Cognitive Control for Robot Task Execution

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Abstract **– This paper discusses an application of cognitive control for robot task execution. The idea is currently being implemented in a humanoid robot ISAC using the Central Executive Agent and the Working Memory System. Using cognitive control, the robot should be able to learn how to execute task using past experience and emotion. This paper also discusses a cognitive control experiment used to test the performance of the system.**

Index Terms – cognitive control, cognitive robot, humanoid robot, behavior control, working memory

I. INTRODUCTION

In recent years, a large number of robot designs follow traditional AI techniques of perceiving and interacting with the world around them. This requires explicit knowledge representation of the environment as well as formal techniques for manipulating internal representations. These approaches allow a robot to perform tasks reasonably well in all cases that the robot is designed for. However, as the world is highly dynamic, representations of the world can be too complex and thus are impossible to be perfectly modelled. Problems arise when a robot falls in situations that the system is not designed to handle, especially in systems that often meet complex environment such as humanoid robots. Most robots can perform only those or similar tasks for which they were programmed for and very little emerging behaviors are exhibited. A solution to these problems is to use different ways to design robots which do not require explicit knowledge of how a task can be performed.

Normal humans are able to cope with dynamic changes in the world. The complexity of the brain amazingly allows it to process perceived information and generate actions based on context of the task, goal, and environment. Except for some innate behaviors, however, humans do not know how to work out their tasks from the first day they are born. Instead, they must learn about their tasks and gain experience from activities during their everyday lives as they grow up. Information from learning is encoded and distributed among millions of neurons in the brain. Neurons must work together in order to think, plan, and control a task execution. Modeling the brain from the fundamental level such as neurons is not a trivial task although such brain-based devices are studied by a group at the Neurosciences Institute [1]. On the other hand, functions of various parts of the brain, such as those studied by computational neuroscientists and cognitive psychologists [2], can also be adapted to use in robots, especially for task execution and learning. Research on human cognitive abilities indicates that cognitive control is a part of human's intelligence that help humans focus on task context and handle tasks fluently [3]. We believe cognitive control is a means to overcome the limitation of classical AI and allows us to develop cognitive robots, robotic systems that will not require pre-programming to execute task but execute task based on past experience and emotion.

II. COGNITIVE CONTROL IN HUMANS

The concept of cognitive control is one of important topics among cognitive psychologists who study human behaviors. One of the topics is the effectiveness of human task performance, which is indicated to be related to consciousness of the individual and the ability to flexibly control the behaviors rather than depending solely on the fixed or reactive actions. High-level cognitive processes including problem-solving, planning and decision-making appear to depend highly on the control over attention, memory, and action selection [4]. The understanding of human's cognitive control ability can help with robotic researchers in to overcome the limitations of traditional way of designing robots.

A. Cognitive Control

The human brain contains a lot of information such as perceptual, semantic, motoric, etc. Representations of such information are created and manipulated by the brain. The brain must be able to translate between different representations or even transform one representation into another altogether. However, during a task performance, only a small set of these resources are needed. Human cognitive skills involve processes of organization of resources necessary for the task at hand, including selection and maintenance of required information and avoid disruption from other influences [3].

Human possesses different types of actions. Some of the actions are stimulus driven. These include sensori-motor-typed actions that are innate to us since we are born. As a human ages, some of these sensori-motor connections are strengthened when they are used primarily. This type of actions tends to be triggered in response to certain inputs regardless of the current goals. On the other hand, some human actions are voluntary. We control what we want to do and how we want to act based on context of the tasks in order to accomplish particular goals. Actions must be selected carefully using information based on past experience and knowledge about the task and environment. In some cases, sensori-motor coordination must be either inhibited or overridden during a voluntary act. The ability to control actions in this manner in order to accomplish a task is called cognitive control [2][3][5][6]. Essentially, cognitive control in humans is the ability to consciously manipulate thoughts and behaviors using attention to deal with conflicting goals and demands [4]. As levels of human behavioral processes range from reactive to full deliberation, cognitive control must be able to switch between these levels to cope with the demand of task and performance, particularly in novel situations. Fig. 1 illustrates the concept of cognitive control.

