

Cognitive Robotics: What it is and Why it is Important for the Assistive Robotics Community

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Abstract – Today robotics technology is broadening its applications from factory to more general-purpose applications in domestic and public use e.g., rehabilitation, search and rescue, etc. However, if robotics technology is to be successful in such environments, it will need to meet new levels of robustness, physical dexterity and cognitive capability. This paper discusses an emerging field called *cognitive robotics* and its importance to the assistive robotics community. Research topics and key features of cognitive robotics are introduced and a case study of internal rehearsal, a key feature of cognitive robots, is described.

I. INTRODUCTION

I began my robotic work in the area of rehabilitation technology more than two decades ago (Figure 1). In my 1995 paper called *Intelligent Robotic Systems in Service of the Disabled*, I argued that “intelligence is necessary in robotics used for rehabilitation in order to reduce the amount of mental activity needed by the user of these robots” [1].

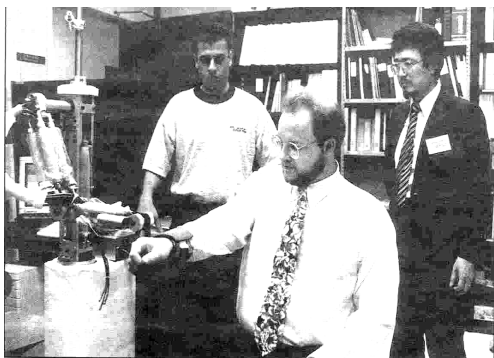


Fig. 1 Haptic-based robotic arm rehabilitation system developed at the Center for Intelligent Systems, Vanderbilt University in the 1990s

Since then, the assistive robotic technology has evolved towards adaptive systems for the disabled. However, as many advanced countries are becoming aging societies, the assistive technology must now serve much larger portion of the population. This new reality in turn will require assistive robotics community to pursue new

levels of robustness, physical dexterity, high-level cognitive capability and trustworthiness in assistive technology. One emerging field of robotics which is expected to make a major contribution to the robotics community including those engaged in the assistive technology is called cognitive robotics. In this paper, I will discuss what cognitive robotics is and why it is important for the assistive robotics community.

II. ASSISTIVE ROBOTICS AND FUTURE MARKET

A Assistive Robotics

Assistive robotics may be classified either contact or non-contact. When the term *assistive robotics* is used, we generally mean stand-alone, contact assistive robotics, i.e. robotic technology that provides assistance to the disabled through physical contact such as intelligent wheelchairs and the Intelligent Sweet Home [2]. (Although prosthetic hands, arms and legs may be considered to be assistive technology, they are not considered to be assistive robotics here.) Assistive robotics also includes non-contact assistive robotics, i.e. robotic technology that provides assistance through interaction without physical contact [3]. Figure 2 illustrates a 90%-plus non-contact robotic feeding system we developed at Vanderbilt. This paper addresses some research and implementation issues for an emerging class of robotics called cognitive robotics that may be applicable to both contact and non-contact assistive robotics.



Fig. 2 Robotic Feeding System developed by Kawamura and others during the 1990s

B. Future Assistive Robotics Market

In the past, I was engaged in a number of technology forecast (e.g. [4]) projects. Technology forecast is an inexact science, but you can use a number of standard techniques to make the forecast as plausible as possible (e.g. [5]). Market forecast, on the other hand, is much more subjective and sensitive to economic conditions, so we must treat such data with a grain of salt. In 2006, NSF Tokyo Regional Office publish a report [6] called, *Robotic Research in Japan*. It cites a Japanese Government projection for robot market (See below) through 2025. The absolute numbers in the figure is not that important. What important in the projection is this: in 2025, more than 50% of robot market is projected to be in “Daily Life” including robotic assistive technology.

