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How to make an autonomous robot as a partner with humans: design approach versus emergent approach

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In this paper, we discuss what factors are important to realize an autonomous robot as a partner with humans. We believe that it is important to interact with people without boring them, using verbal and non-verbal communication channels. We have already developed autonomous robots such as AIBO and QRIO, whose behaviours are manually programmed and designed. We realized, however, that this design approach has limitations; therefore we propose a new approach, *intelligence dynamics*, where interacting in a real-world environment using embodiment is considered very important. There are pioneering works related to this approach from brain science, cognitive science, robotics and artificial intelligence. We assert that it is important to study the emergence of entire sets of autonomous behaviours and present our approach towards this goal.

Keywords: entertainment robot; pet-type robot; humanoid; intelligence dynamics

1. Introduction

In this paper, we would like to discuss how to realize an autonomous robot, especially considering the factors that enable a robot to continue interacting with humans without boring them. We recognize that it is difficult to build a robot by employing only human manual programming and design, thus we need methods that enable the robot to have behaviours emerge beyond the traditional programming paradigm. We assert that it is important to understand the meaning of both a robot's and a human's behaviours to accomplish this.

Although it is still largely a conceptual model, in this paper we describe our approach to achieve our goal. We also propose a general term, *intelligence dynamics*, for new approaches towards understanding and realization of intelligence in the many research fields such as brain science, cognitive science and robotics.

Before starting the discussion, let us introduce several examples of autonomous robots that we have developed. In 1997, we proposed the concept of robot entertainment, to initiate entertainment applications for the establishment of a new robot industry (Fujita & Kageyama 1997). As an example of robot entertainment, we developed a pet-type robot named MUTANT (figure 3), which

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One contribution of 15 to a Theme Issue 'Walking machines'.

Figure 1. AIBO ERS110.

has a dog-like shape (Fujita & Kitano 1998; Fujita 2001). The MUTANT had pseudo-emotion and instinct models to afford natural interaction with humans. In 1999, we started to sell AIBO (figure 1) at about US$2500, which is a commercial product version of the pet-type robot. It was sold only via the internet at that time. However, in Japan, the robots were completely sold out within 20 min for 3000 bodies of AIBO. We expected that there were many high-tech oriented users who would pay this price for AIBO as a computer application possessing cutting edge technology. However, the age distribution of users was wider than we expected. Especially, there were many older users who bought AIBO for pet-like purposes.

In 2000, we announced the development of a small humanoid robot, SDR-3X (Ishida *et al.* 2001), which realizes biped dynamic walking and dance performance using whole body motion control with zero-moment-point (ZMP) control theory. The aim of the development of SDR-3X was also for entertainment applications. Compared with AIBO's pet-type domain, our goal was now to build a partner robot that can talk with a person. Hence, SDR-3X has speech recognition and speech synthesis capabilities, but its vocabulary was only about 100 words. In 2002, as an extension of SDR-3X, we developed SDR-4X (Fujita *et al.* 2003) in which real-time whole body control and real-time biped walking pattern generation are accomplished. Regarding its cognitive capabilities, the robot has a two-camera stereo vision system so it can determine two-dimensional distances at frame rate. This allows SDR-4X to avoid obstacles and plan a path to a target destination. It also has face detection and face identification ability. It can search for a specific user from his/her face, move close to the user and then talk to the user. We developed a large vocabulary continuance speech recognition (LVCSR) technology whose vocabulary is now about 20 000 words. The new speech synthesis technology can generate a singing-a-song voice from musical score information. After the development of SDR-3X we developed SDR-4X II, which is now called QRIO (figure 2).

In order to integrate all the technologies, we developed an autonomous behaviour control architecture named the EGO (emotionally grounded symbol) architecture (Fujita *et al.* 2003). It employs a homeostatic regulation mechanism based on ethological studies by which QRIO can spontaneously behave, including

Figure 2. QRIO SDR-4X II.

dialogue generation, in a manner that regulates internal variables simulating pseudo-desires such as hunger. This also allows control of emotional variables such as anger or happiness.

It has been problematic when we try to realize 'speech capability in natural language', which means how a robot can behave by understanding human utterances. In AIBO, we were restricted to non-verbal communication, where there exists some ability for a user to infer a robot's intent. Understanding here depends on the user's interpretation of displayed behaviour, permitting the user to keep interacting with the robot. However, when we use natural language, it becomes difficult for the robot to maintain effective verbal interaction because the information available in the words and sentences of the robot's speech responses is limited.

It remains a basic problem in artificial intelligence for a machine to understand natural language. Many philosophical discussions have been forwarded, but it does not mean a solved problem yet. The physical symbol grounding problem especially, as proposed by Harnard (1990), delineates the difficulty regarding the meanings of the symbols themselves.

Non-boring interaction or ever-evolving interaction constitutes another major issue in achieving the goal of a partner robot. Despite intensive study in areas such as machine learning, realizing an open-ended system that evolves beyond the software and knowledge that are manually programmed is still effectively beyond reach.

To address the problem, we developed an evolutionary computing mechanism for the generation of new gait patterns for AIBO (Hornby *et al.* 1999; Fujita 2001), and word acquisition for previously unknown visual objects (Fujita *et al.* 2001). We showed that customized behaviours, including verbal behaviours, can emerge with these technologies. Furthermore, we put forward the concept of an emotionally grounded symbol (EGS; Fujita *et al.* 2001, 2003), which allows a robot to generate proper behaviour for a newly acquired object and an associated word. The main idea of EGS is to form an association between a symbol, behaviour and the internal variables that are used for spontaneous behaviour generation by the homeostatic regulation mechanism. One example of the internal variables is 'battery remaining'. Essentially, the system tries to survive in the environment by selecting proper behaviours dependent upon the situation. Using the EGS concept, it could be said that the system understands the meaning of its behaviour because the system predicts the result of the internal variable state as a result of the said behaviour.

When we tried to realize the open-ended system, our approach was first based on designing autonomous behaviours. The system could not generate a new behaviour beyond the existing program and *a priori* knowledge available. It became necessary to realize a mechanism for emerging behaviours apart from the more traditional design approach. Recently, embodiment and dynamical systems are considered as important factors for the emergence of behaviours (Asada *et al.* 2001; Tani 2003). The same concept has become popular in other research fields including brain science (Kawato 1999) and cognitive science (Varela *et al.* 1991; Pfeifer & Scheier 1999)

By integrating these approaches towards gaining an understanding and realization of intelligence, we propose the term intelligence dynamics as a name for the new approach, where the embodiment and dynamics are essential for having intelligence. Without using words of a particular field of study such as 'robotics' or 'brain science', the aim of intelligence dynamics is to conduct breakthrough research on intelligence via interdisciplinary research activities.

In the following sections, we first describe AIBO technologies followed by QRIO. In this material, we focus on how to design autonomous behaviours. Then the concept of emotionally grounded symbol is described. The EGO architecture for autonomous behaviour control is then presented. Finally, we discuss intelligence dynamics as a basis for the emergence of complete autonomous behaviour.

2. Pet-type robot behaviours

To illustrate the design approach, in this section we describe how to implement autonomous behaviour generation for AIBO and its prototype in a pet-type robot application.

We considered that a significant factor of entertainment applications, when compared with conventional utility applications, is the tolerance of technology level. Namely, robots for entertainment applications do not require nearly as high performance in speech recognition and visual information processing that are required in mission-critical industrial applications. The technology level in the late 1990s was, and even at the beginning of the twenty-first century, has not yet fully matured to realize many mission-critical industrial robot applications. As a consequence, we decided to build a number of prototype robots (Fujita & Kageyama 1997; Fujita & Kitano 1998; Fujita *et al.* 1999). These prototypes were mainly used for software development for pet-style robots, to determine what is important for this type of robot. We concluded that the critical requirements all converge on the problem of 'maximizing the life-like appearance' of the robot.