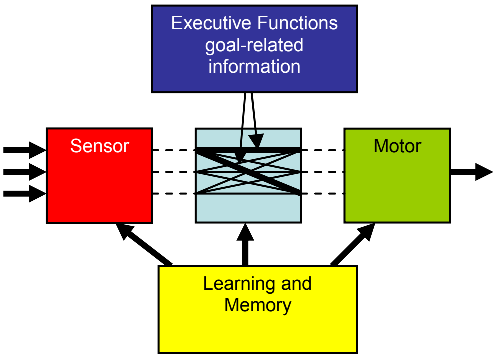

Fig. 1 Cognitive Control [6]

According Fig. 1, executive functions of cognitive control include the ability of the brain to:

- Generate plan and monitor task progress
- Focus of task related information
- Maintain and update goal information
- Inhibit distractions
- Shift between different level of cognition ranging from routine actions to complex deliberation
- Learn new responses in novel situations

B. *Models of Human Cognitive Control*

Cognitive psychologists have tried to create models of human brain regarding cognitive control. These researches try to find a better explanation than that stating there is a homunculus or an imaginary “little man” inside our brain that provides executive functions as well as decision making. Some researchers believe that working memory plays an important role in cognitive control because it provides a mechanism to select and maintain a small number of chunks of task related information in order to influence behaviors during task performance.

One classical model of working memory is that suggested by Baddely [7] in which the control of executive processes is done by a component called the Central Executive. The Central Executive, shown in Fig. 2, controls two working memory systems, namely the phonological loop and the visuo-spatial sketch pad. These two systems are responsible for both the storage and processing of linguistic and visuo-spatial information, respectively.

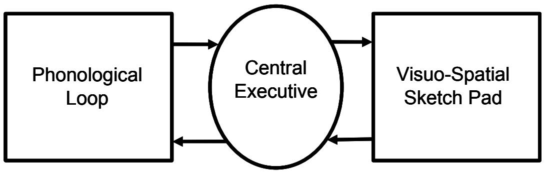

Fig. 2 Baddely’s model of working memory [7]

However, Baddely’s model of working memory is not well accepted by some cognitive psychologists as the detailed functions of the Central Executive are not well explained. Alternately, based on a neuroscience evidence in the brain, different models of working memory are created using Temporal-Difference Learning (TD-Learning) [8]. In particular, TD-Learning, which has similar in function to dopamine cells that project into the prefrontal cortex, can be used for selection and focusing of task-related information during a task execution.

Inspired by these concepts, we are implementing cognitive control in our humanoid robot, ISAC, based on Baddely’s model, where we create a central control mechanism called the Central Executive Agent (CEA), and use TD-Learning to explain how it selects information to be maintained in ISAC’s Working Memory System (WMS) for task execution. Details of the CEA and WMS are explained in the next section.

III. COGNITIVE CONTROL IN A HUMANOID ROBOT

To move towards the goal of developing a cognitive robot, the Center for Intelligent Systems at Vanderbilt University has designed a cognitive robotic control system for the humanoid robot ISAC (Intelligent Soft Arm Control) [9].

A. *Software Architecture*

ISAC's cognitive robot architecture is a multiagent-based system that incorporates several components inspired by different cognitive processes in humans. Information processing in ISAC is embedded within a multiagent-based software architecture called the Intelligent Machine Architecture (IMA) [9][10]. ISAC's cognitive abilities are implemented as collections of IMA agents and memory structures, including one important compound agent called the Self Agent as shown in Fig. 3.