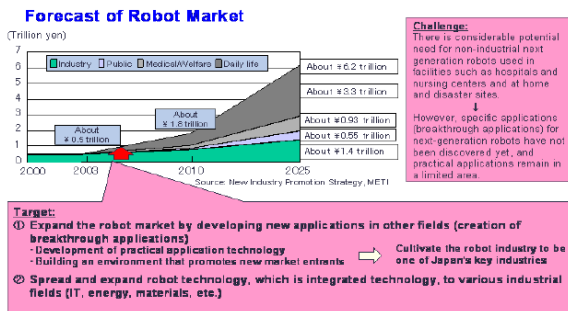


Fig. 3 Robotic Market Projection in Japan [6]

Historically one government agency called AIST (Agency for Advanced Industrial Science and Technology) played a critical role in robotics R&D in Japan. Examples include the Extreme Robotics Project in the 1980s and the Humanoid Projects in the late 1990s to early 2000s. AIST now is pushing another field of robotics called service robots (i.e. robots to perform services useful to the well-being of humans) that include care and welfare robots. Figure 4 shows an R&D roadmap through 2025 as presented by AIST. Type 1 (Cleaning and Guard Robotics) is already in the commercialization phase. According to AIST, the commercialization of Type 2 (Care and Welfare Robotics) is projected to begin in 2010 which is only three years away.

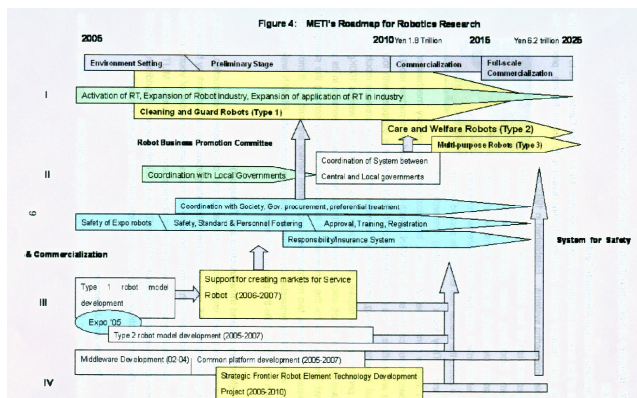


Fig.4 Roadmap of Robotics Research and Development [6]

III. COGNITIVE ROBOTICS

Cognitive Robotics is an emerging field of robotics [7]. Currently there is no generally accepted definition of cognitive robotics since *cognition* like *intelligence* is difficult to define. However, the field of cognitive robotics generally considered to comprise the design and use of robots with human-like intelligence in perception, motor control and high-level cognition. To realize cognitive robots many overlapping disciplines are needed, e.g. robotics, artificial intelligence, cognitive science, neuroscience, biology, philosophy, psychology, and cybernetics. Thus, attempting to tightly define the subject is not constructive as often its nature is amorphous, growing and a strict definition could exclude future relevant work.

Work by Clark and Grush [8] towards a cognitive robot definition is well respected. They list some important considerations for cognition. Two of them are listed below:

- We hold that fluent, coupled real-world action-taking is a necessary component of cognition.
- Cognition, we want to say, requires both fluent real-world coupling and the capacity to improve such engagements by the use of de-coupled, off-line reasoning.

The first point is well accepted among robotics researchers. This is certainly true for assistive robotics as well although the reality is still quite far away from the ideal case. The importance of the second point, however, is not well understood. I will discuss this point further in detail later.

A. Overview of Cognitive Robotics

The origin of modern cognitive robotics comes from the field of cybernetics, the study of control and communication in living organisms, machines and organizations. The term cybernetics was popularized by Norbert Wiener in his 1948 book [9]. Cybernetics had a crucial influence on many important concepts such as goal-directed behavior generation, self organization and situated nature of intelligence, which are now commonly used in the intelligent robotics community.

In the 1960s, researchers in artificial intelligence (AI) pursued the concept of intelligence from a more deterministic point of view. AI, or often known as strong AI, was predicated on the presumption that intelligence or knowledge can be represented as production systems and stored inside of a machine, i.e. computer. Under this definition, computer can be a brain itself. However, researchers in cybernetics claim that intelligence is an attribute of an interaction with the environment rather than a commodity stored in a computer and must be actively constructed by a machine itself. This evolutionary cybernetics approach is also known as the second-order cybernetics [10] (Principia Cybernetica Web, 2001). Similar approach in robotics is now known as evolutionary robotics [11].

