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Planning-driven Behavior Selection Network for Controlling a Humanoid Robot

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Abstract— **A humanoid robot has uncertain sensor data, and produces larger errors arising from the control process than other types of robot having wheels. The humanoid robot for providing service should not only generate proper behaviors to accomplish goals in unstable environments, but also consider flexible scalability to reflect demanding user's requests. We propose a control system based on planning-driven behavior selection network so as to generate autonomous behaviors of the robot rapidly and suitably. In this paper, the behavior selection network, one of behavior-based methods, is modularized considering sub-goals. The STRIPS planning makes a sequence of robot behaviors automatically by controlling the modules. The proposed system can control the robot to cope with the various environments, as well as to achieve goals according to the user's demand. Moreover, since the BSN and STRIPS planning structures are internally independent, the proposed system is scalable flexibly to increasing user requests. We confirm the usability of the proposed system by performing several test scenarios with NAO robot. Experiments show that the proposed system is able to make a behavioral sequence to fulfill goals appropriately, and can create behaviors of the robot in the various situations. We can also confirm an accuracy of 85.7% through applying the proposed system in the real world.**

Keywords— Hybrid control system; Humanoid robot; Behavior selection network; STRIPS planning

I. INTRODUCTION

Humanoid robots have very similar joint structures in human and have been developed to give convenience to human [1]. They are optimal robot platforms that can provide service by being able to do on behalf of the user [2]. In this regard, even though there are a lot of research on these humanoid service robots, creating robust reactions of the robot in the unstable condition using insufficient sensor data to achieve user's requests is still one of difficult problems. Furthermore, the humanoid robot having lots of joints requires more control for responding to the user's demands than any other robot types do, and the robot should be able to perform added requirements; why it needs high-level control systems and should consider scalability. We focus on generating behaviors to address these issues.

There have been much studies on behavior control systems for the robots, and most of them proposed systems which made use of two commonly used methods: reactive behavior-based and plan-based. Reactive behavior-based systems choose actions locally, and can quickly and flexibly cope with the changing world, but it cannot accomplish the goals including compound tasks [3]. On the other hand, plan-based systems, unlike the former, create optimal sequences based on the whole situation, but cannot act for the altering environment. Hence, it is more suitable to resolve the complex problems for long-term goals. With this, a hybrid control system composed of both behavior-based and plan-based methods has been proposed to overcome this limitation. This is a main motivation of the proposed system. Many researchers have tried to devise appropriate hybrid control systems for service robots. Nevertheless, most of them do not consider sufficiently scalability and autonomous behaviors under the condition of the uncertainties in the real situations.

A behavior selection network (BSN) is based on reactive behavior-based system, and has flexibility to run the diverse environments rapidly while having a goal-oriented feature unlike most reactive systems [4]. However, the BSN cannot make a behavioral sequence of the robot to solve complex problems because of conflicting goals. Additionally, the number of behavior nodes in the BSN according to the users' request is added continually when they want to get more service from the robot, and the vastly enlarged nodes lead to slow reaction time. In other words, it has a limitation that cannot resolve various user's requirements. Solving these problems is a main contribution of the proposed method. We propose an approach that controls behaviors of humanoid robot based on a conversation using the hybrid control system, which combines a BSN to rapidly cope with the inconsistent situations with STRIPS planning to achieve a user's requirements and to work out simple problems as well as complex problems.

For responding to requests containing complex problems, we employ the modular behavior selection network (MBSN) which has only one goal. We decompose long-term goals into sub-goals to solve the problem and respond to the requests by controlling a sequence of each module having a sub-goal. For this, the module replaces a primitive action of the original STRIPS planning. At this point, we do not need to consider relations about each module because the planner can configure a sequence automatically using the independently defined conditions of the module. Accordingly, the proposed system has benefits that can be described as explicit structure and that make more effective scalability. In this paper, the BSN and the

STRIPS planning will be modified more flexibly and efficiently to attain the user's requests using the way, which is to reconstruct when the module of BSN fails to realize the sub-goal. Thus, this system copes with the failure of sub-goal efficiently by managing the failure, and it helps the robot generate autonomous behaviors.