The difficulty with this problem statement is that there is not a good evaluation method for 'life-like appearance'. Subjective evaluation with the semantic differential (SD) method (Osgood & Suci 1957) is one possible method, but evaluations must be done with many subjects with careful mental state control during the experience. This may be useful for final product evaluation, but during design and development periods, it is not a proper criterion owing to the time consuming evaluation process. Furthermore, the final design of behaviours and motions must be highly relevant for a 'life-like appearance'. Therefore, we concentrate not on the details of the motions but rather on the mechanism for their generation.

An argument arises that the viewer's suspension of disbelief might be broken if the robot did something really stupid, such as walking repeatedly into a wall. From the viewpoint of complexity, the robot here shows only a simple, single behaviour, which is to walk into the wall, nearly every time it finds itself in the same situation. If we can increase the number of behaviours exhibited in the same external situation, thus increasing the complexity, then repeated behaviour will not occur. In addition, by introducing artificial instincts and emotions, while increasing the number of behaviours, further ensures the realization of non-repeated behaviour exhibition.

The remainder of this section first outlines the design concept for a pet-type robot, and the overall agent architecture of the pet-type robot.

(*a*) *Design concept of pet-type robot*

Reiterating, 'maximizing the life-like appearance' is considered to be the most important problem for pet-style robots. We have reformulated this problem as 'maximizing the complexity of responses and movements'. This serves as our overall approach to configuring an autonomous entertainment robot. The main points involved are as follows.

(i) A configuration of four legs, each of which has three degrees of freedom; a neck with three degrees of freedom; and a tail with one degree of freedom. Altogether this amounts to 16 degrees of freedom. With such multiple degrees of freedom available for motion generation, the complexity of movements is increased.

(ii) The generation of multiple motivations, and the generation of behaviours based on the motivations and selection among the behaviours. There are a large variety of combinations of behaviours, and this exponentially increases the complexity of observed behaviour. The behaviours are generated from:
  - (a) a fusion of reflexive and deliberate behaviour over a ranging time-scale,
  - (b) a fusion of independent motivations given to the robot parts such as the head, tail and legs, and
  - (c) a fusion of behaviours that obey both external stimuli and internal desires (instincts, emotions).

(iii) The internal status (instincts and emotions) changes the behaviour of the robot towards external stimuli. Furthermore, the internal status changes according to external stimuli. Thus, the overall complexity of overt exhibited behaviour is increased.

(iv) Adaptation through learning is introduced, so that the degree of complexity is increased when the robot is observed over a long period of time.

Figure 3. The pet-style robot MUTANT.

Figure 3 shows an example of a prototype four-legged robot, named MUTANT. This robot uses 16 servomotors, each composed of a DC geared motor and a potentiometer to enable flexible movement. The robot is programmed to react to the external world and to humans by using its capacity for expression while employing a variety of sensory processing. The aim is to give the impression that the robot is alive. It is equipped with a micro-CCD camera, a stereo microphone, an acceleration sensor (three-axis), and can perform image processing, acoustic signal processing and position estimation. For example, as shown in figure 4, its basic movements include the following.

(*a*) Searching for a coloured ball, then approaching it and kicking it.
(*b*) Expressing a simulated emotional state such as 'angry'.
(*c*) Giving its paw.
(*d*) Sleeping when it gets tired.

(*b*) *Agent architecture for AIBO*

Starting from the MUTANT feasibility study, we developed the agent architecture for AIBO, whose features are summarized as follows (figure 5).

(i) *Behaviour-based architecture.* We employ a behaviour-based architecture for AIBO. For example, searching-tracking behaviour is one of the behaviour modules. Many different behaviour modules are activated and selected by the action-selection mechanism, which accomplishes the fusion of deliberative behaviour and reflexive behaviour.

(ii) *Randomness.* Each behaviour module consists of state-machines that realize a context-sensitive response. These are implemented as stochastic state-machines, which enable the injection of randomness to action generation. For example, a pink ball is in view, the associated stochastic state-machine can determine that a kicking behaviour is selected with probability 0.4 and a pushing behaviour is selected with probability 0.6. Thus, different behaviours can be generated from the same stimuli, increasing the overall behavioural complexity.

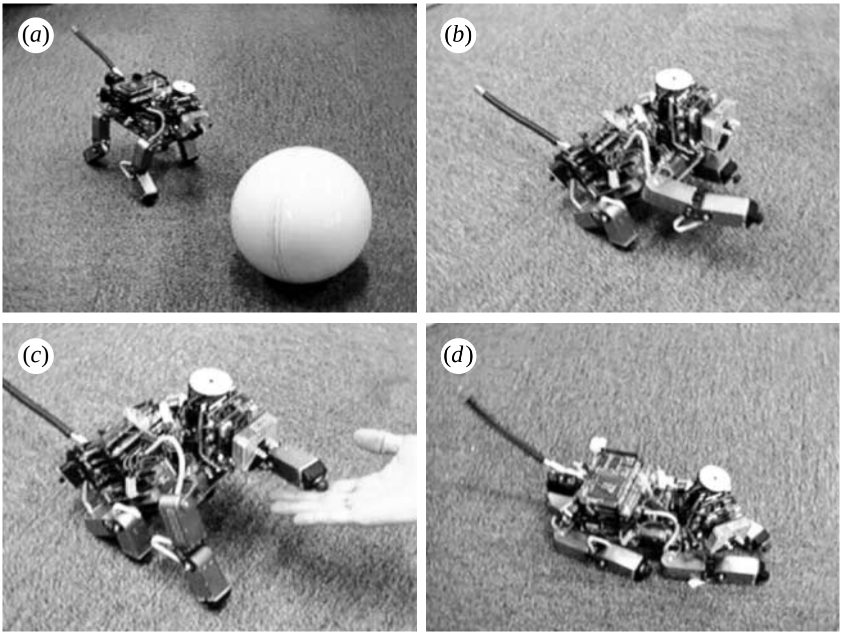

Figure 4. Diverse movements.

(iii) *Instinct/emotions*. Simulating instincts and emotions generates motivations for the behaviour modules. The same external stimuli can then generate different behaviours owing to the internal emotional state, again increasing the overall complexity of manifested behaviour. Of the numerous theoretical proposals put forward for emotions, we settled on six fundamental emotions based on Ekman's model, which is often used in the study of facial expressions (Ekman & Davidson 1994). These include joy, sadness, anger, disgust, surprise and fear. Just as with the instincts, these six values change their values according to equations, which are functions of external stimuli and instincts.

(iv) *Development*. This ability involves long-term adaptation through interaction with users. Development can be considered as a slow changing of the robot's behavioural tendencies. Since we implement a behaviour using a stochastic state-machine, which can be represented by a graph-structure with probabilities, we can change the graph-structure itself, so that completely different responses can be realized. A series of discontinuous changes can be observed during the robot's development over its lifetime.

(v) *Various motions*. Finally, we implemented many motions, sound patterns and light-emitting diode (LED) patterns, which are used for eye-patterns (e.g. smile, angry) for AIBO face. This simply increases the complexity of behaviours numerically.