As the opening paragraph of this section stated, the goal of cognitive robotics is to build a robot with human-level intelligence. There are two problems with this statement. First is “intelligence”. The term intelligence is used in a variety of situations and is difficult to quantify. Another problem is “human-like”. What do we mean by human? Do we mean an ordinary adult? How about children? Even a three-year child can show many levels of intelligence. This simple argument may be enough to show the problems with the term “human-level intelligence”.

In 1993, Rodney Brooks began to work on a first generation “cognitive” robot (COG) which was an upper-torso humanoid. COG was used to generate intelligent behaviors [12]. His effort inspired a number of government and commercial humanoid development projects during the 1990s and early 2000s. One of the strong arguments for humanoid robot development was that there is a strong desire to replicate human behavior within embedded human-like artificial agents and humanoid robots are the best embedded system.

For the assistive technology community, an argument can be made that it is not clear if a human-like embodiment is necessary or not. E.g. no one knows whether an elderly person prefers a human-like robotic companion (Figure 5B) to a robotic wheelchair that provides specific needs for the person (Figure 5A). I would say the jury is still out. By the way, this tradeoff between *general-purpose robots vs. specialized robots* is one of the oldest debates in industrial robots. However, the choice here is more complicated since we must include not only cost and development efficiency as design criteria but trustworthiness and comfort as well that are not easily quantifiable.

It is, however, interesting to notice that the US Army is now developing a humanoid robot called BEAR (for Battlefield Extraction Assist Robot) [13] to scoop up wounded soldiers from the battlefield and transport them over long distance. It will be controlled remotely through vision and voice interfaces and is expected to be ready for testing by 2012 (Figure 5C).

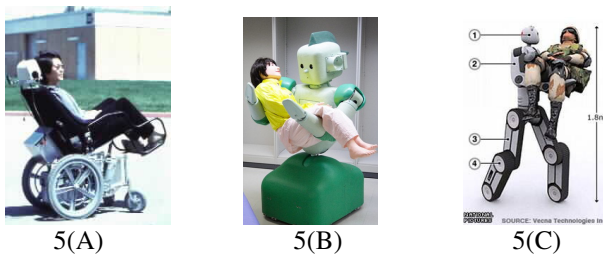


Fig. 5A Head Controlled Wheelchair. VA Palo Alto, CA, Rehabilitation R&D Center (<http://guide.stanford.edu>)

Fig. 5B RI-MAN (Riken Man) will be equipped with 4 sensors: visual, vocal, smell, and touch. Its unique feature is that it can perform jobs that require muscle power. It h and arms by sensing the strength of pressure as five touch

in its arms and breast, and can control the movement of its body. (Still in early testing stage)

Fig. 5C BEAR (Battlefield Extraction Assist Robot). Source: Vecna Technologies, College Park, MD

B. Research Topics

In 2006 international researchers representing many of the above-mentioned disciplines attended the International Workshop on Cognitive Robotics, Intelligence and Control (COGRIC) [14], where participants discussed the present state and the future of cognitive robotics. Important features of cognitive robots identified are listed below. From discussions, it was concluded that it is not worth debating boundaries between intelligence, cognition and consciousness. Lifelong adaptability and developmental learning were mentioned as future opportunities.

Key features that participants identified (random / not prioritized) are:

- Ability to perceive the world in a similar way to humans (or better) (e.g., “active perception”, “ecological approach to perception”)
- Ability to communicate with humans using natural language (robust human-robot interaction such as overcoming the *frame of reference problem*)
- Ability to develop cognition through sensory-motor coordination (e.g., “morphological computation”)
- Ability to use attention and emotion (not in a sense of social robots) to control behaviors.
- Ability to have a sense of self awareness.
- Ability to form a mental representation or a model of the user.
- Ability to execute fluent, coupled real-world action-taking and hold the capacity to improve such engagements by the use of de-coupled, off-line reasoning.

In the following sections, I will discuss the importance of the last two features for the assistive community.