Not only to evaluate the accuracy of the proposed system in the real world, but also to estimate the suitably responsive behavior in the changing world, we implement and evaluate our approach in NAO robot which is a kind of the humanoid robot developed by a French company, Aldebaran Robotics. The rest of the paper is organized as follows. Section 2 discusses the related work. Section 3 describes the system. Section 4 demonstrates experiments, and finally Section 5 concludes the paper and suggests future works.

II. RELATED WORK

A. STRIPS Planning

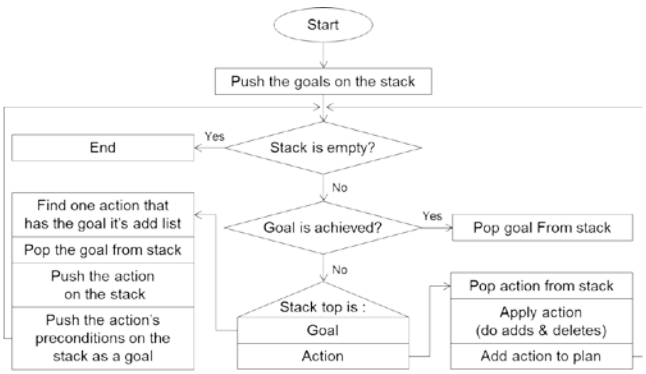

Fig. 1. The process of STRIPS planning

Planning techniques consider achieving goals in the idealized environment mostly. Since the techniques have own weakness of low flexibility in the complex environment, many researchers have followed to solve this problem. The STRIPS planning is one of them, and it consists of states, goals, and action [5][6]. This planning technique makes a sequence of actions to perform the initial state of the world into the final state of the world automatically. At this time, the form of an action is expressed by (*pre*, *del*, *add*). *pre* is a list of the preconditions, which have to be valid immediately before the action is applied. *add* and *del* indicate a list of the effects after the action ends. Figure 1 shows how the STRIPS planning makes a plan by considering state and goals. Although this planning technique can create a sequence of the independent actions to solve complex problems, it is not easy to apply to the problem achieving goals rapidly in a changing environment.

B. Behavior Selection Network

A BSN proposed by Maes generates behaviors for an autonomous agent by attaching goals to the behavior-based system [7]. Figure 2 shows the whole structure. In the behavior node, the list of preconditions c_i have to be fulfilled before the node can become active; the add list a_i and the delete list d_i represent the expected effects of the node; each node has a level of activation α_i. Thus, a behavior node can be described by a tuple (c_i, a_i, d_i, α_i).

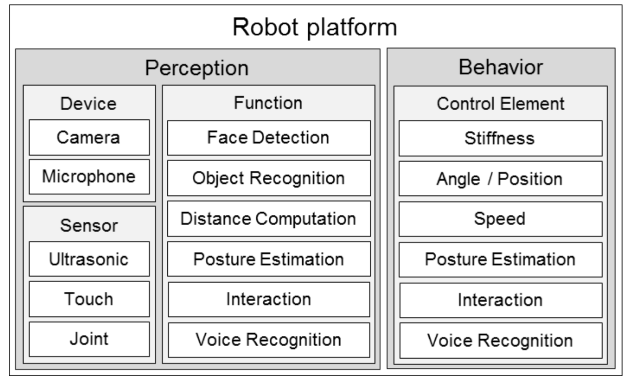

Fig. 2. The whole structure of behavior selection network

Formally, given behavior node X = (c_x, a_x, d_x, α_x), behavior node Y = (c_y, a_y, d_y, α_y), and current conditions p, each link from X node to Y node can be defined as below:

- Sucessor: X has Y as successor, ($p \in a_x \cap c_y$)
- Predecessor: X has Y as the predecessor, ($p \in c_x \cap a_y$)
- Conflictor: Y conflicts with X, ($p \in c_x \cap d_y$)

Figure 3 shows the process for generating a behavior. Unless any node is selected in satisfying node with both (a) condition and (b) condition, the behavior selection system constantly reduces the threshold until the node is selected, and one of them is chosen randomly when two nodes fulfill all the conditions.