Thus, when compared with MUTANT's architecture, we added more complexity with the 'development ability'. It is still a manually designed approach; however, it has a 'customized feature', which means that at the

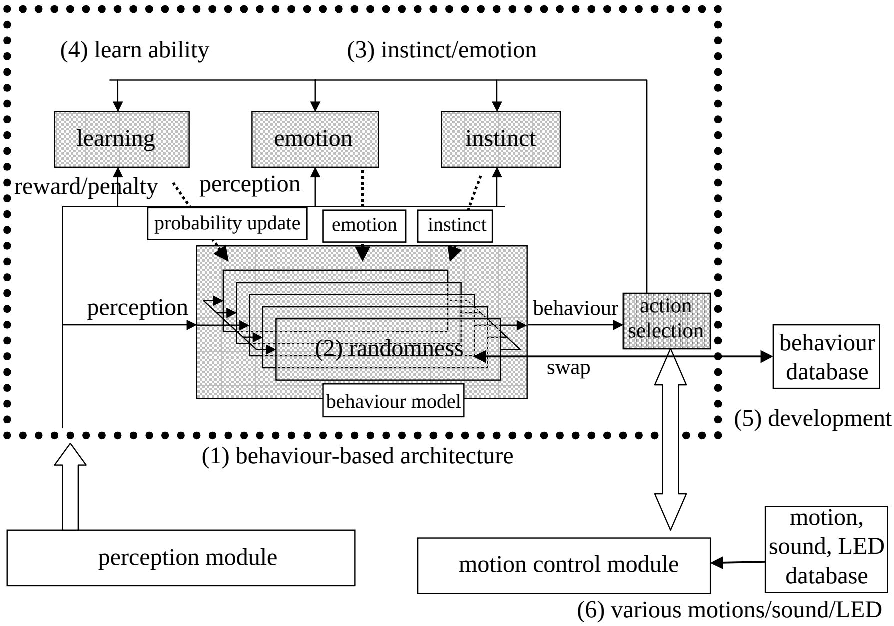

Figure 5. Agent architecture of AIBO.

beginning all AIBOs behave in the same way. However, after continues user interaction, the behavioural tendency and the motion itself becomes different depending on how a specific user interacts with AIBO. There are a limited number of bifurcations in the development. Therefore, we developed a 'learning ability', which is also a 'customize' feature, and increases the behavioural complexity even more.

(vi) *Learning ability*. Using the probabilities within the stochastic state-machine, we incorporated reinforcement learning into the architecture. For example, assume that when a 'hand' stimulus is presented in front of the robot there are several possible responses. Let us say, for example, there are five possible behaviours, with one being 'give me a paw'. At the beginning of learning, the probability for each possible behaviour being manifested for this stimulus is 0.2. When the 'give me a paw' behaviour is selected with its initial probability, then the user gives a reward such as petting the robot's head. This causes an increase in the probability of the behaviour from 0.2 to 0.4, and the other behaviours' probabilities decrease to 0.15. Then, when again a hand is presented to the robot, the 'give me a paw' behaviour has a higher probability of being selected. Thus, a user can customize AIBO's response through reinforcement learning, also increasing the complexity of behaviours.

Thus, in the AIBO project, we designed many behaviours and motions as products. We also added some customization features such as development and learning. However, these technologies were still within the manual design paradigm. Since AIBO is a commercial product, we needed to guarantee its safeness and reliability.

3. QRIO as a partner robot

When we developed SDR-3X, we tried first to develop motion control for a biped robot and to reuse AIBO technologies for most of the remaining parts. We used the OPEN-R architecture for SDR-3X, which is a standard framework for robot entertainment systems (Fujita & Kageyama 1997). We had previously developed voice recognition technology with about 100 word vocabulary for AIBO, and it was easy for us to port this software to SDR-3X (Ishida *et al.* 2001). Voice recognition was used for voice commands. For example, if a user said, ‘kick a yellow ball’, then SDR-3X obeyed the command, first by searching for a yellow ball, then moving close to it and finally kicking it. After developing SDR-3X, we decided that our objective is now a partner robot, which should exhibit more friendly interaction with a user. Thus, we decided to develop speech dialogue technology by which a user can talk interactively with the robot.

In parallel, we realized that a human configuration of the robot has a big impact on humans, which is quite different from the impact of AIBO. This may be explained by the existence of a mirror neuron (Rizzolatti *et al.* 1996). The mirror neuron is a neuron that is activated when a monkey watches another monkey’s motions. The activated neuron is the same neuron when the observer monkey performed the same motions. Thus, the perception of motions can be considered as ‘analysis by synthesis’. We could then assume that when a human observer watches motions of the humanoid robot, in the observer’s brain, the same neuron that is activated when the observer does the same motions may be activated. This neuron is not activated when the observer interacts with a non-human-shaped robot.

As we mentioned above, the shape of a robot is important for human–robot interaction, because a user’s behaviours can be controlled or afforded by the human-shaped robot. In the remainder of this section, we describe QRIO’s technologies and its behaviour control mechanism.

(*a*) *Core technologies and architecture*

In order to develop a partner robot, we must emphasize the robot’s dialogue capability when compared with SDR-3X or AIBO’s earlier architectures described previously. This goal requires us to enhance our software architecture not only to simply add a dialogue module, but also to provide other essential functional modules such as ‘memory’ capability. We consider that the following functions are necessary for an architecture to develop a partner robot, which establishes them as requirements for our goal.

(i) *Requirements*

(i) *Spontaneous behaviour.* We prefer a robot that behaves spontaneously. Namely, we would like to build a robot that can spontaneously talk to a user, take a rest, search for something, etc. In addition, if a user wants to talk with the robot, the robot should usually respond to the user. However, it may also be acceptable that the robot sometimes refuses to respond to the human’s request. How often the robot refuses or accepts a command can be considered as part of the personality of a robot. In this paper, we will not discuss personality but rather the underlying architecture for how to build such behavioural tendencies.

(ii) *Reflexive behaviour and deliberate behaviour.* It is very important for a life-like robot to respond rapidly to threat stimuli. In addition, it is also very important for such a robot to track an object such as the moving face of a talking user to provide good interaction. On the other hand, an intelligent partner robot must also behave using deliberate reasoning such as path planning. How to integrate reflexive and deliberate behaviours is a key issue for our autonomous behaviour control architecture.

(iii) *Spatial perception with memory.* Since the vision sensor has a limited view angle, it is impossible to observe simultaneously the multiple objects whose locations are distributed in an area wider than the view angle. The robot needs the capability of memorizing the objects' spatial locations, so that it can behave intelligently towards objects naturally distributed in a real-world setting.

(iv) *Dialogue with memory.* It is still difficult for a robot to understand the meaning of a human's spoken language. However, there are several methods for a robot to vocally respond to a human's utterances in the absence of a complete understanding. One such method is to use some of the words that the speaker previously said. If the robot uses these memorized words, after a while in the proper situation, the human feels the robot possesses some intelligence.

(ii) *Approach*

To achieve the requirements described above, we take the following approach.

(i) Homeostasis regulation for spontaneous behaviour.
(ii) Layered architecture for integration of reflexive and deliberative behaviours.
(iii) Short-term memory (STM) for spatial perception.
(iv) Long-term memory (LTM) for dialogue with memory.

Next, we describe the entire software architecture including an explanation for each of these aspects.

(iii) *Architecture*

Figure 6 shows the logical architecture for the autonomous behaviour control architecture of SDR-4X. Roughly speaking, it is divided into five parts, which are (i) perception, (ii) memory, (iii) internal state model, (iv) behaviour control and (v) motion control.