IV. IMPORTANCE OF INTERNAL MODEL FOR ASSISTIVE ROBOTS

A. Internal Model of Human

One of the growing application areas of assistive robotic technology is computer-integrated surgery [15]. In such a surgery, developing a patient-specific model prior to the operation, storing it as an internal model within a computer-integrated surgery system and updating it during the operation is critically important. (Figure 6)

Similar information flow occurs when we meet with someone. In that case, consciously or unconsciously we develop an internal model of the person and keep updating it as we get to know the person better. This internal model is often called a *mental model*. This model is different from another internal model called a *user model* used in human-computer interaction (HCI). The user model is used to

represent a user’s cognitive processing capabilities such as how many times the user clicks a Help button, but we will not consider this type of internal model in this paper.

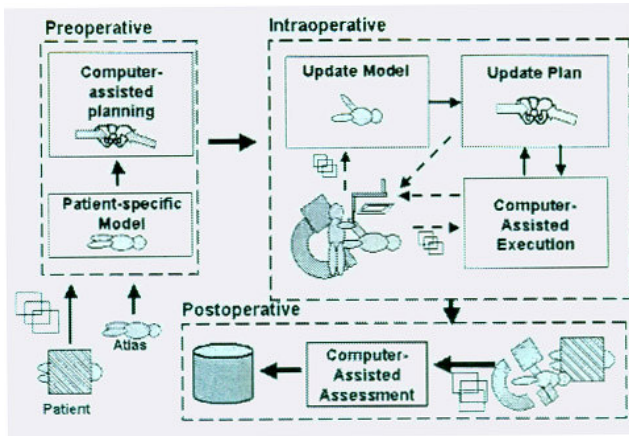


Fig. 6 Information Flow of Computer Integrated Surgery Systems [15]

How are a patient-specific model in computer-integrated surgery (CIS) systems and a mental model in our daily life different? Both models contain (1) physical or external features such as height, sex, body shape, etc., and (2) internal features. The internal features, however, are quite different between the two models.

For CIS systems, internal features may include blood pressure, body temperature, shape of internal organs, etc. For mental models in daily life, internal features may include the degree of affect of the person, motivation, willingness to cooperate, etc. Modeling internal features or states for robotics is getting more important as robots are increasingly used in social settings [16][17].

For the assistive robotics, modeling internal states of the user (i.e. the person to whom care is provided) is equally important in order for assistive robotics to be able to provide personal care.

B. Human-Robot Interaction

In the ISAC cognitive architecture (shown in the appendix), the person with whom the ISAC humanoid robot is interacting with is represented as a distinctive agent called the Human Agent (Figure 7). Currently the Human Agent receives information about the person’s physical state from the robot’s sensors and estimates the person’s internal state such as intention [18].

Another key agent in the architecture is the Self Agent. The Self Agent represents the robot’s self, and is responsible for cognitive activities such as imagination and motivation [19]. Assistive robots such as RI-MAN in Figure 5B will be able to perform far superior service if they are equipped with both a user’s mental model and a robot’s self module that interacts with the user’s mental model internally as shown in Figure 7.

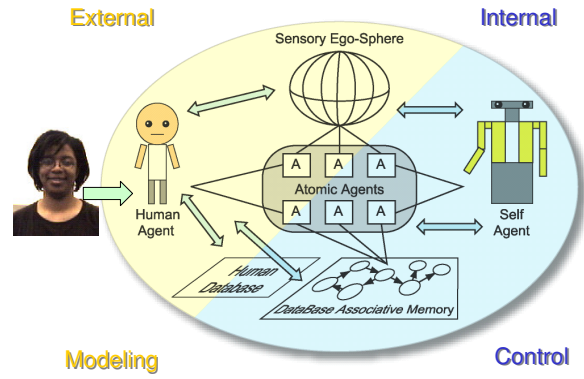


Fig. 7 Human-Robot Interaction within the original ISAC Cognitive Architecture [14]

V. INTERNAL REHEARSAL

This section introduces our effort towards realizing another important feature of cognitive robots, i.e. the ability to execute fluent, coupled real-world action-taking and hold the capacity to improve such engagements by the use of off-line, grounded reasoning [8].