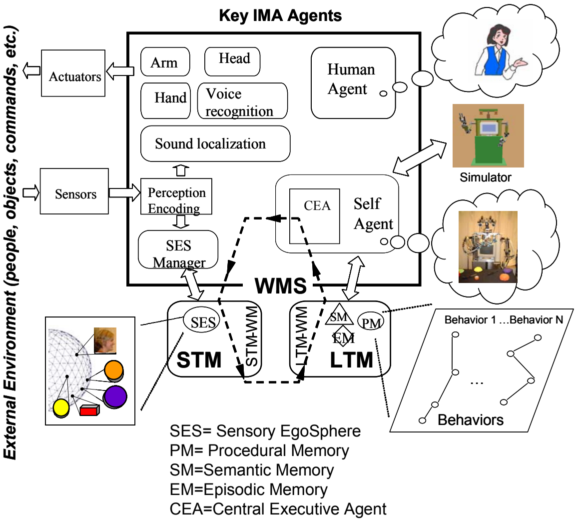

Fig. 3. ISAC's Multiagent-Based Cognitive Robot Architecture

B. *The Self Agent*

The Self Agent (SA) is our initial attempt to develop the *sense of self* in a humanoid robot [11]. This is done through monitoring the robot's own internal state as well as the progress of task execution via sensor signals, agent communications and working memory using a set of tightly-coupled atomic agents. The internal representation of the robot's self should continually be updated and enhanced to allow the system to reason and act based on its status and the context of assigned tasks [12]. The SA also responds to commands given by humans through another compound agent called the Human Agent, and is responsible for controlling task execution. Fig. 4 illustrates the current design of the Self Agent and its interaction with other components. So far, the Intention Agent, the Pronoun Agent, and the Description Agent have been implemented [9]. We are currently developing the Central Executive Agent and the Emotion Agent to provide cognitive control to ISAC.

C. *Memory Structures*

Memory structures are utilized in ISAC's cognitive robot architecture to help maintain the information necessary for immediate tasks and to store experiences that can be used during decision making processes.

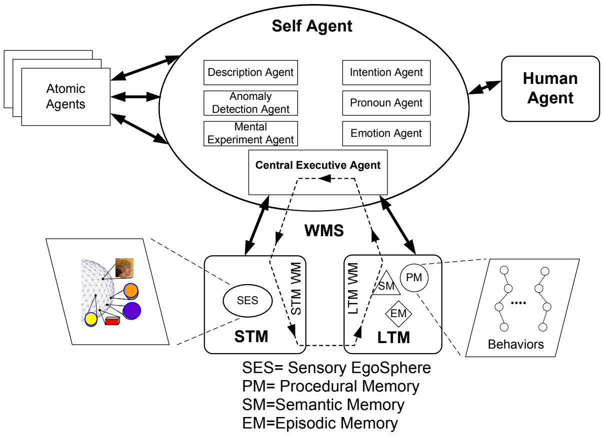

Fig. 4. Current Design of the Self Agent.

The short-term memory (STM) stores sensory information on a structure called the Sensory Ego Sphere (SES) [13]. Memories in the SES can be retrieved using stimulus content such as key words or colors, or time of posting. The stored information decays over time.

The long-term memory (LTM) stores information such as learned skills, semantic knowledge, and past experience for retrieval in the future. As a part of the LTM, Procedural Memory (PM) holds motion primitives and behaviors needed for movement, such as how to *reach to a point* [14]. Behaviors are derived using the Spatio-Temporal Isomap method proposed by Jenkins and Matarić [15]. Semantic Memory (SM) is a data structure about objects in the environment. Episodic Memory (EM) stores past experience including goals and task sequences that ISAC has performed in the past. An episode in the EM stores content of the working memory in time steps throughout the task every time a task is performed. An episode in the EM can be learned from both real experience and human teaching. EM implementation is described in more details in [16].