(i) *Perception part.* In the perception part, there are three sensor channels, which are vision, audio and tactile sensors. In visual perception, there are two major functions: (i) to detect a floor to walk while avoiding obstacles and (ii) to detect and identify human faces. In the audio channel, speech processing is the primary function, which includes sound direction estimation, sound event identification and large vocabulary continuous speech recognition

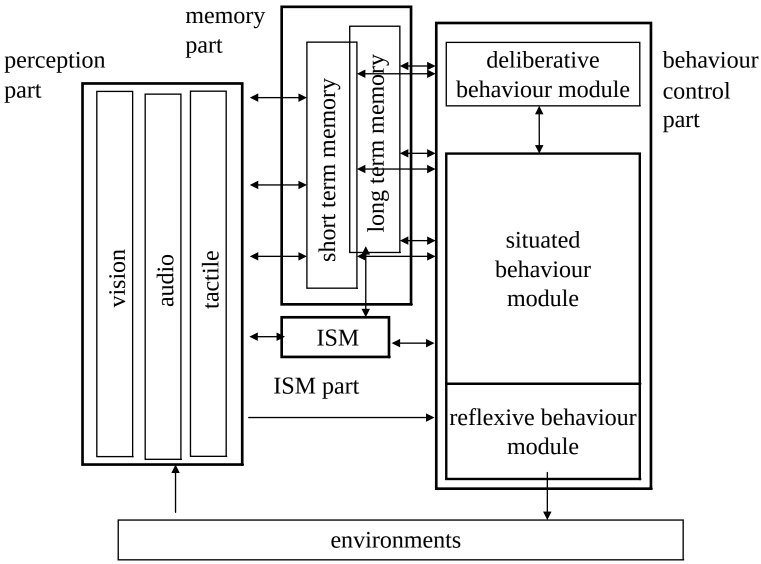

Figure 6. Logical architecture of QRIO.

(LVCSR). In the tactile sensor channel, the signals from touch sensors are processed and identified as various types of touching such as 'hit' and 'pat'.

(ii) *Memory part*. In the memory component, there are two sub-modules: STM and LTM. STM addresses the requirement of spatial perception with memory. From sound information, the robot can know the source's direction, and from the results of face detection, it can know the face's direction and its approximate distance (assuming that the face size is roughly known). Using this detected information and determining its position from the robot's kinematics, SDR-4X can compute its position relative to detected humans and objects. This location is then stored in STM. Using STM information, the robot can handle tasks involving several humans and objects that are located outside the limited view range.

Figure 7 illustrates the functioning of STM. Figure 7*a* shows the case when a robot sees a ball (circle). Using information regarding the size of the ball as well as an average of humans' face size, the distance can be determined. The dotted lines show the camera's view angle. Inside the view range, there is a person (man1) whose face is detected. Figure 7*b* shows the situation when a voice signal now comes from the left-hand side of the robot, which is out of the camera's view range and at an unknown distance (shown by the fan-shape). Figure 7*c* shows that the robot turns to the voice signal's direction and finds man2, whose face is detected and distance determined. The robot remembers the position of the ball and the man1 during this process.

Regarding LTM, there are two memory types available. The first is an associative memory and the other is frame-type (symbolic) experiential memory. The associative memory is primarily used to remember an identified face, an identified voice and an acquired name. Since face learning, speaker learning and unknown word acquisition are carried out using statistical

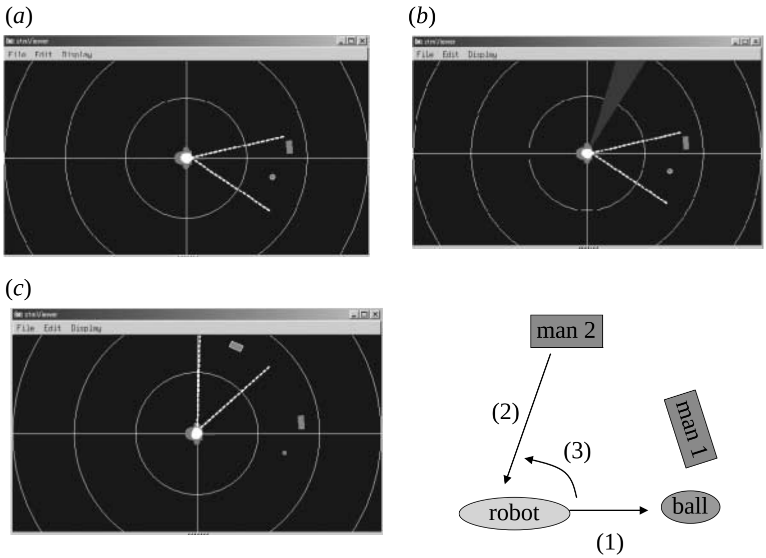

Figure 7. Short-term memory.

methods, neural networks can be used to implement the associative memory. Using the associative LTM, SDR-4X can identify a user from either his/her face or voice. SDR-4X can then recall the experiential memory associated with this specifically recognized user. Using this second form of LTM, experiential memory, SDR-4X can behave differently towards each individual based on the memory's contents.

Experiential memory was implemented using a frame-type symbol memory. For example, through conversations with a user, SDR-4X can build a frame-type memory for that individual, which includes the user's birthday, favourite items and so on. These memories can be recalled in different situations.

A fundamental difficulty in symbol processing is called the symbol grounding problem. This can be addressed by the associative LTM which can be considered to contain physically grounded symbols, grounding it to the physical world via perceptual channels (Brooks 1986). We further expand this idea to associate the physically grounded symbol with emotional information, and use the concept of an EGS, through which the robot can behave properly towards its acquired symbolic representations (Brooks 1991*a*,*b*).

(iii) *Internal state model part.* In the internal state model (ISM), various internal variables alter their values depending on the passage of time and incoming external stimuli. Basically, a behaviour is selected in order to keep these internal variables within proper ranges. ISM is the core for spontaneous behaviour generation and response to external stimuli, which is one of the basic requirements described in §3*a*(ii).

(iv) *Behaviour control module part.* There are three different behaviour control modules (BCMs): the reflexive behaviour control module, the situated behaviour control module and the deliberative behaviour control module.

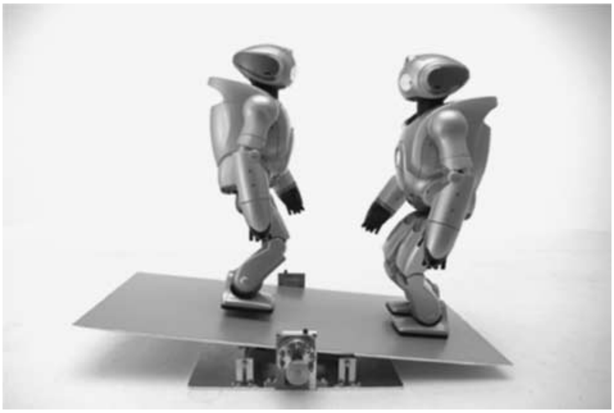

Figure 8. Walking on unbalanced terrain.

The reflexive behaviour control module depends on the configuration of SDR-4X, so that response to external stimuli can be carried out very quickly. Since it is easy to program rapid responses using mechanical configuration-dependent equations, a portion of the reflexive behaviours are implemented in the motion control part described in §3*b*. The situated behaviour control module includes many situated behaviour modules, each of which can be properly utilized for a particular situation based on external stimuli and ongoing internal drives. We developed this behaviour module based on an ethological study (Charniak & McDermott 1985). The situated behaviour module is relatively easy to develop, compared with behaviour modules that can work in more general situations (Ekman & Davidson 1994). Therefore, it is easy for us to develop many situated behaviour modules, so that the entire behaviour module set covers many different situations. Furthermore, we consider that dialogue can be performed by the situated behaviour module architecture. This is implicitly suggested in the research program named the Talking Head Project (Fujita & Kageyama 1997), where many language games are implemented to acquire a language capability for synthetic agents including robots. In our implementation, there are many dialogue-related behaviour modules, each of which is activated when the corresponding situation is satisfied. We will describe the situated behaviour module in more detail later. In the deliberative behaviour control module, computationally heavy tasks such as path planning are conducted. In the implementation, we use the same behaviour modules for the deliberate behaviour tasks. Then, complex tasks, such as the path planning process, are actually called from the situated behaviour module, so that multiple tasks are processed in parallel in the behaviour control module.

