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Adaptive pick-and-place behaviors in a whole-body humanoid robot with an autonomous layer based on parallel sensor-motor modules

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Abstract

The aim of this research is to achieve adaptive carrying behaviors using the whole body of a humanoid robot; in other words to create humanoid robots' "pick-and-place" behaviors. We developed a small-sized whole-body humanoid robot. The robot's body consists of 22 DOFs, lots of sensors, an onbody micro processor network, and a wireless modem. The robot's brain consists of primitive sensor-motor reflex modules running in parallel as a lower layer and an event-driven planner that starts/stops appropriate modules as a higher layer. Using this system the robot can hold, lift up, and put down various objects without knowing its size, hardness or weight. We believe this work will be one of footholds toward achieving various whole-body behaviors of humanoid robots, especially carrying behaviors.

Keywords: Humanoid robot; Whole-body behavior; Reactive sensor-motor module; Autonomous layer

1. Introduction

Whole-body humanoid robots that have two arms and two legs are an integration of various technologies. Nowadays there are increasing demands for this type of robot because they have a potential to do numerous kinds of work; in other words, they are not limited to one type of work but are capable of various tasks. Research on whole-body humanoid robots has been increasing throughout the world [13,22,4,7].

In future, they may work in areas where people live, and help humans with various tasks. Among these tasks, one of the most important and most desired task would be to carry various objects. The variety of carrying forms must be rich. For instance, when a humanoid robot moves an object from one room to another, it may have to take an object out from under a table, carry it into another room, and place it on a shelf. Thus, the complexity involved in "pick-and-place" work of humanoid robots will be very different from that of industrial robots. Humanoid robots must obtain information about the objects they deal with through their sensors, plan how they carry the objects, and be adaptive and robust against unexpected disturbance during the behaviors. Although there have been some researches on object-handling (pick-and-place) by humanoid robots [11], almost all of them consist of actions not using the whole body but using one or both hands, and don't consider the weight of the object.

We aim at achieving various adaptive pick-and-place behaviors using the whole body of a humanoid robot. For this, we developed a small-sized humanoid robot which has many actuators and sensors. It can hold, lift up, and put down an object without knowing its size and weight, in adaptive whole-body behaviors.

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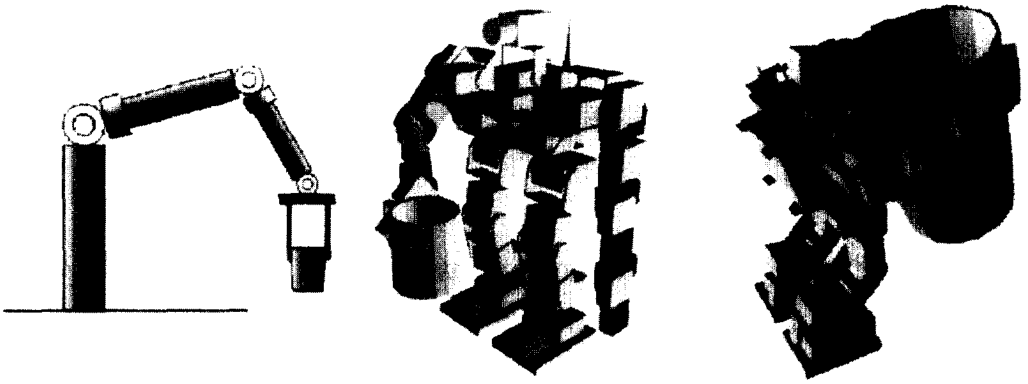

(a)
- Fixed to base
- Using only end-effector

(b)
- Mobile (no base)
- Using only end-effector

(c)
- Mobile (no base)
- Using whole-body

Fig. 1. Pick-and-place behaviors.

2. Pick-and-place behaviors by a whole-body humanoid robot

2.1. Humanoid robot

Robots have been working, separated from humans; for example in industry. In future, robots would work, sharing the space with humans; for example at office, or at home. Humanoid robots have the potential to help humans with various tasks. Recently, researches on humanoid robots have been increasing. In these researches, human-form robots have become able to walk, climb stairs [8], dance, etc. Now and in the future, the focus of the researches on humanoid robots will be more practical applications such as carrying a heavy object, or cleaning a room. Object handling is one of the key applications. Especially, it will be very important to use the whole body of the humanoid robot, even without knowing the properties of the handling object, and with adaptability, autonomy, and robustness.

2.2. Pick-and-place task

The pick-and-place task is a typical task of object-handling by robots. Object-handling by humanoid robots can be considered as a variation of pick-and-place tasks. There are two large differences between manipulators and humanoid robots in pick-and-place behaviors (Fig. 1). Firstly, humanoid robots do not have any fixed bases. Thanks to this, they can carry objects to a wide area. At the same time, they have to balance themselves. Secondly, humanoid robots can use their whole body to handle the object. By this feature, they have the possibility of handling quite a large object.

Fig. 1 shows the differences. In (a), which shows a traditional pick-and-place by a manipulator, the robot has a fixed base and uses only its end-effector. Fig. 1(b) shows a pick-and-place by a humanoid robot. Humanoid robot is not fixed to any bases, but in the figure, the robot uses only its end-effector. In Fig. 1(c), which shows a whole-body pick-and-place by a humanoid robot, the robot doesn't have any fixed bases, and uses its whole body to handle the object.

2.3. Characteristics and requirements of pick-and-place behaviors by humanoids robot

Humanoid robots' pick-and-place behaviors have following characteristics and requirements.

(i) *Objects of unknown weight, shape and hardness.* Usually a humanoid robot will not be told the weight, size and hardness of an object it must deal with. In environments such as office or home, there will be various kinds of objects the robot will have to carry. It would be best if the robot acquires the properties of the objects by itself.