The Working Memory System (WMS) is modeled after the working memory in humans, which holds a limited number of "chunks" of information needed to perform a task, such as a phone number during a phone- dialing task. It allows the robot to focus attention on the most relevant features of the current task, which is closely tied to the learning and execution of tasks [17]. In our implementation, the WMS consists of two functional parts: a set of working memory slots that can be accessed by other agents, and a device to select chunks of memory to place in those slots based on the current task context. The WMS works with the CEA to provide cognitive control similar to that seen in humans. This working memory model is based on models from computational neuroscience which details are discussed in [18].

D. *Implementation of Cognitive Control in ISAC*

ISAC's cognitive control is implemented using a control mechanism called the Central Executive Agent (CEA). The CEA interfaces with the WMS similarly to the central executive in Baddeley's human working memory model, described previously in section II. *B*. Functions of the CEA include task planning, action selection, action execution, and action learning.

Action selection and execution within the CEA is done in a modular fashion as described in [19]. ISAC is given a set of behaviors, such as waving, reaching, and hand shaking. These behaviors are explicitly taught to ISAC prior to the task assignment and have been assigned an initial set of expected rewards for various actions. To perform an action, the CEA selects a set of behaviors that have highest expected rewards based on the action being requested, and places them in the WMS. Behaviors are combined to generate final action based on relevancies to the task at a particular sampling time. Results from the task execution are used for calculation of expected rewards for the TD-Learning in selecting behaviors to perform a similar action in the future. Fig. 5 illustrates the interaction between the CEA and the WMS during an action selection and execution process implemented for ISAC.

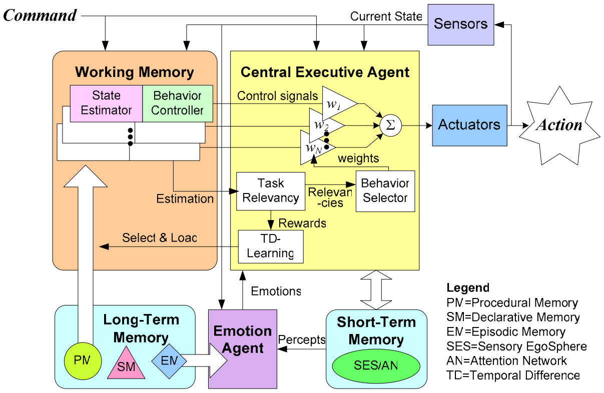

Fig. 5. Interaction between the CEA and WMS during an action

In addition to expected reward for action selection, past experience is stored in the EM each time ISAC performs a task. These remembered past experiences can be combined and used by the CEA as a guideline for performing similar tasks. Upon receiving a new task, a small number of similar tasks performed previously are loaded from the EM into the WMS [16]. ISAC will determine how to perform the new task based on generalization of the tasks in the WMS. In novel situations, the CEA also looks for the memories most related to the current task and attempts to combine these memory episodes in a manner that the execution of the current task is allowable. This way, new approaches for executing new tasks can always be obtained. This approach of combining learned episodes in order to execute novel tasks follows along the lines of schemata-based learning, a common area of robotics research. Recent work by Grupen [20] has shown how schemata-based learning can be applied to robot grasping.

E. *Cognitive Control and Emotion*

Emotion plays important role in human decision-making [21]. As the interaction of attention and emotion in the human brain is increasingly well-understood [22], we are adding an Emotion Agent to the Self Agent to provide feedback of the environment in similar way of the emotion system described in [23]. Emotional state of the robot describes what the robot feels toward the task and the environment. Emotion can be used to influence behavior as well as trigger an action execution. [16] describes the initial design of the emotion agent.

As an example, we have designed a cognitive control experiment using emotion as a factor for decision making as described in the following section.

IV. COGNITIVE CONTROL EXPERIMENT

We have designed and implemented an integrated cognitive system experiment as introduced in [11] based on the CEA, attention, emotion and the adaptive working memory system as follows:

Before the experiment is commenced, ISAC must be endowed with a set of initial knowledge. Knowledge, such as descriptions of certain objects, knowing how to track objects, and an episode of past experience involving "fire", will be taught. In the experiment, ISAC will be presented with a task and, and later, an event will occur to introduce a conflicting input, where ISAC must decide whether to shift attention from the task being performed. The system uses cognitive control to make decision with reinforcement from emotion instead of traditional rule-based methods, as shown in the process flow in Fig. 6.