(v) *Motion control part.* We realized real-time integrated adaptive motion control and real-time gait pattern generation, enabling SDR-4X to walk on unbalanced terrain (figure 8), adaptively move against an external force, fall down with shock absorbing motions and execute recovery motions (figure 9). Fast feedback is used in order to realize this real-time control, which can be considered similar to the reflexive behaviours previously described.

Figure 9. Falling down and recovery motions.

Autonomous behaviour can be realized through integrating these parts. Among the components, ISM and the behaviour control module are keys to realizing natural autonomous behaviour generation, each of which is discussed further in §3*b*.

(*b*) *Spontaneous behaviour generation*

(i) *Homeostasis regulation*

We now explain the role of ISM from the autonomous behaviour control point of view. The basic mechanism of action selection for our behaviour control model is to evaluate both external stimuli and ongoing internal drives. We employ the ‘homeostasis regulation rule’ for action selection (Arkin & Balch 1997). Namely, internal variables are specified that must be regulated and maintained within proper ranges. Behavioural actions and changes within the environment produce corresponding changes in these internal variables. The basic rule for action selection is to use the regulation of the internal variables as a motivational ‘drive’ signal for the behaviour modules (figure 10). For example, if one of the internal variables named ‘energy’ is less than the acceptable regulation range, then certain behaviour modules that increase the robot’s ‘energy’ receive a larger motivational drive signal, so that these modules are activated for potential selection. If one of these modules is selected, the resulting behaviour produces an increase in ‘energy’. External stimuli also activate corresponding behaviours. For example, even if ‘energy’ is within an acceptable range, if the robot observes a battery, then the ‘battery charging’ behaviour activation becomes high and active for potential selection. Thus, the homeostasis regulation mechanism naturally and properly selects behaviours automatically.

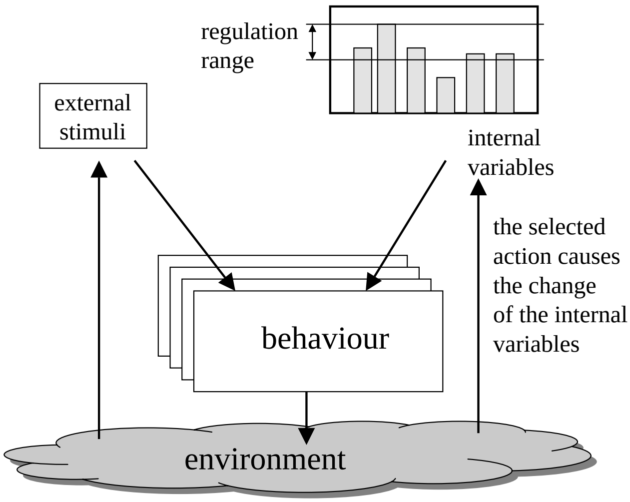

Figure 10. Homeostasis regulation for action selection.

(ii) *Requirements for behaviour module control*

In this section, we explain the situated behaviour control module relative to the overall behaviour control module discussed in §3*b*(i). When compared with the behaviour-based architecture employed for earlier systems such as AIBO, we improved the basic functions of the behaviour module based on the following requirements.

- (i) *Concurrent evaluation.* In order to behave properly in a real-world environment, we employ a situated behaviour-based architecture (Brooks 1986; Mataric 1992; Pfeifer & Scheier 1999), where a behaviour module is designed for a particular situation. By building many situated behaviours, we can achieve a robot that can behave in many different situations. It becomes important for the behaviour modules to monitor the situations concurrently, so that the proper behaviour can be selected in a dynamically changing real-world environment. Thus, concurrent evaluation of many situated behaviour modules is a basic requirement for our behaviour control architecture.
- (ii) *Concurrent execution.* Assume that SDR-4X can read a newspaper with its right hand, and can drink a cup of coffee with its left hand, or in general, assume that a robot can execute different tasks with each hand. Somehow the system needs to know what kind of mechanical resources are needed to achieve the task objectives. It is necessary for our architecture to perform concurrent execution.
- (iii) *Pre-emption (behaviour interrupt and resume).* Consider the situation discussed earlier in figure 7. Assume that at first the robot talks with man1, and then man2 calls from the left-hand side direction. The robot then has to turn towards man2 during the conversation with man1, and the associated behaviour (conversation) should be stopped. In this situation, we need a control architecture that can stop a behaviour and then resume it after finishing an emergency task. This is the requirement of behaviour interrupt and resume.

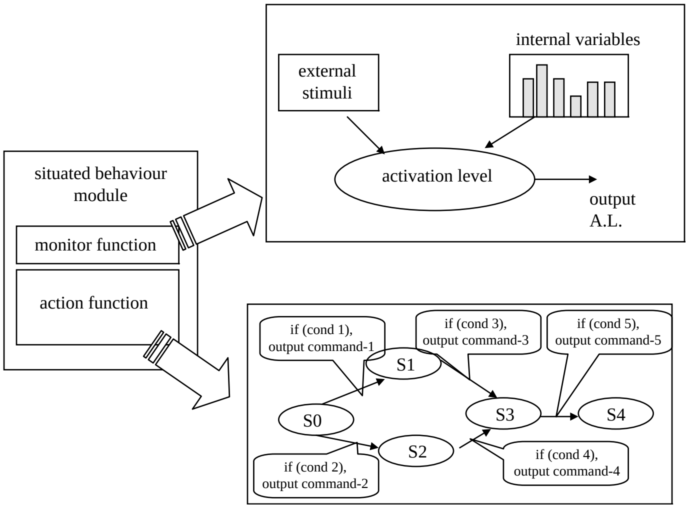

Figure 11. Monitor and action functions in a situated behaviour module.

(iii) *Approach*

Our approach to achieve these requirements is threefold, and summarized below.

(i) *Situated behaviour module with evaluation function and action execution function.* First, we design two basic functions for the situated behaviour module. One is the 'monitor function' and the other is an 'action function' (figure 11). The monitor function is used for evaluating the situation and calculating an activation value, which indicates how much a given behaviour is relevant in the current situation. The action function is used for executing the behaviour. We employ a state-machine for the action function. That is, depending on the state and input, the action function decides to output action commands. The monitor function is periodically called by the behaviour control system, so that the system continually evaluates the situation for the situated behaviour modules.
Note the monitor function evaluates both the external stimuli and internal variables. By adjusting some of the monitor function parameters, we can create several different personalities for SDR-4X. For example, if we add more weight on external stimuli, then SDR-4X tends to select a behaviour in response to the external stimuli but not based on its internal drives. On the other hand, if we add more weight on the internal drives, then SDR-4X tends to select a behaviour depending more on SDR-4X's internal motivations, which looks more like a 'selfish' robot. In addition, if we control the parameters that assign the priority of the regulated internal variables, we can also design different personality types for SDR-4X. Thus, the architecture using the homeostasis regulation mechanism with ISM can create many personalities for SDR-4X.