To do this, the robot must be equipped with adequate sensors on its body. Especially, in a whole-body behavior which deals with an unknown object, force or torque information is crucial. Humans also make full use of this sort of information in dealing with heavy objects. At the same time, visual information is also important to distinguish the objects, etc. The robot should also have touch sensors and/or force sensors to detect the information about the contact with both the objects and the ground. Accelerometers and/or gyroscopes are necessary to know its posture, which cannot be known from model-based calculations when it carries a heavy object.

(ii) *Using whole body.* Although industrial robots only use their hands or grippers to pick up objects, a humanoid robot can use its whole body if needed, as is described in Section 2.2. Whole-body actions are the specialty and advantage for humanoid robots. By using the whole body they would be able to carry quite heavy objects that they cannot carry by using only their hands.

Whole-body object-handling by humanoid robots can be compared to whole-arm manipulation [19] or power grasping by multi-fingered robot hand. The resemblance is having multiple contact points at not only the end-effector but also the middle of the link. Researches on power grasping [2,23] is a good guide to the study. The difference is, as described in Section 2.2, that humanoid robots are not fixed to any bases. Humanoid robots can carry objects, and have to keep balance by themselves.

To realize whole-body behaviors, an adequate system architecture is needed. The research on grasping with multiple contact points gives a suggestion to the needed system architecture. We developed a system based on the combination of parallel sensor-motor modules, which makes it possible to create whole-body behaviors relatively easily.

(iii) *Efficiency.* The motion and the posture of the robots must be efficient enough to carry comparatively heavy objects. The robot might be unable to carry a heavy object which it could carry in an efficient motion. It is quite difficult for us to search a sufficiently efficient motion by analyzing the dynamics of both the robot and various objects, or by tuning parameters. An autonomous searching or planning method is necessary in conjunction with some learning method. As a result, the robot would have a rich variation of actions as well.

The robot does not even need to carry an object. The robot can push the object [14], the robot can stand up, tumble over, and lay down the object [20,21], and the robot can also use pivoting [1]. The possible varieties of object-handling behaviors by humanoid robots are so wide. In addition to searching an efficient motion of carrying, it will be also necessary to search what is the most efficient way to move the object. The proposed approach, described in Section 3.1, includes an architecture where some learning method can be applied in two levels.

(iv) *Various situations.* There will be various situations where the robot picks up or puts down an object. The object may be under a table, or may have to be put on a shelf. The robot will have to recognize the situation, and plan how it should carry out the task.

(v) *Mobility.* To carry an object, the robot has to walk holding (or pushing) an object. The form of walking should be different depending on the weight, size, or shape of the object. It should have either a variety of walking forms or an ability to acquire the necessary motion automatically.

The proposed architecture (Section 3.1) considers expanding the robot's ability to move. In Section 6, the possibility of achieving 'walking with holding an unknown object' using our approach is discussed.

(vi) *Adaptability and autonomy.* Although this point has been discussed, one of the most important features of this type of humanoid robot is the mechanism which makes the robot adaptive, autonomous, and robust against disturbance. For the robot will have to deal with various unknown objects and may receive various unexpected disturbances during tasks. For a robot to have these characteristics, the essential point is that the system includes a part in which sensory information and actuator information are directly connected and output is immediate in response to inputs. The architecture we propose (Section 3.1) includes a sensor-motor layer for this purpose.

2.4. The research goal

Although there has been an increasing number of researches on whole-body humanoid robots, there has been little discussion on how the robots balance when carrying a heavy object. The goal of the research is to realize the humanoid robots' whole-body pick-and-place behaviors. The robot will use its whole body cooperatively, adjust its posture autonomously, and have adaptability against disturbance. The robot will handle an object even if it doesn't know the precise weight, shape, and hardness of the object. The aim of the research is to discuss how to build this kind of robot, to develop a prototype, and to show what are important topics. In the following section, we describe how we try to achieve the discussed requirements.

3. How to achieve the goal

3.1. The robot's brain with an autonomous layer based on parallel sensor-motor modules

To realize adaptive autonomous robust pick-and-place behaviors, the system ought to have a mechanism which connects sensor and actuator information directly. Since Brooks suggested the subsumption architecture [5], there have been various proposals for realizing intelligence based on the combination or network of reactive modules [6,3,17]. Considering these architecture, we decided to make the 'brain' of our robot divided into two layers.

The lower layer of the brain consists of the primitive sensor-motor modules running in parallel. This layer has primitive autonomous reflex functions, such as balancing, or force adjusting. Each module inputs some sensor information, calculates using a certain formula, and outputs differentials of some joint angles. Each output is added to the current joint angle.

The upper layer of the brain controls the combination of the sensor-motor modules in the lower layer. This layer starts and stops modules in the lower layer in event-driven style. This layer also gives a formula to each module, which realizes an autonomous function. When an event occurs, the upper layer stops some modules and start some other modules. By activating the appropriate modules with the appropriate parameters at the appropriate time, a whole-body behavior is realized.

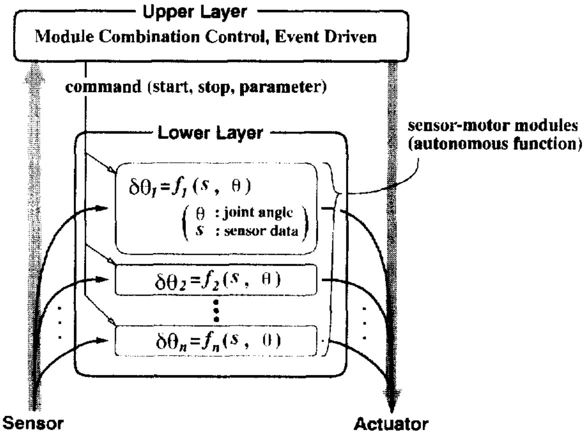

Fig. 2. Two layered architecture in the robot brain.