1) Activation induction
← environment, goals, protected goals
2) Activation spreading
← successor links, predecessor links, conflictor links
3) Activation normalize
← global parameter
4) Behavior selection
← following three conditions
a) all precondition = true
b) activation level > threshold
c) activation level > all other nodes

Fig. 3. The procedure of the behavior generation

Although the BSN can generate behaviors of a robot rapidly in the changing environment, it is difficult to achieve goals including complex problems [8].

C. Hybrid Control System

The term hybrid means to combine two or more different methods [9]. The hybrid control system to generate robot behavior is defined by the following two types [10]; the reactive system allows the robot to select an optimal action instantaneously in the given environment because this method uses local information obtained from sensor of the robot. On the other hand, the deliberative system manages the plan about the global world to achieve goals. Deliberative system can be thought of as planning technique. Classical planning has the problems which are inflexible in dealing with the varying environment in a real world while requiring lots of preprocessing steps.

TABLE I. PREVIOUS STUDIES ON HYBRID CONTROL SYSTEM

Authors	Methods	Domain
Min, et al. [11]	BSN and priority-based sequence	Mobile service robot
Yun, et al. [13]	MBSN and predefined sequence	Humanoid service robot
Mendonace, et al. [14]	Fuzzy cognitive map based reinforcement learning	Mobile robot navigation
Christopher, et al. [15]	Control parameter modulations and probability-based sequence	Mobile robot navigation
Quintero, et al. [16]	2-layer actions and automated sequence	Autonomous mobile robot

In this regard, many studies have been conducted as shown Table I. Min, et al. proposed the goal-oriented BSN system to generate behavior of the delivery service robot [11]. The system used BSN and priority-based sequence plan which can be changed by the user's input and the robot conducts behavior over the sequence. MBSN is that designed by Tyrell for only one goal [12]. It is divided into the sub-goal units because large-scale behavior nodes have problems which increase the processing time and the collision of goals. Yun, et al. developed a humanoid control system using MBSN and predefined sequence [13]. At this time, MBSN is selected in a fixed order from the planner. Mendoca, et al. proposed an autonomous navigation system using fuzzy cognitive map [14]. They used the model to represent the robot's dynamic behavior in both reactive and deliberative layers. Christopher, et al. also suggested autonomous navigation system, but it is different from the former [15]. This system connects the robot's emotion and reactive system composed of multiple layers, and adopts the planning technique using the probability. Lastly, Quintero, et al. proposed the control of autonomous robots using automated planning techniques and 2-layer actions [16]. The hybrid control system not only can solve the problems of each method, but also can maximize each benefit. However, since previous studies have not sufficiently considered the scalability problem and unstable environment, there are limitations in achieving long-term goals through solving complex problems in the real world.

III. THE PROPOSED SYSTEM

A. System Overview

For responding to user's requests appropriately, a humanoid robot should generate proper behaviors to achieve goals rapidly in the unstable environment, and the control system needs the flexible scalability which can be added easily according to user's increasing requests. To overcome these problems, we propose a control system based on the planning-driven BSN. The system can control a humanoid robot reacting to the external environment while achieving user's requests, even though the robot uses unstable sensor data. Therefore, the proposed system can be applied to service robots for responding to user's requests in a real world, and it can solve autonomous problems of the robot which is not able to drive without an environment map.

The whole architecture of the proposed system is shown in the figure 4. This system consists of a control module to generate autonomous behaviors of a humanoid robot appropriately in a changing environment, a conversation module to analyze the user's intention using dialogue, and the robot platform for collecting environmental information and realizing user's command practically. The control module combines the BSN method of behavior-based system with the STRIPS planning method of plan-based system to generate reactive behaviors as well as deliberative behaviors.