(ii) *Resource management with tree-structured architecture.* In order to achieve the concurrent execution requirement, the behaviour control system needs to know what types of resources are needed when the system selects specific

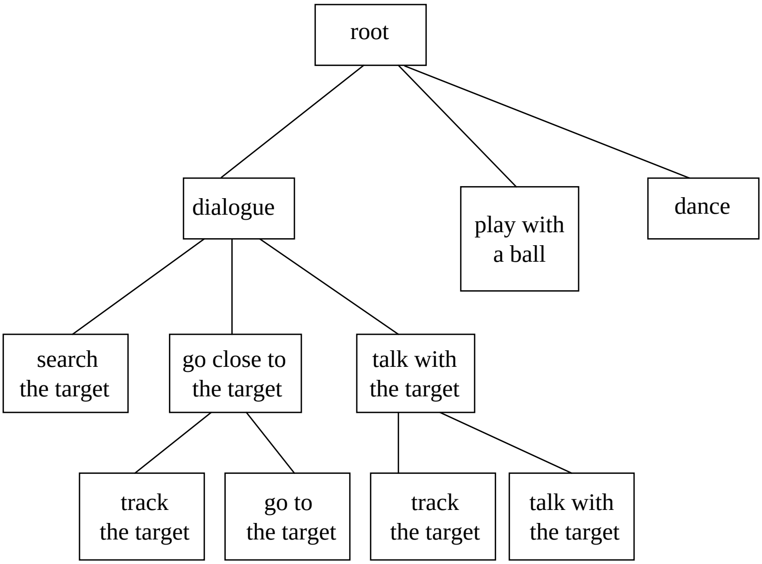

Figure 12. An example of the tree-structure of situated behaviour modules.

behaviour modules for execution. When the system then evaluates the behaviour value, the behaviour module also provides information regarding the behaviour's required resources. Competition of activation values is done in the following order. First, the behaviour with the highest activation value is selected and then if there still remain additional available resources, another competition is conducted between the remaining behaviour modules, which can use any remaining resources. By continuing to select behaviour modules until there are no remaining resources available, the behaviour control system can execute multiple behaviour modules that use different resources in parallel. A tree-structure is introduced to coordinate many behaviour modules. Usually a behaviour can be naturally divided into multiple sub-behaviours. For example, as shown in figure 12, a 'dialogue behaviour module' can be decomposed into a 'search the target (a human) behaviour module', 'go close to the target behaviour module' and a 'talk with the target behaviour module'. The tree-structure allows a behaviour designer to develop a situated behaviour module easily by elaborating the behaviour from the top of the tree to the leaf level.

Another advantage of the tree-structure is in sharing the behaviour's target. Assume that two different behaviours have to be executed in parallel. The first behaviour is the 'dialogue behaviour tree' whose target object is a human to talk with, and the second behaviour is 'play with a ball behaviour tree' whose target is a ball to play with. The target identifier of the face is commonly shared with the behaviour sub-modules in the 'dialogue behaviour tree' and the target identifier of the ball is also commonly shared with the behaviour sub-modules in the 'play with a ball behaviour tree'. This mechanism enables concurrent execution of multiple behaviours whose targets are different from each other. Thus, resource management using a tree-structured architecture efficiently achieves the concurrent execution requirement.

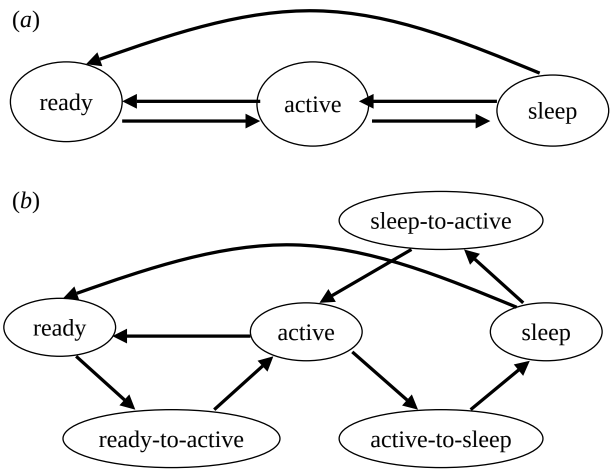

Figure 13. State transition of a situated behaviour module; (*a*) simple version and (*b*) revised version.

(iii) State management of the situated behaviour modules: in order to achieve the behaviour interruption and resume requirement, we consider that there should be at least three states for the behaviour modules, which are 'ready', 'active' and 'sleep' as shown in a simple version in figure 13*a*. All behaviours are initialized as 'ready' at the start of execution. If the activation level of a behaviour module is sufficiently high to warrant selection, then the behaviour control system changes the state of the selected behaviour module to 'active'. Now the action functions of the behaviour modules with an 'active' state are called so that the proper behaviours are executed. If the execution of the selected behaviour module finishes properly, the system changes the behaviour's state from 'active' to 'ready'.

Now assume that the situation changes while some behaviour modules are being executed, and a behaviour module with a much higher activation level, which may be an emergency behaviour, needs to be executed. Then, the system changes the state of the previously executing behaviour module from 'active' to 'sleep' (not 'ready'). After finishing the emergency behaviour, the system changes the 'sleep' behaviour module back to 'active' so that the behaviour module can resume its action function upon returning from its suspended condition.

For convenience, we further introduce the additional states, 'ready-to-active', 'ready-to-sleep' and 'sleep-to-active' as shown in figure 13*b*. These additional states are used for natural interrupt handling of behaviours. Assume that SDR-4X is talking with person-A (using the dialogue behaviour module), and then person-B calls to the SDR-4X from the left-hand side of the robot. The behaviour control system changes the state of the dialogue behaviour module to 'sleep', but it is more natural for the humanoid to first say, 'just a moment please' to person-A. In general, we need an action sequence before a behaviour module goes to sleep. In order to achieve this, the behaviour control system changes the 'active' behaviour module to 'active-to-sleep' state, where this transition action sequence can be executed before the module goes to sleep. Similarly, 'sleep-to-active' state can be used to say such things as 'sorry for keeping you waiting' when SDR-4X finishes the task for person-B, and then returns to conversing with person-A.

(*c*) *Designing behaviours for QRIO*

Let us return to the issue of designing behaviours for the architecture described above. Chiefly, we have to design behaviour modules in the behaviour control module part, involving the design of the behaviour tree structure, and the monitor functions and the action functions for these behaviour modules.

Regarding the action functions, we need to design the behaviour tree structure as seen in figure 12. Then, we have to design the monitor functions and the action functions in the behaviour modules (figure 11).

Regarding the monitor functions, it is difficult to design the computation of the activation level that depends on both of the external stimuli and the internal variables, as it depends on how to change the internal variables when a robot executes the corresponding behaviour. This is difficult to program beforehand. We need a learning mechanism for determining the monitor functions in the real world. This issue is addressed in a later section.

4. Handling unknown objects and words

When we consider a real world environment when designing the software, it is difficult to define in advance all the objects that a robot will encounter. It becomes necessary for the robot to learn unknown objects. Similarly, it is necessary for a robot that speaks natural language be able to learn the meaning of new or unknown words when operating in the real world.

Using Hidden Markov Model technology, we realize unknown word acquisition (Fujita *et al.* 2001) so that we can provide a name to an unknown object. This is a so-called physically grounded symbol because the symbol of the target object is grounded to the physical world through the perception channels.

Unknown word acquisition has been studied by various researchers (Roy & Pentland 1998; Iwahashi & Tamura 1999; Kaplan 2000); however, there are no studies regarding what kind of behaviour should be applied to the newly acquired object, not by command but by autonomous behaviour generation. We proposed a method to make an association between a visually acquired object, an acquired name by audition, and the change of the robot's internal variables, so that the robot can execute a proper behaviour when the object is presented. This association can be learned by trying to execute various behaviours to/with the object, to obtain the associated change of the internal variables.