This architecture is shown in Fig. 2. By using this architecture, we can make each primitive function without having to consider other functions the robot ought to have, and when a new function is needed we can just make the function individually and add it to the system. Since whole-body behaviors of a humanoid robot often consist of combinations of many primitive functions, we can build the behaviors by making each function and combining them. This architecture provides a kind of answer to the requirements discussed in Section 2.3(ii). If we would like to expand the mobility of the robot (Section 2.3(v)), we can make a function 'walking' as reflective sensor-motor modules and add them to pick-and-place behaviors, as discussed in Section 6. The system also provides adaptability, autonomy and robustness (Section 2.3(vi)), since sensor-motor modules in the lower layer can make quick response to the actuators according to the sensory information.

As for the efficiency (Section 2.3(iii)) and planning according to the recognized situation (Section 2.3(iv)), learning should be introduced in the system. Learning can be applied to both layers of the system. In the lower layer, there can be some ways to derive the expression of each sensor-motor module. Though in this paper we derive the expression by analyzing and parameter tuning, when the efficiency or optimization is considered, learning methods are effective. Learning is also effective when searching appropriate combination of the modules. This is a learning in the upper layer.

3.2. Remote-brained approach

In order to implement the system, we took the remote-brained approach [9,10]. The brain of the robot is conceptually and physically separated from its body. They are connected through a radio link. The brain receives all sensor information through the both radio modem and video transmitter, and sends all actuator information through the radio modem. Using this approach, we can develop the brain without thinking of various restrictions the body may impose.

The body of a humanoid robot generally has many actuators, and should be equipped with many sensors as well, as is discussed in Section 2.3(i). There must be a structure which will realize the route of sensor and actuator information, like the nervous system of a creature. The structure we developed is described in Section 4.2.

4. Development of the humanoid robot system

4.1. The robot's body

We developed a humanoid robot that has 22 degrees of freedom (DOF). The 22 DOFs consist of five DOFs at each leg, five at each arm and two at the head. The height is about 44 cm and the weight is about 4.1 kg. All actuators are radio control servo modules. The servo module has a geared motor and a proportional position control servo circuit inside. We can see the approximate torque the motor outputs, by watching a motor driving signal (PWM format) in the circuit. The signal is almost proportional to the torque as shown in Fig. 3, where S3801, S9303, and S9204 are the types of servo modules. Thus we can obtain torque information of all actuators, without attaching any other components.

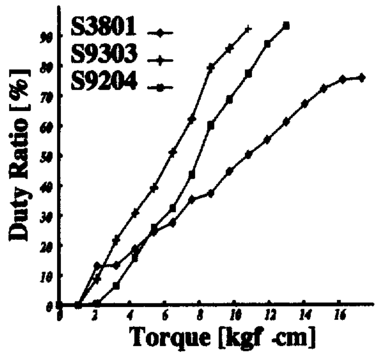

Fig. 3. The relation between torque and motor driving signal.

Four force sensors are attached on the sole of each foot, to detect the reaction force from the ground and the center of the force, which are used to detect the zero moment point. A three-axes accelerometer is attached on the chest, to detect the direction of gravity. A CCD color camera is attached on the head. The specifications of the actuators are shown in Table 1.

4.2. Onbody processor network

When realizing our system, a key point was the route of sensor and actuator information. This may be compared to the nervous system of a creature. We realized the nervous system of a robot by constructing an onbody processor network [12]. Network nodes are embedded in various parts of the body and connected with actuators and sensors locally (Fig. 4). This network collects sensor information from the whole body, and distributes control signals to the whole body. Using this network, it is easy to attach and detach sensors and actuators.

To construct this network, network nodes must have many I/Os for sensors and actuators, and an

Table 1
Specification of servo motor modules

Parts	Specification	Value	[unit]	Position
RC-Servo (S3801) Futaba	Maximum torque	14.0	[kgf cm]	ankle (pitch,roll), knee (pitch), crotch (pitch), shoulder (pitch)
RC-Servo (S9303) Futaba	Maximum torque	7.2	[kgf cm]	crotch (yow), shoulder (roll,yow), elbow (roll)
RC-Servo (S9204) Futaba	Maximum torque	12.6	[kgf cm]	wrist (roll)
Torque sensor		cf. Fig. 3		all joints

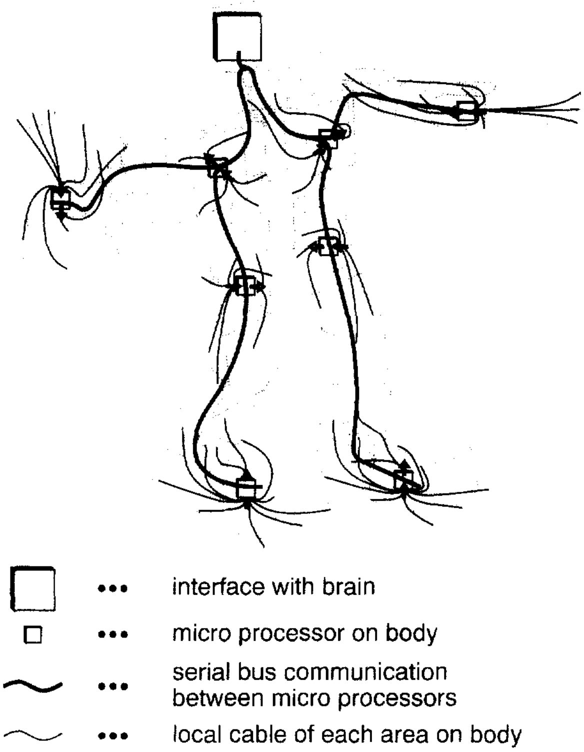

Fig. 4. The concept of onbody processor network.

inter-processor communication channel. Under these conditions, we selected Hitachi H8/3334YF-ZTAT, an 8-bit micro processor. Table 2 shows the specifications of the processor. An important feature of this processor is the I^{2}C-bus (Inter-IC bus) Interface, a multi-master serial bus interface designed by Philips [18]. The bus transfer rate is up to 400 kbps. Using our software library, it is about 140 kbps.