It is known that humans are able to have sensory experiences in the absences of external stimuli as illustrated by experimental results of e.g. Lee and Thompson [20]. It thus seemed reasonable to assume that the existence of an “inner sense” where sensory experiences and consequences of different behaviors may be anticipated.

Our approach differs from a classical internal world model approach. Instead, it is based on the “simulation hypothesis” by Hesslow [21] which accounts for the ‘inner world’ in terms of internal simulation of perception and behavior and thus may be termed as a “grounded internal simulation” utilizing one type of internal representation of perception and behavior.

A Design of the Internal Rehearsal System (IRS)

In our architecture, the Self Agent handles the dual sensorimotor loops as shown in Figure 8 [22]. The First-Order Response Agent (FRA) is responsible for the reactive and routine responses of the system while the Central Executive Agent (CEA) is responsible for the cognitive response.

The Internal Rehearsal System (IRS) takes the working memory chunks as the motor commands, the current situation as the external state and sends a rehearsed result to CEA. If IRS produces a poor prediction, CEA will suppress the Activator Agent, replace the working memory chunks, and tell the Activator Agent to switch action.

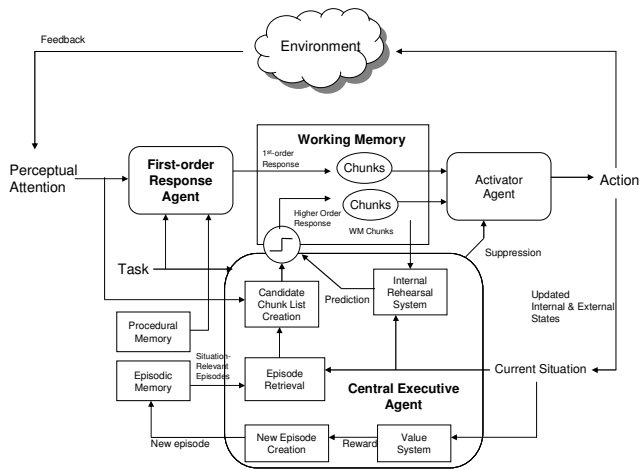


Fig. 8 ISAC Self Agent Cognitive Cycle

When IRS is invoked by CEA, it takes the current behavior chunk as the motor command and the current environment ISAC is in as the current state. After CEA selects a behavior to perform the skill described by the task, IRS internally rehearses the behavior with the percept corresponding to the current. If a collision occurs with the percept during the rehearsal, IRS returns the percept, the step in interpolation where the collision occurred, and the total number of joint steps in the interpolated motion to CEA.

The following experiment is designed to evaluate how FRA, CEA, and IRS work together. The experiment involves two percepts: Barney (target) and a Lego toy (obstacle) (Figure 9).

1. A task to *reach-to-Barney* is given to ISAC. FRA immediately places ReachRight and Barney into the working memory (WM) as chunks.
2. Using the chunks, IRS will try to reach to the Barney with the right arm, but predicts a collision with the Lego toy.
3. CEA will suppress the Activator Agent based on this prediction from IRS.
4. CEA will use the episodic retrieval technique and replace the chunk ReachRight to ReachLeft.
5. IRS will reach to the Barney with the virtual left arm. This reach will be successful.
6. CEA will let the Activator Agent proceed to reach to the Barney using the left arm.

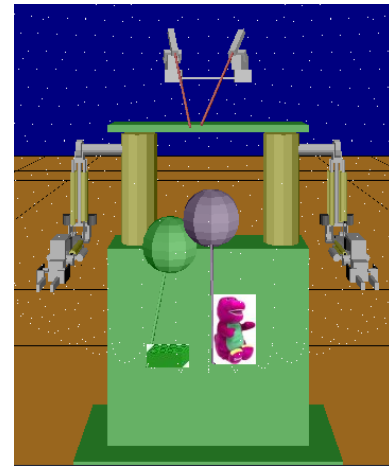


Fig. 9 ISAC Simulator Displaying Two objects as Spheres

B. System Performance

When ISAC was given a command to reach to the Barney, FRA placed two chunks “ReachRight” and “Barney” into the working memory. (Note: ISAC normally manipulates objects with right hand.) Both the Activator Agent and IRS began to process these chunks. IRS completed the computation within 3.202 seconds and sent its results to CEA. At the same time, the Activator Agent sent a motion command to the Right Arm Agent to perform the reaching motion. The Right Arm Agent would take 10.985 seconds to perform this type of reach if no obstacle exists.