Assume a robot knows the triple of behaviour (Beh), a target object (Target), and the change of internal variables (DeltaInt), and the monitor function of the behaviour module described in §3 can compute the activation level by estimating the internal variables after a robot executes the corresponding behaviour. Thus, it can be considered that the target object is grounded to the internal variables. Alternatively, the meaning of the target object can be defined as how much the internal variables change. For example,

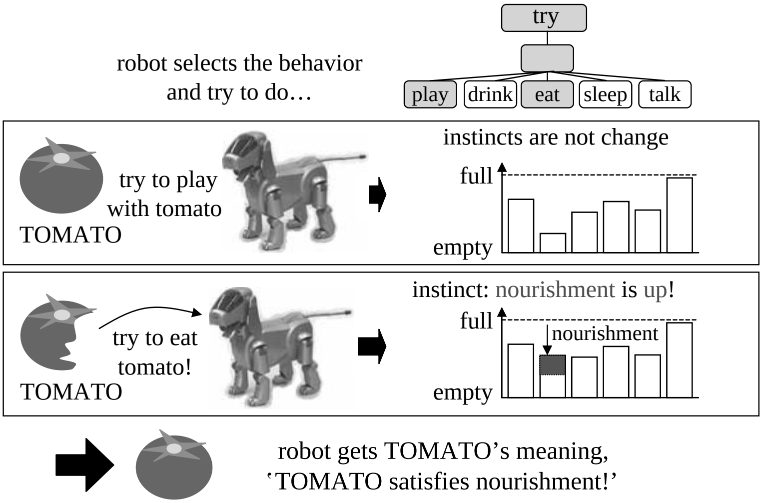

Figure 14. A concept of emotionally grounded symbol.

as shown in figure 14, if the eating behaviour applied to a particular target causes a change in the value of the 'nourishment internal variable', then it can be considered to be 'food'. Although we did not explicitly describe the meaning of eating behaviour and its relationship to the target object, the robot acquires the meaning of the behaviour and the object by the association of the triple (Beh, Target, DeltaInt). Since the internal variables are used to generate emotions as well, we call the concept as 'emotionally grounded symbols' (Fujita *et al.* 2001; Arkin *et al.* 2003), and we call the resulting architecture the 'EGO architecture' (Fujita *et al.* 2003; Hoshino *et al.* 2004; Tanaka *et al.* 2004; Sawada *et al.* 2004*a*,*b*).

5. Intelligence dynamics

Intelligence dynamics is a field of research activities for the understanding and realization of 'intelligence' instead of symbolism that is the hallmark feature of conventional artificial intelligence (AI). Recently, many researchers in various fields pointed out problems of traditional AI and started new research approaches towards 'intelligence'. These have been independently developed in brain science (Kawato 1999; Atkeson *et al.* 2000; Haruno *et al.* 2001), cognitive science (Varela *et al.* 1991; Pfeifer & Scheier 1999), psychology (Reed 1997), robotics and AI (Asada *et al.* 2001; Tani 2003). Our aim in proposing 'intelligence dynamics' is to make breakthroughs in the study of 'intelligence' by further integrating these activities over the various research fields. The main features of this approach are (1) embodiment, (2) dynamics and (3) constructive approach.

(i) *Embodiment.* Recently many researchers pointed out that it is necessary for 'intelligence' to have a body interacting with environment. This approach insists that the cognitive process should be described with both the neural/brain system and the environment. On the other hand, traditional AI usually insists that the cognitive process resides only in the brain.

(ii) *Dynamics*. The dynamical systems approach emphasizes that the cognitive process should be described with both bottom-up of sensory-motor dynamics and top-down of abstracted pattern dynamics. Then, the competition and cooperation of the bottom-up and the top-down dynamics naturally make global dynamics as cognitive process. On the other hand, traditional AI usually describes the top-down cognitive process by symbols and logic, which are difficult to handle competition and cooperation with the bottom-up of sensory-motor signals.

(iii) *Constructive approach*. The constructive approach asserts that in order to understand a function of the brain and its cognitive processes, we should build a body to evaluate the resulting hypotheses, theories and models. On the other hand, conventional brain science is only anatomical and analytical. Conventional cognitive science is also analytical, but recently they have also begun using a constructive approach.

Let us briefly compare intelligence dynamics and conventional AI. What is intelligence as studied in conventional AI? Originally the goal of conventional AI was to realize human-level thought and human behaviour (Charniak & McDermott 1985). However, the main approach to the goal focused on logical reasoning and logical behaviour. Therefore, they mainly employed symbolic representations and their manipulations by logic formula. Starting by building knowledge using symbolic representations and logical equations, they tackled the problem by making symbol representations of the problem and manipulating the resulting symbols based on logical formulae. Natural language is also coped with in a similar way. A word sequence is represented as symbols and is analysed based on a representation of grammar rules. The system then generates the correspondence between the words and categories such as subject, predicate and so on. The meaning of the symbol is composed of the leaf and frame representations.

There are well discussed concerns in the use of the conventional AI approach as described above, some of which include the frame problem and the symbol grounding problem. The frame problem insists that it is difficult or impossible to describe the real world with symbol representations, because the representational complexity becomes explosive when we consider the dynamically varying real world. However, symbolic representation is very powerful in limited static worlds such as chess. The fact that a computer chess program using conventional AI beat the human world chess champion in 1997 shows the usefulness of the conventional AI.

Intelligence dynamics emphasizes relations among observed, predicted and recalled time sequences in sensorimotor space, which are caused by interactions between a body and environment. 'Intelligence' must be described by these relations. Regarding dialogue with natural language, intelligence dynamics emphasizes the levels where various kinds of intentions such as 'drawing attention' and 'shared attention' are carried out in a non-verbal manner. These levels are acquired or self-organized through interactions between a body and its environment, including the presence of humans. From self-organization of these levels, we believe that verbal interaction could emerge under some social constraints, where physical and emotional grounding are achieved. However, we also recognize that this remains a big challenge.

Another important factor in intelligence dynamics is imitation (Kuniyoshi *et al.* 1994). The importance of imitation is also emphasized in brain science with 'mirror neurons' (Rizzolatti *et al.* 1996) and in cognitive science as 'mimesis' (Inamura *et al.* 2004). The existence of mirror neurons implies that a human interprets another human's actions as actions by him or herself, providing an understanding of their meaning. Therefore, embodiment is important to understand the meaning of behaviours. Mimesis is defined as activities that the action patterns acquired by imitation are reused in the rehearsal of motions and in communications with others. Thus, mimesis emphasizes the importance of imitation which is a basic function of communication.

In summary, intelligence dynamics constitutes a research field for intelligence by emphasizing the importance of embodiment and dynamics. In intelligence dynamics, the intelligence is not symbolic representation provided by a programmer, but is acquired through interactions between a body and the environment including a human presence.

(*a*) *Our approach in intelligence dynamics*

There should be many and various approaches in intelligence dynamics. Here, we describe our approach. Simply speaking, our target is to realize an open-ended system where people do not become tired of interacting with the system. Therefore, we should not focus on the particular functions of the system, but should consider the entire autonomous system so that various behaviours emerge as an ever evolving system. Emergence of human intelligence from scratch is to simulate the history of a human evolution, which is too far removed from realization. Therefore, it is better to divide and consider functions acquired through evolution of living things and functions developed after it is born. We will use 'evolution' for the former and 'development' for the latter. We focus initially on functions acquired by development and try to set up functions acquired by evolution first manually, so that we could achieve our realization of the open-ended system.

To consider functions acquired by development and evolution, let us consider the following cognitive functions (figure 15):

(i) functions acquired by evolution, such as reflex and instinct behaviours,
(ii) development strategy acquired by evolution,
(iii) functions self-developed through interactions in the environment, and
(iv) functions acquired through interactions with a caregiver or with social constraints.

It may be difficult for intelligence to emerge without functions encoded in genes, however, and the evolution of human beings from primitive life is still poorly understood, and thus it is still unclear how all functions in our open-ended system will emerge. We allow for the design of functions such as reflexive behaviours and instinct behaviours.