Table 2
Specifications of H8/3334YF-ZTAT

Item	Specification
Clock	16 MHz (5V), 10 MHz (3V)
Flush memory	32 k
RAM	1 k
Timer	8 bit × 2, 16 bit × 1
Watch dog timer	1
PWM timer	2
SCI	2
I^{2}C	1
A/D	10 bit × 8
D/A	8 bit × 2
I/O prot	I/O × 58, Input × 8
IRQ	9

Fig. 5 shows two kinds of small microprocessor boards we designed. The left one is a trial board. We made this kind of boards by way of trial and tested several types of trial boards, and then designed the right one. The right one is embedded in each ankle and each shoulder of the body. Fig. 6 shows the arrangement of the boards on robot's body. Through the radio modem, the network and remote brain are communicating.

4.3. Implementation of the brain

The two layered architecture in the brain is implemented in the remote workstation. The lower layer, the autonomous function layer, is implemented using multi-thread C programming. Sensor-motor modules, which work as autonomous functions, are dynamically assigned to the threads, and communication between the threads (modules) depends on global variables with mutual exclusion locks. Each module in this layer inputs sensor information, makes a calculation by a given function f (see Fig. 2), and outputs actuator information. The actuator information is output in a differential form ($\delta\theta$). The outputs from all modules are added to the global actuator data.

The upper layer, the combination control layer, is written in object-oriented Lisp, EusLisp [16,15]. This layer watches sensor values to detect an event, and to decide when and which module to start or stop. The interface between the layers is based on socket communication.

4.4. Whole system

Fig. 7 shows the whole system. Local processors on the body are connected to the onbody network, and communicating through radio modems. The brain consists of two layers. The lower layer is an autonomous-function layer based on parallel sensor-motor modules, and the upper layer controls the combinations of the lower modules.

5. Experiment

Based on the architecture described in Section 3.1, we developed adaptive whole-body pick-and-place behaviors in the actual humanoid robot we developed.

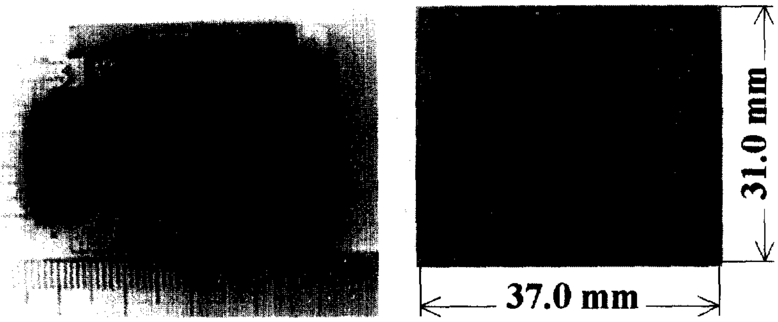

Fig. 5. Onbody processor boards (trial and distributed).

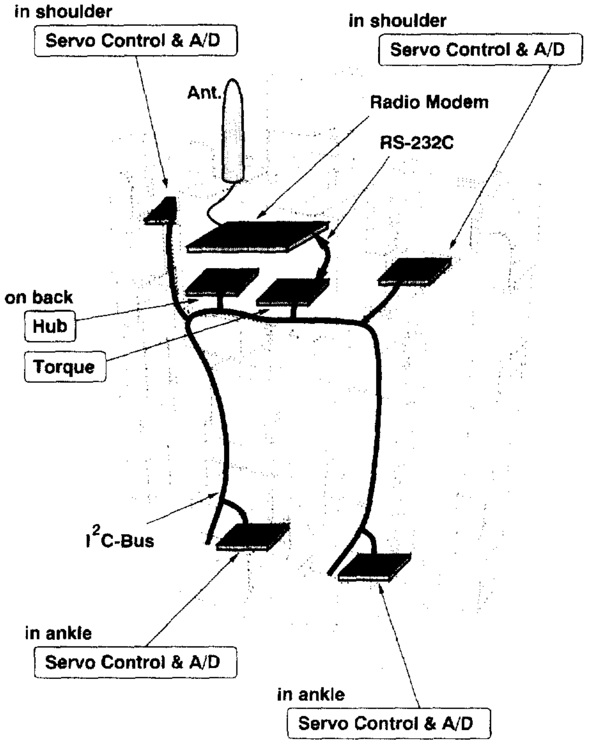

Fig. 6. The arrangement of processors in the onbody processor network.

In this section, the realization of the behaviors is described.

5.1. Hold, lift up, and put down an unknown-weight object

Fig. 8 shows examples of combinations of the sensor-motor modules in the lower layer of the robot brain. A function 'hold' consists of six modules; each shoulder, each elbow, and each wrist. A module watches the torque and angle of the right shoulder, and outputs a value to adjust the torque. Each module watches each torque and angle. By combining these similar modules in shoulders, elbows, and wrists, the function 'hold' is realized. A function 'balance' is done in the similar way. A module watches the torque of both ankles, and outputs a value to keep balance. By the combination of similar modules dealing with knees and crotches, the functions 'balance', 'stand up', and 'lift up' are realized.