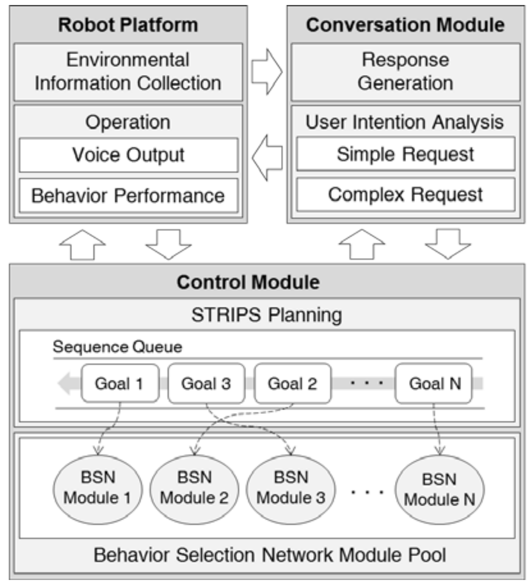

Fig. 4. The whole architecture of the proposed system

The STRIPS planning which makes a sequence composed of sub-goals through controlling independent modules of the BSN so as to perform user's requests containing complex problems. Thus, the proposed system can respond to various user's requests. The system has benefits that have scalability and can be represented as distinct structure. In this point, a selected node of the BSN composes the action sequence like planning systems. However, there is a definite difference in terms of flexibility in changing the conditions between the BSN, which makes a sequence dynamically, and the planning system, which performs a fixed sequence. The BSN can be described as an optimal method to control the robot using the information of the sensors on various environments such as the real world. The proposed system can control the autonomous robot flexibly by using the feature which makes a sequence automatically from each method.

B. Robot Platform

Figure 5 shows a composition of the robot platform and describes each part specifically. To offer the information required for each module, a humanoid robot collects the data, and the robot sends the data converted into fitting type to each module. For this, the part of the perception recognizes the external environment with the user's requests using embedded devices and a variety of sensors. Furthermore, to avoid damage of the humanoid robot while performing the requests, the robot should be controlled by considering overall balance and flexibility, so it is important to set stiffness and speed of each joint. The part of the behavior controls each element to complete the user’s requests.

The robot platform plays a role, realizing user's requests by a familiar way as follows. Firstly, the robot switches the receiving message from conversation module into voice like humans. Secondly, it implements the real action using the behavior node created from the hybrid module. The process of running the low-level actions composed of the behavior node in consecutive order is needed. For example, when 'grab a cup' node is selected, it needs the three low-level actions as the following steps; spread out both arms, lift up both arms, and grab a cup.

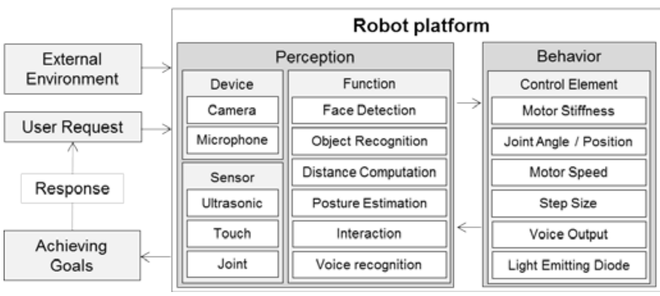

Fig. 5. The composition of the robot platform

C. Conversation Module

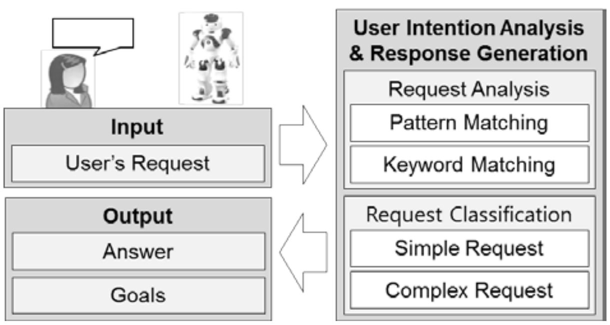

Fig. 6. Architecture of the conversation module

Figure 6 shows the structure of the conversation module to recognize and analyze the user’s requests. The request is classified using a pattern matching method and a keyword matching method as a simple request or a complex request, and then outputs the answer and goals. The pattern matching method and the answer use a predefined script. However, If only the same response is produced by similar requests, in terms of the Human-Robot Interaction (HRI), it might be considered as a problem. To address this issue, one of the proper answers will be chosen randomly for natural interaction with the user, it is transmitted to a robot. Furthermore, this module provides information about the related user's request. For example, unless the robot knows 'room B225', when the user says that "Bring documents to go to the room B225 ", the robot can explain this situation through the process which checks the information to the robot platform using this module.

