From Adaptive Control to Cognitive Control

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Abstract – This paper describes our efforts to develop a robot with a human-like sensorimotor intelligence using a multiagent-based robot control architecture and human-like intelligent control. Such control may be called cognitive control. Features of cognitive control addressed in this paper include attention- and emotion-based adaptive action selection and learning using working memory.

Index terms – cognitive control, machine perception, self agent, working memory

I. INTRODUCTION

In the opening message at the HAM Workshop in March 2004, Professor K. Furuta stated that “It may be said that “Human Adaptive Mechatronics (HAM) is a new discipline based on the integration of mechanical, electrical, information technology and the human sciences including medicine and psychology. Thus, HAM will have a diverse range of applications from intelligent human-machine interfaces for tele-surgery procedures to technology designed to assist in rehabilitation.” A key word here is integration. For example, humans have the capacity to receive and process enormous amount of information from the environment and still can exhibit integrated sensorimotor intelligence such as cognitive control as early as two years old [1]. A good example of such sensorimotor intelligence by adults is the well-known Stroop effect [2]. Thus it is a challenge for HAM designers to find ways to emulate human’s robust sensorimotor mechanisms called cognitive control. I call such human-like cognitive control integrated sensorimotor intelligence.

Most goal-oriented robots currently can perform only those or similar tasks which they were programmed for and very little emerging behaviors are exhibited. What is needed is an alternative paradigm for behavior learning and task execution. We believe that robust and timely responses to the full range of contingencies often present in complex task environments will require something more than the combination of traditional sense-plan-act approaches [3]. Specifically, we see our brain’s cognitive flexibility and adaptability as desirable design goals for a next generation of intelligent robots. Several cognitive architectures have been implemented for the purpose of testing human psychological models [4][5], but such models have not widely been applied to robotics.

This new generation of robots including HAM machines should be able to recognize and deal with situations in which its traditional goal-oriented reasoning abilities fall short of meeting complex task demands.

II. Information Processing in Humans

Engineers have long used control systems utilizing feedback loops to control mechanical systems such as robots. This practice has led to a more robust control technique called adaptive control. In adaptive control, changes in the robot dynamics are tracked and compensatory changes in the controller are introduced. Figure 1 illustrates one of a class of such adaptive (or learning) control systems [6].

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Human brain, on the other hand, is known to process a variety of stimuli in parallel. This process, known as perception, encodes stimuli into representations or percepts. For example, according to the Dimension-Action (DA) model of Cohen, et al., stimuli are processed based on its dimension [7][8]. Fig. 2 illustrates the concept of stimuli processing in the DA model. The encoded stimuli or percepts then are sent through a gating mechanism into the working memory. The working memory allows the robot to focus attention on the most relevant features of the current task and provide robust operation in the presence of distracting irrelevant events [9].

III. MULTIAGENT-BASED COGNITIVE ROBOT ARCHITECTURE

A humanoid is an example of a robot that requires intelligent behavior to act with generality in its environment. As the complexity of a task grows, so do software complexities necessary to process sensory information and to control actions purposefully. The development and maintenance of complex or large-scale software systems can benefit from domain-specific guidelines that promote code reuse and integration through software agents. Information processing in our humanoid robot ISAC is integrated into a multiagent-based software architecture based on the Intelligent Machine Architecture (IMA) [10]. The IMA is designed to provide such guidelines for code reuse and allows for the development of subsystems from perception modeling to behavior control through the collections of IMA agents and associated memories, as shown in Figure 3 [11].

III. COGNITIVE CONTROL AND THE CENTRAL EXECUTIVE AGENT

Our initial attempt to realize cognitive control in ISAC was through an IMA compound agent termed the Self Agent, a set of atomic agents trying to achieve a common goal. This concept was inspired by Minsky's work in the *Society of Mind* [12].

A. Cognitive Control

Cognitive (or executive) control in humans is the ability to "consciously manipulate thoughts and behaviors using attention to deal with conflicting goals and demands" [13]. 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. According to a number of cognitive psychologists, cognitive control in human
performed through the working memory in the prefrontal cortex (PFC) [14][15]. Furthermore, attention and emotion play an important role in human’s decision and task execution [16].

**B. Self Agent**

The Self Agent (SA) represents the sense of self [17] through monitoring the robot’s own internal state as well as the progress of task execution via sensor signals, agent communications and working memory [18]. 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.

The SA also responds to commands given by humans through the Human Agent. Figure 4 illustrates the current design of the Self Agent and its interaction with other components.

**C. Central Executive Agent**

ISAC’s cognitive control functions are modeled after Baddeley and Hitch’s psychological human working memory model [19]. Their model consists of the “central executive” which controls two working memory systems, i.e., phonological loop and visuo-spatial sketch pad. Cognitive control in ISAC is implemented using the Central Executive Agent (CEA) that interfaces with the Working Memory System (WMS).

CEA functions include task planning, action selection and action execution. Thus, CEA must be able to handle both sensor-based percepts and goal-oriented symbolic data processing.