5.2. Sensor-motor modules in the lower layer of the brain

To develop adaptive pick-and-place behavior using the whole body, we made necessary functions to be run as sensor-motor modules in the lower layer. A few types of the functions are described below.

(i) *Function 'hold'.* The function 'hold' is realized by the combination of some modules. Each module adjusts the torque of each shoulder, each elbow, and each wrist, by proportional torque control using the following formula:

$$\delta\theta_i = G_{\mathrm{h}i} \cdot (\tau_i - r_i) \qquad (1)$$

where

- i is the joint number (shoulders, elbows, wrists),
- $\delta\theta_i$ is the joint angle (difference),
- τ_i is the sensed torque,

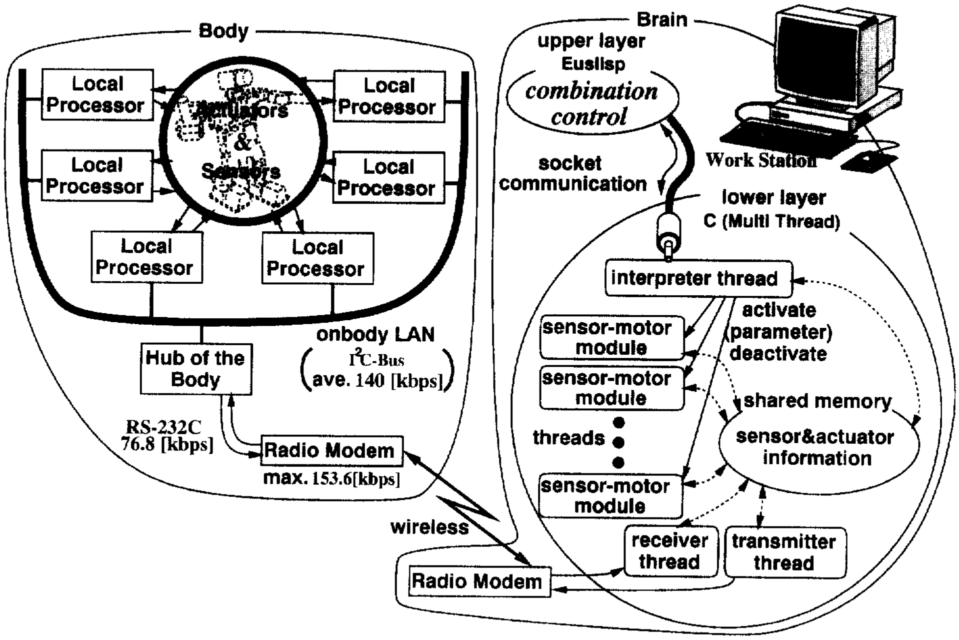

Fig. 7. The whole system.

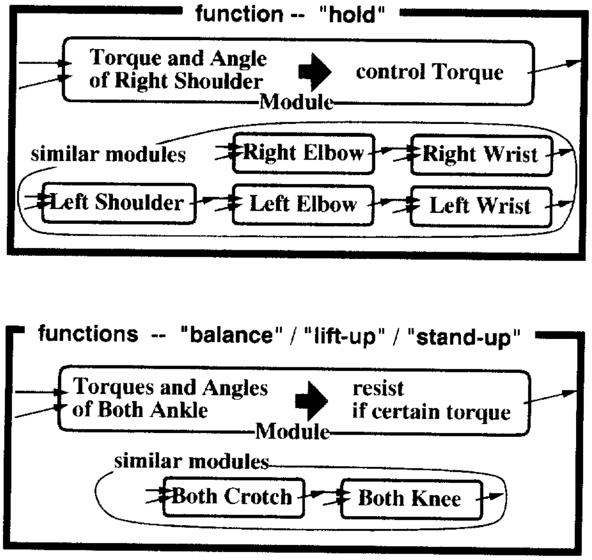

Fig. 8. Two examples of the module combination.

- r_i is the reference torque,
- $G_{\mathrm{h}i}$ is the gain (h indicates 'hold').

By this formula, the output torque of joint number i is controlled to the reference torque r_i. By running this kind of modules in shoulders, elbows, and wrists, the robot becomes able to hold an object without knowing the precise size or hardness.

Table 3 shows the values of the parameters $(r_i, G_{\mathrm{h}i})$ used in the experiment. These values are experimentally decided so that the robot could hold an object without slipping and also would not crush a soft object.

(ii) *Function 'balance', 'lift up', and 'stand up with object'.* How can the robot keep balance with an unknown-weight object? In Fig. 9, G' is the centroid of the robot only, and G is the centroid including the object. When G is located at the front of the crotch joint θ_1, if the joint rotates counterclockwise in the figure, G moves to right above the joint-axis. When G is right above a joint-axis, the joint needs to generate little torque, and can balance at least at the upper part than the joint-axis. When lifting up an object from the floor after holding, the robot can use this module. By using the module the robot can lift up the object from the floor. And by starting the similar modules in not only the crotches but also knees and ankles, the robot keep balance and stand up with the object.

Table 3
Parameters of modules for the function 'hold'

Parameter		Joint		
i	(Joint name)	Both shoulders	Both elbows	Both wrists
r_i	[kgf cm]	4.88	2.92	1.97
$G_{\mathrm{h}i}$	[degree/kgf cm]	0.273	0.175	0.169

Table 4
Parameters of modules for the functions 'balance', 'lift up', and 'stand up with object'

Parameter		Joint		
i	(Joint name)	Both crotches	Both knees	Both ankles
T_i	[kgf cm]	4.02	5.64	7.18
$G_{\mathrm{b}i}$	[degree/kgf cm]	0.181	0.123	0.0821

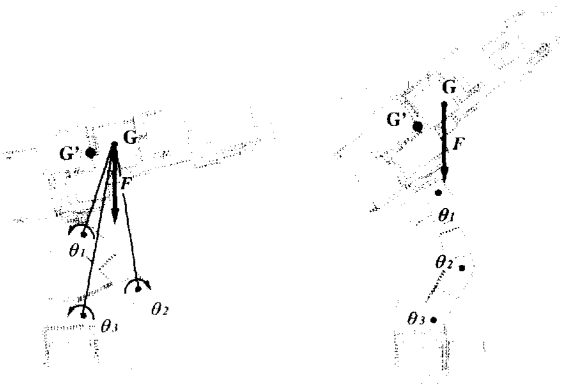

Fig. 9. Balancing with an unknown-weight object.