D. Control Module

Regardless of the user's simple request or complex request, the approach that combines STRIPS planning with BSN plays the role in flexibly generating the behavior of the robot responding to the changing environment like a real world, and also can create behaviors of the robot to accomplish the user's request appropriately. The control module is organized to maximize the advantage of each method and minimize the disadvantage.

A STRIP planning of this module consists of the initial state, the goal, and a set of actions. In this paper, the initial state is set from the robot and predefined information, the goal is fixed from the conversation module, and then a set of actions are defined with the modules of the BSN. Each module has its predefined precondition, additional effect, and deleting effect. Accordingly, when the goal is set, a plan is made by modules automatically to achieve the goals.

- Definition 1. Modular Behavior Selection Network

Let $SG = \{sg_1, sg_2, ..., sg_m\}$ be a set of sub-goals. A goal $G = \{g_1, g_2, ..., g_n \mid g_i = \{sg_a, sg_b, ..., sg_d\}\}$ is a set of the goals. The BSN is a quadruple $<W, E, G, A>$, where W is global parameters, E is environmental elements, G is goals, and A is behavior nodes, respectively. Therefore, $M_i = <W, E_i', sg_i, A_i>$ is one of the MBSNs, where $P \supseteq P_i'$, $E \supseteq E_i'$, and $A \supseteq A_i'$. The activation of the ith behavior A_i is defined as follows:

$$A_i + \sum_n W_e E_{i,n} + \sum_m W_g G_{i,m} \tag{1}$$

W is the global parameter for giving weight value. w_e and w_g are values to induce activation energies from environment and goals, respectively. $E_{i,n}$ represents the nth environment element, and $G_{i,m}$ is connected to the mth goal. Both $E_{i,n}$ and $G_{i,m}$ should be 0 or 1. After that, behavior nodes consider the type of their links as follow:

$$A_i = A_i + \sum_i (W_p P_{i,j} + W_s S_{i,j} - W_c C_{i,j}) \tag{2}$$

W_p, W_s and W_c are the weight values to exchange activation energies through predecessor, successor and conflictor links, $P_{i,j}$, $S_{i,j}$ and $C_{i,j}$, denoting whether the ith and jth behaviors are connected by each type of links, respectively.

- STRIPS Planning

The STRIPS planning problem P is a triple $<I, G, A>$, where I is an initial state set, G is a goal state set, and $A = \{a_1, a_2, \ldots, a_n\}$ is an action set, respectively. Therefore, $\prod = \{a_a, a_b, \ldots, a_d\}$ is the plan.

- Planning-driven Behavior Selection Network

$\delta = <I, G, M_i>$ is the proposed method, which is the planning-driven behavior selection network. I comes from the robot and predefined information, and G comes from the conversation module. M_i has a sub-goal, and it is controlled to achieve the goal. Therefore, $\prod = \{M_a, M_b, ..., M_d\}$ can be described by the plan if $g_n \ni \exists sg_s \approx M_i$.

When the robot needs to achieve sub-goals including simple problems, it can be resolved rapidly by using the BSN, because BSN does not have a fixed sequence, but it creates the robot's behavior flexibly through spreading activation energy reflecting the environment, goals, previous behavior node, etc. However, the BSN still has a limitation which cannot attain goals containing complex problems or long-term goals. We propose the system which can overcome this limitation by applying a planning technique. We employ a STRIPS planning method, which makes a strategy for achieving the complex requests by creating the sequence of the robot behavior automatically. The system makes a sequence of decomposed goals using the modularized BSN in place of primitive actions of the STRIPS planning. All of the MBSN acts independently to each other. These architectures can be used to enhance the scalability of the proposed system because of an action set used in the STRIPS planning method. The BSN can be largely divided into the three parts which consist of environment, behavior, and goal. As each element gives influence to spreading the activation energy, it can vary with the parameters which mean weighted value in each part. The environment part is reflecting surrounding elements; goal part is composed of sub-goals. Selected behavior node is sent to the robot, and then it is connected as a real action on the robot. The BSN is designed for the simple request and copes with the environment reactively, and STRIPS planning is considered for the complex request and control the execution sequence of the sub-goals unit as shown in figure 7.