In the development process, a living thing grows physically. The muscle power, weight and the length of arm and foot change, and in parallel the living thing acquires skills to control its body while growth continues. Similarly, sensors also increase in their sensitivities and resolution over time as well.

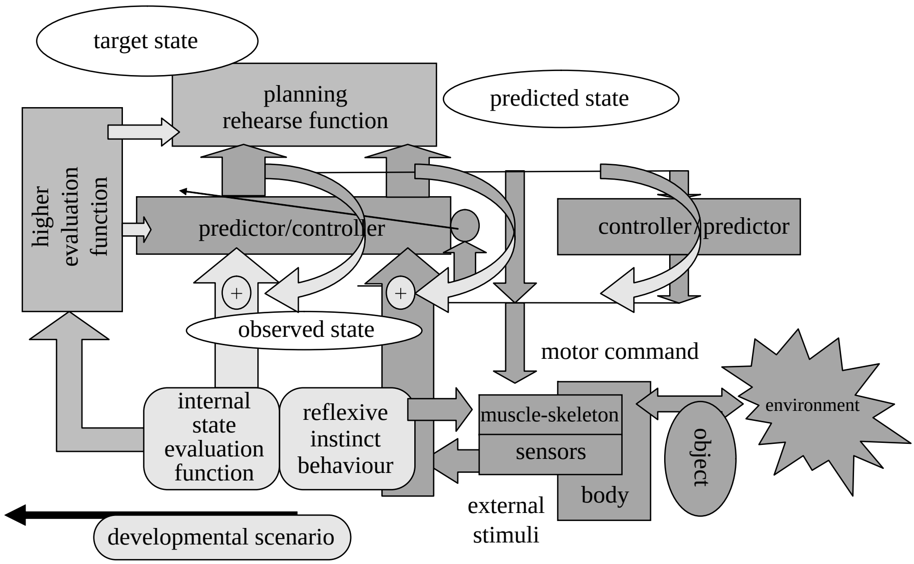

Figure 15. Proposed approach for open-ended system.

Moreover, targets of interest change according to growth. Namely, a development scenario such as the growth of the body, the performance of motors and sensors and related behaviour tendencies are encoded in the genes. The development scenario helps the efficiency and convergence of learning. Especially, the scenario helps in controlling the complexity of tasks in a proper order and timing. According to the scenario, if the system achieves this goal, then the system has interest in a new target, and so on. This is similar to controlling the complexity of the environment (Asada *et al.* 2001). The development scenario is considered as a result of evolution. We allow the setting of the development scenario to be done manually.

As we pointed out, according to the development scenario, while changing its targets of interest, freezing and defrosting of degrees of freedom and other factors, the system learns implicit models of its body and environment in self-development fashion through its interactions with the environment. If learning is based on evaluation functions set by the development scenario, some primitive motions and its sequences that corresponds to the evaluation function develop over time. It should be noted that the motivation of the learning is essential for the open-ended system to be ever developing. Thus, how to realize a mechanism by which proper motivations emerge is one of the main topics of our research.

As addressed in studies of reinforcement learning, a simple probabilistic behaviour selection algorithm such as softmax tends to fail in the real world because the size of the state and action spaces becomes huge. To help the convergence of learning, reflexive and instinct behaviours are important, because it limits the actions in particular situations usually leading to a good selection to yield a reward. In addition, the existence of a caregiver and the use of imitation as an instinct behaviour are also important for the convergence of the learning. Imitating a caregiver's behaviour helps in organizing the behavioural primitives that are used in social interactions. Imitation and teaching by a caregiver assist in the learning of the implicit models of its body and environment as well.

Thus, the functions associated with evolution such as instinct behaviour, the development scenario and imitation are important for efficient development, and in our approach these functions are allowed to be set manually.

(b) *Functions acquired by development*

By being given functions acquired by evolution, the open-ended system acquires models of its body and environment through interactions. However, as we mentioned above, it is not easy for the system to distinguish the body and environment model without any additional conditions. Y. Kuniyoshi (2004, personal communication) proposes the hypothesis that an embryo's movements in amniotic fluid with skin sensor feedback self-organize the body model in the brain. If the environment is pseudo-static, it may be possible for the system to learn the environment model by its motions. In any case, the development scenario is essential to self-organize separate models of body, object and environment.

While learning the body, objects and environment, the open-ended system has to have motivations for behaviours to learn the models. In a reinforcement learning framework, selecting actions to maximize the value function can be considered as behaviour motivation. In general, if we can set an evaluation function, then the system spontaneously behaves to maximize the evaluation function. To acquire these models, the error of the prediction by the models can be the evaluation function for the behaviours. In the same way, the error of the controller can be the evaluation function for the skill acquisition.

In order to build an open-ended system, which is ever developing itself, we examined flow theory (Csikszentmihalyi 1990). In flow theory, a human tends to choose proper challenging tasks according to his/her skills. For example, if a rock-climber has proper skills to challenge a vertical wall, namely, sometimes the climber succeeds to climb up the wall, but sometimes fails, it is a good challenging task according to the climber's skills. Then, the climber continues to try to challenge the task. However, if it is too difficult with the climber's skills, or if it becomes too easy, the climber does not like to challenge the task. Thus, a proper challenging task is necessary to continue learning.

In our proposal (Sabe 2005), we use FLOW theory for prediction, control and plan components. First, the system chooses some input/output variables of the prediction. Then, the system chooses an action based on some rules and trains the predictor with the observed results. If the error of the predictor decreases efficiently, the system continues to learn the predictor for the chosen variables. Otherwise, the system chooses other variables.

The learning motivated the efficiency of the improvement of the predictor learning, and the motivation could be considered as 'exploration motive', which is one of the intrinsic motives in psychology.

If the system succeeds in planning on how to reach the target state with a proper action sequence, then it can generate the action sequence in the real world without searching. During the executing of the action sequence, the controller can learn the trajectory of attractor, which is a mapping from sensor space to motor space. However, usually the predictor is not accurate enough to reach the target in the real world, therefore the predictor has to learn again with the results of the real-world execution. Then, the planner again plans a new action sequence to execute in the real world with the learning of the controller, and so on. Even if the predictor and planner generate the correct sequence, the controller may not be well trained. In such a case, the controller has to learn more corresponding to manipulation motive in the intrinsic motives.

The same things can be said for the planner. If the planning cannot be made for the chosen variables, it is still difficult for the system. The motivation for the planner learning can correspond to 'achievement motive' of the intrinsic motives.

Now we can summarize our approach for realization of the continuously developing open-ended system.

(i) Functions acquired by evolution are provided manually. Other functions must emerge according to the development scenario acquired by evolution.
(ii) Implicit body, objects and environment model are acquired by interactions.
(iii) The behaviours for learning and various goals emerge based on the evaluation functions acquired by evolution.
(iv) The behaviours for challenging proper problems are continuously being developed by the intrinsic motivations based on the flow theory.

6. Summary

In this paper, we discussed what is relevant for an ever-developing open-ended robot system. Describing our implementation of a pet-type robot AIBO and a humanoid robot QRIO (SDR), we presented the state of the art of autonomous robots. When we consider how to handle the acquisition of new objects, some mechanisms to generate a proper behaviour to the object are described. However, there remain many design issues in this approach.

We are interested in the current movements in many research fields, such as brain science, cognitive science and robotics. They emphasize that the interactions between embodiment and environment including humans are necessary for intelligence. We propose to call this set of research activities as intelligence dynamics, to break through to the realization of an ever-developing open-ended system, with which a human will not be bored when interacting with it.

Regarding these activities of intelligence dynamics, we describe our approach, which emphasizes the complete emergence of autonomous behaviour. It is still a conceptual level of description, but we will work further to accomplish our goal to achieve a breakthrough in the research of intelligence.

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