To realize this kind of modules, the following formula is used:

$$\delta\theta_i = \begin{cases} 0 & |\tau_i| \leqslant T_i, \\ G_{\mathrm{b}i} \cdot \tau_i & T_i < |\tau_i|, \end{cases} \qquad (2)$$

where

- i is the joint number (crotch, knee, ankle),
- T_i is the threshold torque,
- $G_{\mathrm{b}i}$ is the gain (b indicates 'balance'),

If it were not for the T_i, a vibration would occur.

Table 4 shows the values of the parameters (T_i, $G_{\mathrm{b}i}$) used in the experiment. These values are also experimentally decided so that the robot could keep balance and would not vibrate.

(iii) *Other functions.* In addition to above two types of functions, some other functions were made. Function 'squat' makes the robot squat to ordered extent in a given sequence. Function 'open-arms' opens both arms of the robot. Function 'keep-head' watches the joint angles of crotches, knees, and ankles, and adjusts the pitch angle of the head. If some other function is needed, we can make one or more modules so as to realize the function, and add it to the lower layer.

5.3. Whole-body behaviors by the combination of the modules

Whole-body behaviors are organized in this way by various primitive modules running in parallel ('hold', 'balance', 'lift up', and 'stand up', appropriately). As a result, the humanoid robot can squat, hold an object without knowing the size and weight, lift it up, stand up, and put it down. These are the pick-and-place behaviors of a whole-body humanoid robot.

The upper layer is watching certain sensor data, in other words, watching an event. For example, it detects when

- holding is completed (watching arm torque),
- lifting up is completed (watching crotch torque),
- standing up is completed (watching knee angle),
- holding object is taken by somebody (watching shoulders torque).

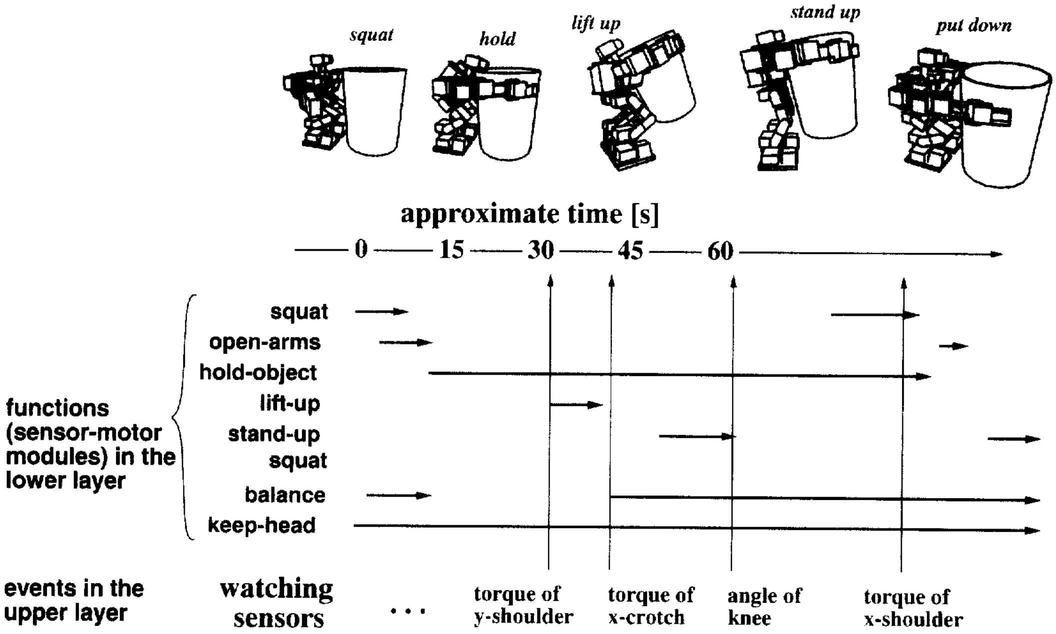

Fig. 10. Module start/stop sequence during holding and lifting up an object.

Fig. 11. Holding objects of various size, hardness and weight.

When an event occurs, the layer starts another appropriate module. Fig. 10 shows an example of a module start/stop sequence when the robot holds, lifts up, and puts down an object. The combination changes of the modules are dependent upon the sensor information which the upper layer is watching. The changes are driven by events.

5.4. Experimental results

Fig. 11 shows two scenes where the robot has lifted up two objects of different size, hardness and weight, using the same program. In the photographs the robot is bending backward at a different angle, to balance with the weights of the objects. In the left it holds a

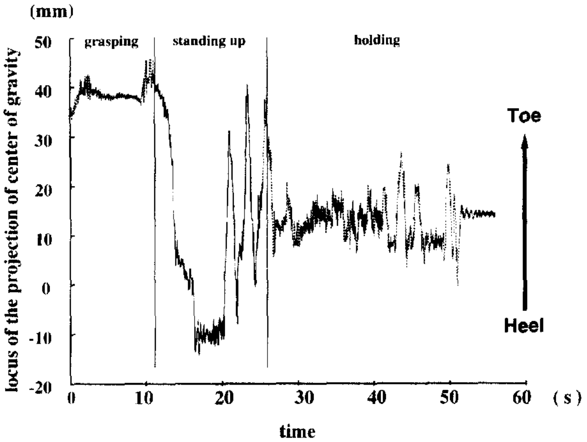

Fig. 12. The locus of the center point of force at sole (left leg).

soft cushion (100 g) and in the right it holds a steal trash can (500 g).