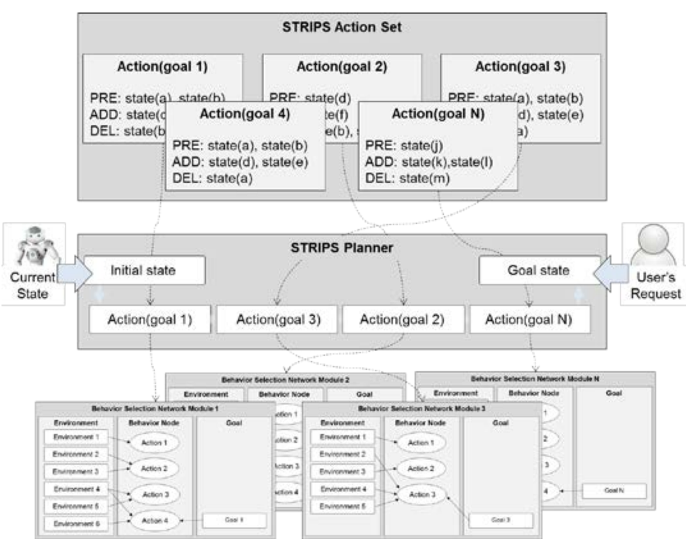

Fig. 7. Process of generating a behavioral sequence

During the user's command execution using the plan sequencers, if the humanoid robot is faced with a problem which is unexpected situations, the robot would fail to realize its sub-goals, and then it cannot perform the next plan. To solve this problem, we modify this module so that a failure of sub-goals can be managed, and the plan can be revised. If a node is abnormally repeated or the number of total steps is unusually exceeded, which is considered as a failure for achieving the goal. It sends the event to STRIPS planner so that the plan is revised through the process that renews the current situation and formerly failed goals. In the end, the STIPS planner regenerates a modified sequence, and the robot can provide services requested by the user.

IV. EXPERIMENTS

A. Experimental Environment

We apply the proposed system to NAO, humanoid robot platform, to verify the usefulness of the system. We can show that the proposed system overcomes the previously mentioned problems requiring a reactive control system while performing behaviors corresponding to the user's intention. The NAO robot is an optimal robot platform to implement similar human's cognitive structure because it has more sensors and 21 degrees of freedom (DOF) than other type of robots. NAO includes several sensors to estimate self-posture or state such as a 3-axis accelerometer and 2-axis gyro-meter in the chest, 4 force sensitive resistors, and sensors of each joint. The NAO also contains 2-microphones, 2-camera, and 2-bumper sensors for collecting various environments. Such a structure of the NAO is useful to perform tasks on behalf of the user. However, this type of robots needs more sophisticated control process on many joints compared to other types, because there is the problem that errors occur. Humanoid robots demand higher-level control system requiring quick and flexible process in various environments.

B. Analysis of Behaviors on the Changing Environment

Scenario 1: Users request to NAO that the OBJECT_A to be delivered from PLACE_S to PLACE_X, when the NAO's current position is PLACE_S.

TABLE II. EXPERIMENTAL CONTEXT AND SETTING UP GOAL IN THE SCENARIO 1

Step	State & Environment	Aim to behavior
1	Place=S, Empty Hands, Invisible A	Search for A
2	Empty Hands, Visible A, Untouchable A	Move to A
3	Empty Hands, Visible A, Touchable A	Grab A
4	Hold on Object	Escape from S
5	Place=Hall, Hold on Object, Invisible A	Search for X
6	Hold on Object, Visible A	Move to X
7	Near Obstacle	Avoid Obstacle
8	Hold on Object, Visible A	Move to X
9	Place=X, Hold on Object	Put down A at X

The experiment was based on the scenario to verify appropriate reaction to the changing world. Table II shows the occurring virtual environment in each phase. Accordingly, we aim to confirm the suitable reaction to accomplish a target goal. The system architecture is designed for this experiment as shown in figures 8, 9 and 10. For example, 'search for A' node is defined as follows:

