consciousness selects and produces an action at the immediately higher level. Model design was tested using the proposed interface screen and two small mobile robots, and a limited use of temporal and spatial information of environments was shown. Future works will be to design an action selection criterion for more than two symbolic behaviors at level 5, and to find how such a crterion should be linked to emotions.

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