Fig. 13 shows the sequence photographs of an experiment, where the humanoid robot squats, holds a trash can, and lifts it up.

Fig. 12 shows the locus of the center point of force (projection of the center of gravity, along the major axis (lateral plane)) at the sole (left leg), which is measured by a force sensor of the sole, during the experiment. The vertical axis shows projection of the center of gravity along the major axis of the foot, and the horizontal axis indicates time. The length of the robot's foot is about 115 mm.

The line between grasping and standing up indicates the moment when the held object rises up from the floor. At the moment, the projection of the center of gravity is located nearest to the toe. Then, by function 'balance' (Eq. (2)), the center of gravity comes to approximate the center of the sole.

During standing up, the figure shows that the projection of the center of gravity moves forward and backward, by the modules of function 'balance' of knees ankles, and crotches. The movement is limited in the small area (in about 50 mm), as is seen in the figure. This shows that the robot is stably holding an unknown-weight object.

Fig. 14 is the log of the offset angles of servo motors, which shows the output torque, of ankle, knee, and crotch (left leg) during the same experiment. The line between grasping and standing up indicates the moment when the held object rises up from the floor. The torque of crotch joint, which was increasing until the moment, then begins to decrease by the function 'balance' (Eq. (2)). About four seconds later after the rising up, the crotch torque comes to the minimum torque by the function 'balance'. During this four seconds, the center of gravity of both robot's upper body and the object is moving to right above the joint axis of the crotch. Thus, the robot is able to lift up an unknown-weight object.

The line between standing up and standing shows the time when the robot is standing up holding the object. At this moment, the absolute torque of ankle and crotch is a little larger and that of knees is a little smaller. It can be said that this is because, at the moment, the center of gravity is located to right above the joint axis of knees, and also it's not precisely above the joint axis of ankles and shoulders. (See Fig. 9.) On the other hand, just before or after the moment, the absolute torque of knees is larger, and that of ankle and crotch is smaller. By doing this way, the sum of the absolute torque of all joints gradually becomes small, and the robot can transit to an efficient holding condition. Fig. 15 shows that the robot adjusts by itself adapting to a unexpected disturbance. In this figure the robot can balance even if the weight of the holding object changes.

6. Summary, conclusion and future work

Whole-body object-handling by a humanoid robot was realized. The two-layered system of the robot brain was developed. Autonomous function layer, the lower layer, consists of primitive sensor-motor modules running in parallel. The upper layer controls the combination of the lower modules running in parallel. The upper layer controls the combination of the lower modules in event-driven style. The advantages of this system are

(i) being able to deal with unknown-propertied objects by many sensor and parallel sensor-motor modules;
(ii) being able to use the whole body by the combination of parallel sensor-motor modules;
(iii) having adaptability, autonomy, and robustness thanks to the lower layer in which the sensory information is directly connected to actuator information;