When IRS finished, the following output was sent to CEA: [15 68 lego_toy]. This means that during the simulation, IRS determined a collision with the Lego toy in the fifteenth step of the verb/adverb interpolated reach behavior out of the total of 68 interpolated steps. Figure 10 shows the trajectories of the right arm collision points during the rehearsal. CEA took this result and determined that it did not reach to Barney. CEA then suppressed the Activator Agent and prevented the right arm from further action.

CEA then decided to use an episode involving the left arm and replaces the working memory chunks with “ReachLeft” and “Barney”. IRS and the Activator Agent were once again initiated, and IRS internally rehearsed the reach skill and determined no collision with the Lego toy. Indeed, IRS found a collision with Barney, a success, as shown in Figure 11. Both the wrist and end effector points entered the Barney percept sphere on the sixteenth step of the Verb/Adverb interpolation. The output of IRS was [16 69 barney_toy] after 2.983 seconds. CEA determines this as a success and did not impede the Activator Agent thus allowing ISAC to reach to Barney using his left arm. The final result of the experiment is shown in Figure 12.

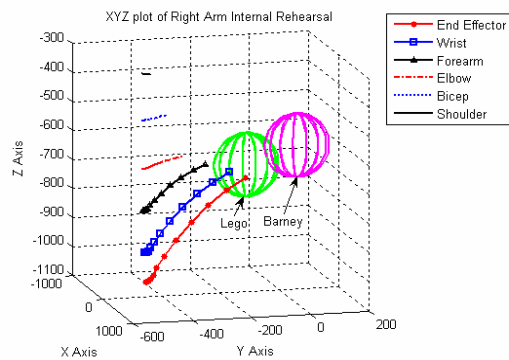


Figure 10. Right Arm Internal Rehearsal

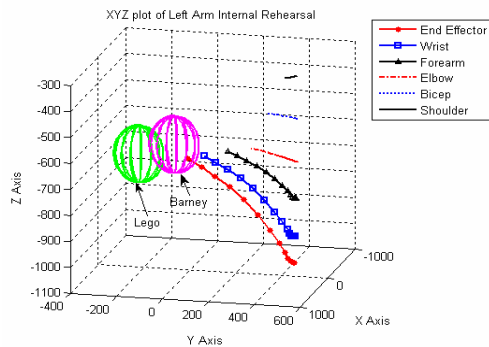


Figure 11. Left Arm Internal Rehearsal

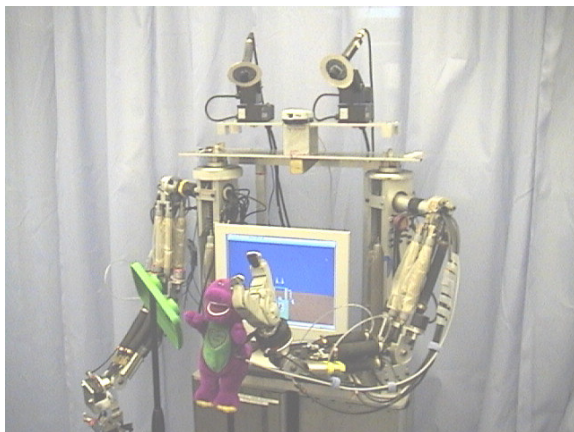


Figure 12. ISAC Reaching to Barney with Left Arm

VI. CONCLUSIONS

As our society becomes an aging society, the assistive robotic technology must serve much larger portion of the population than it now serves. This will require new levels of robustness, physical dexterity, high-level cognitive capability and mutual trust. In this paper, one emerging field of robotics called *cognitive robotics* was introduced and two key features were discussed. One was the ability for implementing a mental model. Modeling a mental