- Precondition: Empty Hands, A Somewhere
- Add list: Perceive A
- Delete list: A Somewhere

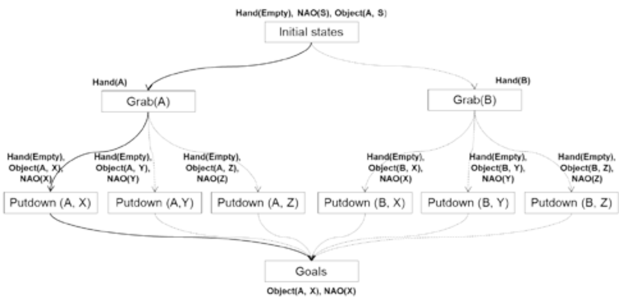

Fig. 8. Planning flowchart for the delivery request

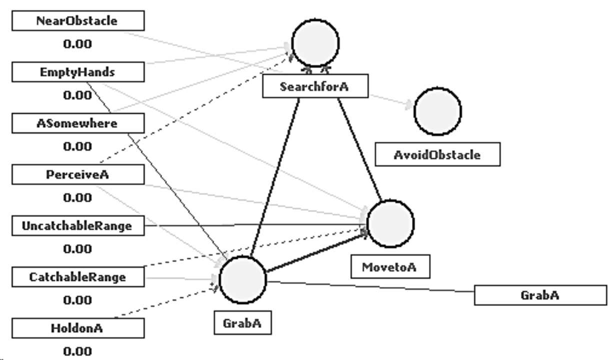

Fig. 9. The BSN module design for catching object_A

As a result of the experiment, goals are set using the user's request, and the plan is created in order to achieve the goals from the initial state as shown in figure 8. Each of the BSN is selected by this plan. Figure 11 shows the behaviors created. We can confirm that the proper action is selected when compared with the goals set. Most of all, the result demonstrates that each BSN copes robustly with varying situations while achieving the sub-goal.

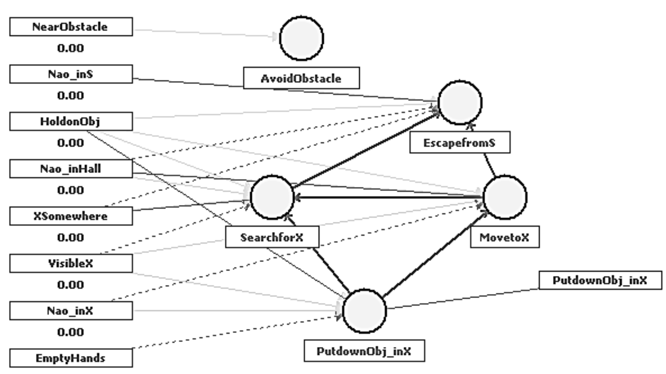

Fig. 10. The BSN module design for putting down

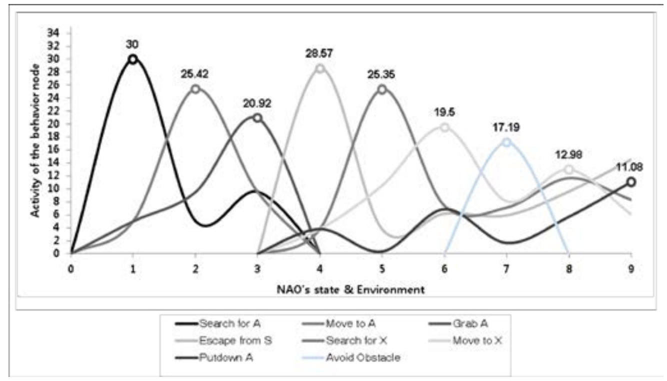

Fig. 11. Activity of behavior node about the changing environment

C. *Analysis of the Accuracy of the Proposed System*

Scenario 2: This experiment is extended from Scenario 1. We add a command that the NAO comes back PLACE_S, after delivering OBJECT_A from PLACE_S to PLACE_X.