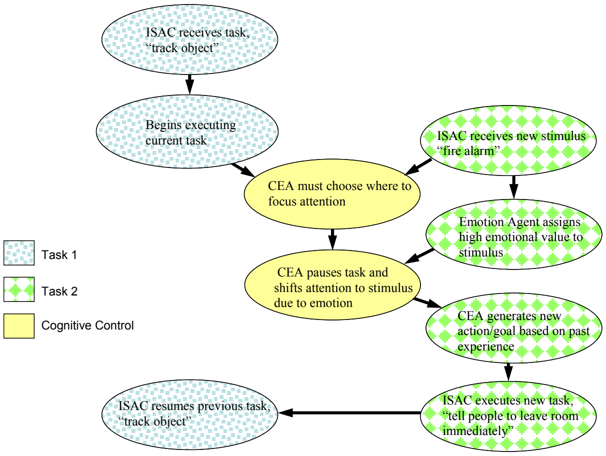

Fig. 6. Process flow of the cognitive control experiment

In the beginning, ISAC is asked by a person to identify and to track an object. Recognized objects are shown on the SES and an ISAC's Focus of Attention (FOA) [24] is put toward the objected being tracked. While this task is being executed, an outside stimulus, in this case a fire alarm, will be added. This new stimulus will create a second FOA to which ISAC must decide either to pay attention to or disregard. Concurrently, the emotion agent, having a previous recorded experience with the fire alarm stimulus, creates a high emotional salience and reinforces the new FOA. Based on the strength of this emotional salience, the CEA then chooses to change attention to the new stimulus. The CEA pauses the current task, asks the episodic memory for episodes involving the "fire alarm" stimulus, and creates a new action/goal set based on past experience. ISAC then executes the new action informing everyone present to "Please leave the room immediately". Upon completion of this action, ISAC can then resume the previous task.

The system operation of this experiment is summarized in Fig. 7.

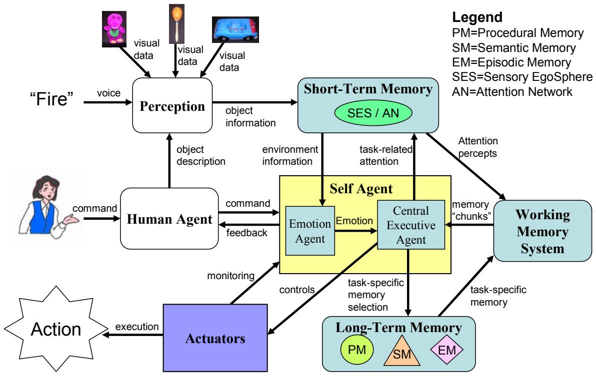

Fig. 7. Interactions among IMA agents and memories during the cognitive control experiment.

V. CONCLUSION

To go beyond the traditional way of developing robot intelligence using classical AI techniques, we have adapted human cognitive abilities based on cognitive psychology research called cognitive control to be used for task execution and control in our humanoid robot ISAC. Instead of using pre-programmed knowledge such as rule-based systems, the robot acquires its knowledge through learning and past experience. Knowledge and experience are stored within memory structures and retrieved during task executions. Cognitive control is applied to ISAC using a control mechanism called the Central Executive Agent along with a temporary storage area for task-specific information called the Working Memory System. The CEA must select appropriate actions for a task execution based on past experience. Emotion is also used for feedback of the system and can also be used to bias action selections such as in the situation shown in the experiment. The robot is able to adapt its learned knowledge, with bias from emotion, to help making decisions in conflicting situations. In the future, the robot should also be able to decide its course of action in case of novel situations using stored knowledge and emotion in the similar manners to the situation presented in this paper.

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