model in robotics is still in its infancy and more research will be needed. Another was the ability to emulate brain's 'inner sense' where sensory experiences and consequences of different behaviors may be anticipated. Eventually this ability should extend to more robust human-robot interaction in which robot can interact internally with human. In summary, the field of cognitive robotics will make a major contribution in coming years to the robotics community including assistive robotics community. It is the author's hope that more robotics researchers will become interested in cognitive robotics.

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APPENDIX

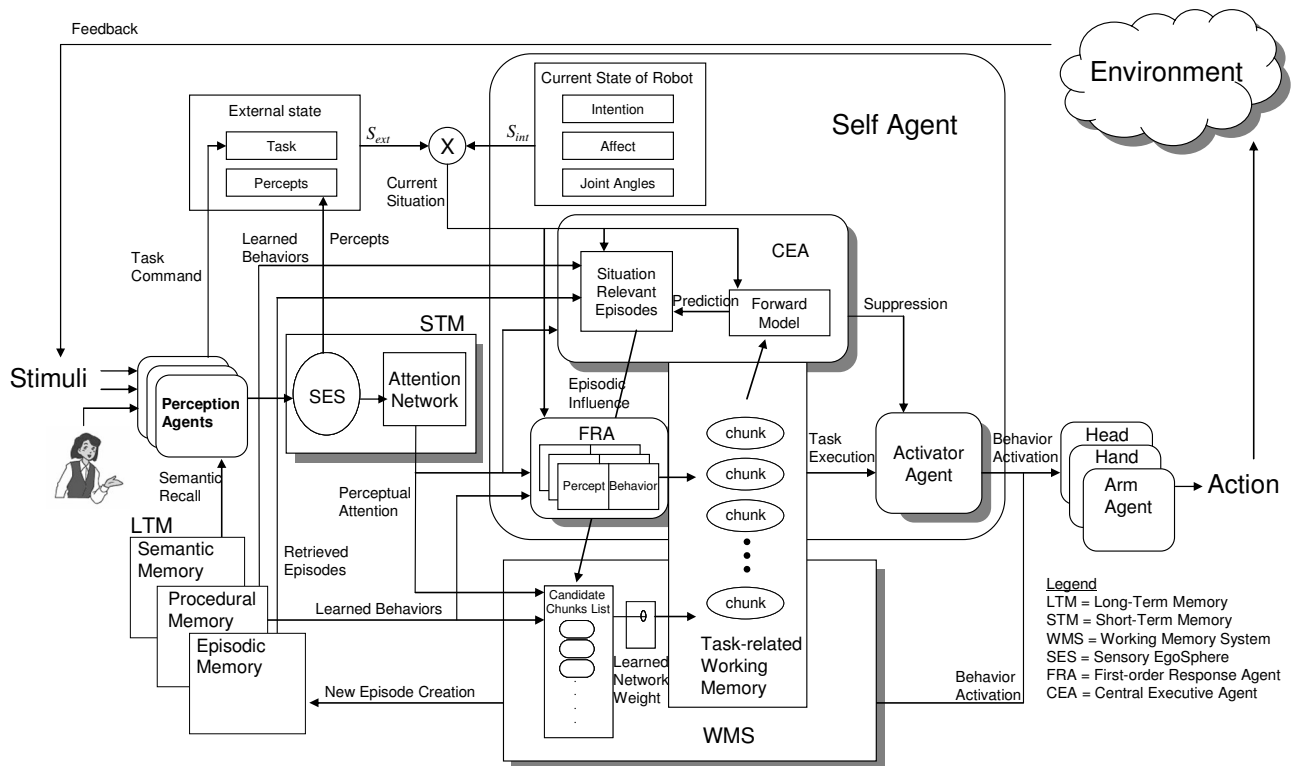


Fig. A1 Multiagent-Based Cognitive Robot Architecture [23]