CEA handles sensor-based percepts that are assigned the focus of attention by the Attention Network [20]. Perceived sensory inputs that have a high emotional salience will cause the Attention Network to pay attention and CEA will execute a task sequence as shown in Figure 5.

![Figure 5. Interaction between CEA, STM and WMS during a task execution](image)

**IV. COGNITIVE CONTROL AND THE WORKING MEMORY SYSTEM**

**A. ISAC’s Memory Structure**

ISAC’s memory structure is divided into three classes: Short-Term Memory (STM), Long-Term Memory (LTM), and the Working Memory System (WMS). The STM holds sensory information about the current environment, while the LTM holds learned and taught behaviors, semantic knowledge, and past experience. The WMS holds task-specific STM and LTM information and streamlines the information flow to the cognitive processes during the task execution. Our STM is implemented using a sparse sensory data structure called the Sensory EgoSphere (SES). The SES, inspired by the egosphere concept defined by Albus [21], serves as a spatio-temporal STM for a robot [22]. Long-term memory (LTM) is divided into three types: Procedural, Episodic, and Declarative. LTM stores information such as skills learned and experiences gained for future retrieval. Detail descriptions of LTM implemented for ISAC could be found in [11].

**B. Working Memory System**

Working memory “represents a limited-capacity store for retaining information over the short term and for performing mental operations on the contents of this store” [1]. There is much evidence for the existence of working memory in primates [15]. Such a memory system is said to be closely tied to task
learning and execution.

Inspired by this, we are investigating the utility of integrating the (adaptive) working memory structure into a robot in order to provide the embodiment necessary for exploring the critical issue of task execution and learning. Our hypothesis is that this integration will lead to a more complex, but realistic robotic learning system involving perceptual systems, actuators, reasoning, attention, emotion, and short- and long-term memory structures [23].

IV. CURRENT COGNITIVE CONTROL EXPERIMENT

We have designed an integrated cognitive control experiment based on the CEA, the Attention Network, and the Working Memory System as follows:
1. ISAC is trained by human to learn specific object using voice, vision, attention (Learn by association)
2. ISAC is asked to point to one of the learned objects (Use of short-term memory of the object and long-term procedural memory) (Figure 6)
3. ISAC is asked to visually track the object held by a human (Color tracking) (Figure 7)
4. During visual tracking, fire alarm rings. ISAC must quickly make decision whether to stop the task at hand or react to the alarm based on the current situation (Cognitive control).

Steps 1-3 have already been individually tested [24][25], but have not been integrated with the rest of the components. In Step 4, ISAC’s cognitive control must

- Pay attention to new stimulus
- Use emotion and past episodes to activate cognitive control.

Fig. 6. ISAC is asked to point to one of the learned objects.

Figure 7. ISAC tracking Barney

This cognitive control experiment is being implemented through integrating the working memory and the central executive together with the existing IMA agents as shown in Figure 8 (See next page).

This experiment tries to demonstrate that the artificial cognitive machines such as HAM machines should not completely governed by pre-programs and therefore will learn from past and current experiences with the outside environment.

VII. CONCLUSIONS

Realization of general-purpose robots with adult-level intelligence continues to be the dream of many robotic researchers. During the past decade, we have seen major advances in the integration of sensor technologies and AI-based reasoning and learning into domain-specific robots and expect this trend to continue.

The next challenge for robotic researchers will be the integration of human-like cognitive control into robots. This paper described our efforts towards this challenge through the realization of a cognitive robot using a central executive, attention, emotion, and a working memory system.

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REFERENCES


APPENDIX

A Biologically Inspired Adaptive Working Memory System for Efficient Robot Control and Learning

(NSF Grant # EIA-0325641) [2004 – 2008]
PI and Co-PIs: D. Mitchell Wilkes, Kazuhiko Kawamura, and David C. Noelle, Vanderbilt University and Marjorie Skubic and James M. Keller, University of Missouri – Columbia

Research Objectives & Approach

In the primate brain, the tension between the desire for flexibility and the need for efficiency is thought to be largely addressed by the interaction between working memory and executive control faculties in the prefrontal cortex (PFC) and systems supporting relatively automatic forms of behavior in more posterior areas. Our research objectives and approach include:

- to develop powerful perception algorithms capable of encoding sensory events as abstract and compact working memory chunks.
- to develop cognitive architectures for flexible motor control, utilizing an adaptive working memory to guide the search for situation-appropriate motor skills.
- to demonstrate the utility of an adaptive working memory for robot control.

Expected Outputs

- Computational methods facilitating the development of robots and other cognitive systems capable of learning from experience to respond flexibly in novel situations was one goal. The further development of ISAC’s cognitive architecture is one result.
- Refined computational neuroscience models of human memory, tested in the real world with good results so far is another goal.
- A freely disseminated open source software toolkit for robotic adaptive working memory systems called the Working Memory Toolkit is a third major result stemming from this grant.