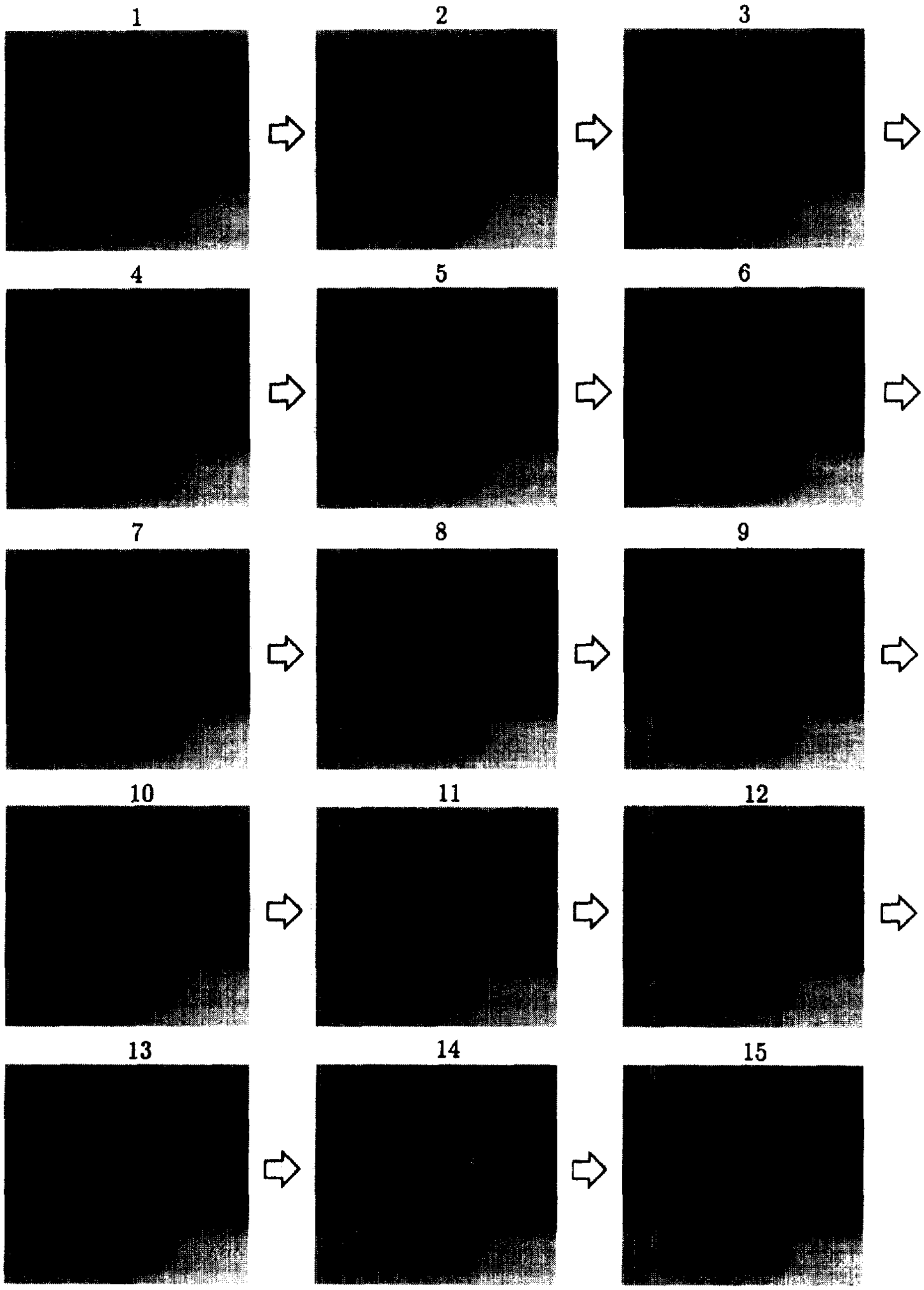

Fig. 13. The humanoid robot squats, holds an object, and lifts it up.

(iv) having the possibility to apply the learning method to both the module expression and the module combination, which enables the robot to search efficient motion and to plan appropriate behaviors according to various situations;

(v) having the possibility to add any functions so long as the function can be described as sensor-motor modules. We have developed the behaviors of stepping in a place using information of force sensor attached on the sole of each foot. This

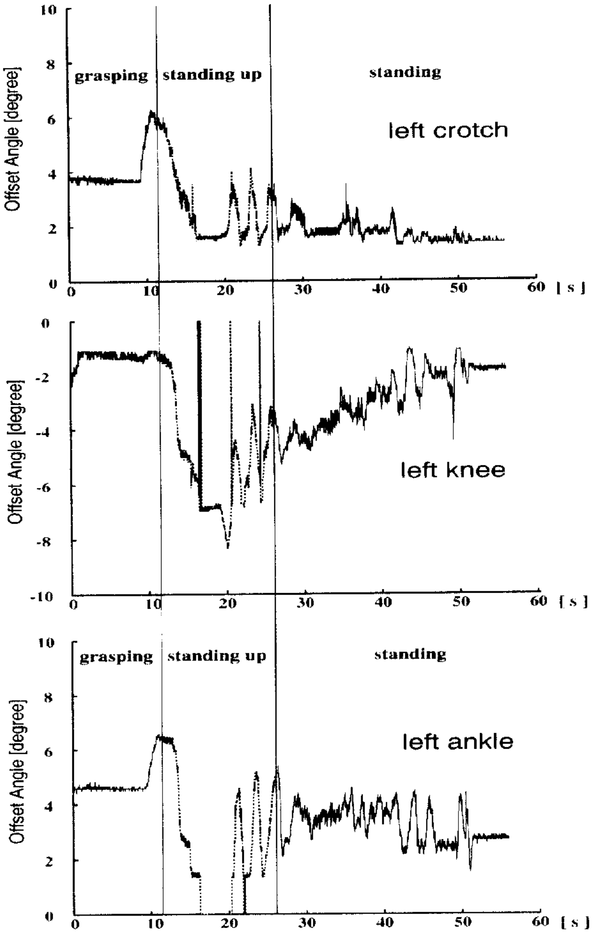

Fig. 14. The offset angles of legs during holding and lifting up a bucket (left leg).

behavior is made as a sensor-motor module, which can be combined with the modules described in this paper. Current problems are that the motors' maximum torque is not enough, and because of the delay of communication the gain G_{bi} has to be set small; if it were not small, the robot would become unstable.

A 22-DOF humanoid robot with onbody processor network was developed. Some experiments to evaluate the approach were described. By using the described approach, the robot is able to hold, lift up, and put down an object without knowing the weight, size, and hardness, and also with adaptability, autonomy, and robustness all the time.

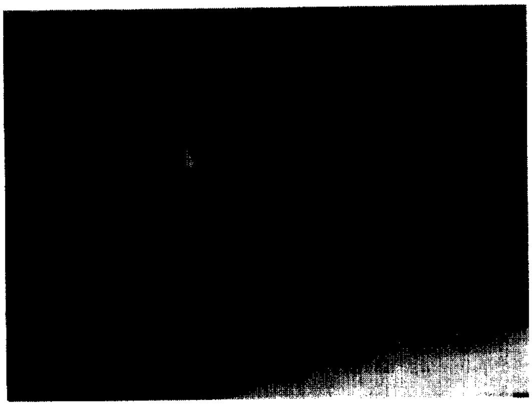

Fig. 15. A cup of water is being poured into the cup which robot holds.

We are trying to develop more variations of behaviors, to achieve various carrying forms. There are still lots of problems to be solved: walking while holding an object, working out strategies for picking or holding, graspless manipulating such as pushing, pivoting or tumbling over, and so on. We believe this work will be one of the footholds toward these subjects. The next tasks in this research include embedding the sensor-motor modules into the onbody network, considering collision of the modules, and using learning methods in both the expression of function modules and the combination of the modules.

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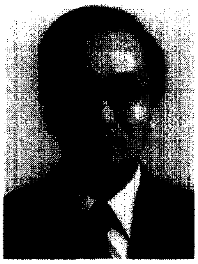

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