To work out more complex problem, the proposed system can be easily extended because the system has the independent and clear structure as shown in figures 12 and 13.

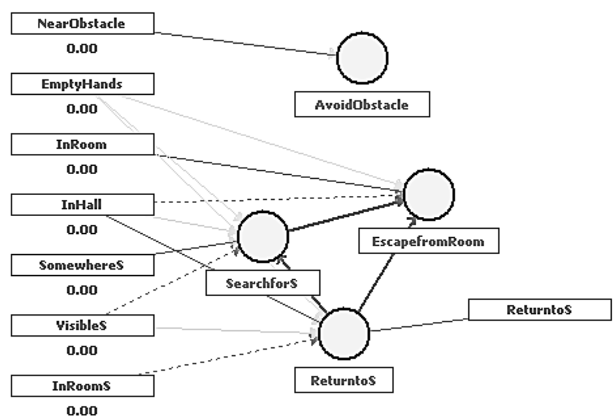

Fig. 12. The BSN module design to come back to original position.

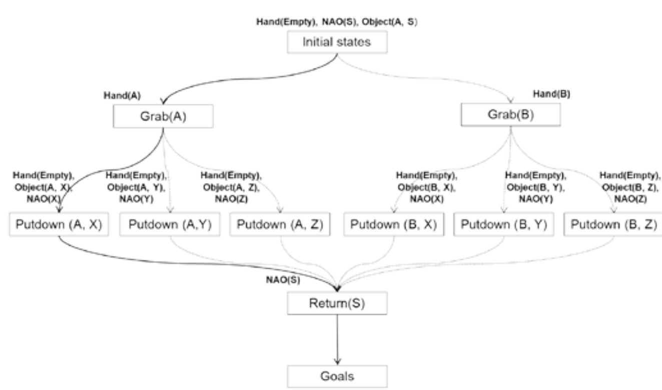

Fig. 13. Planning flowchart for added request

Fig. 14. The NAO control process using the proposed system

For this experiment, we apply the proposed system to the NAO, and performed a total of 30 experiments as shown in figure 14. Figure 15 shows the change of the number of selected behavior nodes from the same command on the equivalent environment. For example, A_X means that the NAO comes back to PLACE_S, after the NAO has delivered OBJECT_A from PLACE_S to PLACE_X. Test *N* means the number of tests. As a result, we can confirm that large errors arise when the humanoid robot is controlled. Nevertheless, the proposed system can control the NAO with an accuracy of 85.7% because the system copes reactively with the environment.

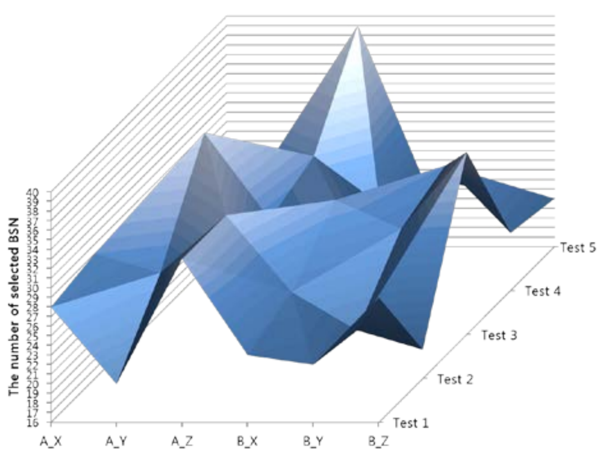

Fig. 15. The number of selected behavior nodes according to changing the number of executions

V. Conclusions

Even though a humanoid robot has uncertain sensor data, the robot should respond to user's request including simple tasks as well as complex tasks. To solve these problems, we propose the hybrid control system employed the MBSN and STRIPS planning to quickly cope with unstable environment while achieving the goals. The proposed system also has a scalability for responding to the user's increasing request. We verified through experiments of the proposed system that a robot responded proper reaction on the various environments, and demonstrated an accuracy of 85.7% on the real environment. In the future, we need to verify the proposed system through additional experiment which needs to solve more complex problems, and we have a plan to improve the system through designing more BSN modules.

Acknowledgment

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