The Role of Episodic Memory and Emotion in a Cognitive Robot

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***Abstract* – The design and creation of an episodic memory system for a cognitive robot is detailed. This memory system is interfaced with a machine emotion system with the goal of producing intelligent behaviors in a cognitive humanoid robot. The design of the system is tested and analyzed through the explanation of a case in which emotion assists in the retrieval of an episode.**

Index Terms* – *cognitive robot, episodic memory, cognitive agent, working memory

I. Introduction

Cognition in humans is exhibited through the characteristics of "short and long term memory, categorizing and conceptualizing, reasoning, planning, problem solving, learning, [and] creativity" [1]. A cognitive system employs a combination of artificial intelligence techniques within a structure derived from human psychology in an attempt to produce the above-listed characteristics. A cognitive robot is an embodied cognitive system implemented on a robot.

With the listed characteristics in mind, a cognitive system is being implemented on ISAC, or Intelligent Soft Arm Control, humanoid robot. As the name suggests, ISAC is equipped with air-powered actuators designed to work safely with humans [2].

Psychologically, humans are ascribed to have many different types of memory: short and long-term memory, working memory, semantic and episodic memory among others. ISAC contains parallels to many of these memory types, however the concern of this paper is the formation of an Episodic Memory system.

The purpose of an Episodic Memory system is to allow the learning of episodes, or temporally sequenced records of specific events that occurred to the cognitive agent [3]. Within the computational neuroscience community there is a recognition that there are two mutually exclusive goals of long-term memory: learning interleaved, generalized representations of behaviors and perceptions and learning isolated, one-shot episodes. The former memory formation type is generally attributed to densely activated neuronal firing patterns, or codes, within the human neocortex, while the latter is achieved through sparse coding in the human hippocampus [4].

An effectively designed episodic memory system must accomplish the task of retrieving the correct episodes for a given situation. In the following section, we will outline how ISAC's episodic memory system is designed to retrieve the correct memory using memory statistics and emotion.

II. ISAC's Cognitive System

Computation on ISAC takes place within the framework of the Intelligent Machine Architecture (IMA), a true multi-agent system designed to promote code-reuse [5]. Individual agents work together to produce complex behavior.

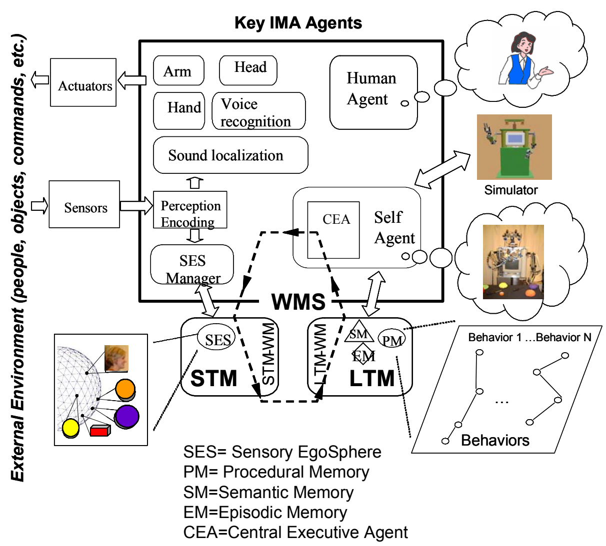

Figure 1: ISAC's Cognitive Robot Architecture

The cognitive system detailed in Figure 1 is embodied in ISAC – the system interacts with the world through ISAC's actuators, voice, and computer display systems, and receives information about the world from ISAC's sensors.

ISAC's memory is divided into three classes: Short-Term Memory (STM), Long-Term Memory (LTM), and the Working Memory System (WMS). The STM holds information about the current environment while the LTM holds learned behaviors (in the Procedural Memory or PM), semantic and perceptual knowledge (in the Semantic Memory or SM), and past experiences (in the Episodic Memory or EM). The WMS holds task-specific STM and LTM information and streamlines the information flow to the cognitive processes during a task.

ISAC's sense of self is represented in a compound agent (an agent consisting of several simple agents) called the Self Agent. The Self Agent [6] is the location of ISAC's planning systems, executive control, self-monitoring, task selection, and other functions attributed to human cognition.

A component of the Self Agent called the Central Executive [7] retrieves information from the memory systems through an active memory storage daemon called the Working Memory System.

The Working Memory System monitors the needs of the Central Executive Agent, the contents of the memory systems, and the output of the perceptual system to populate itself with the most relevant data pieces, or “chunks”. Each type of memory has a different method of chunk retrieval and its own limited-capacity Working Memory. Because the Working Memory is automatically populated with a limited number of chunks, the executive functions within the Central Executive Agent do not have to sort through massive amounts of information [8].

A structure called the Sensory EgoSphere (SES) holds STM data. The SES is a data structure inspired by the egosphere concept as defined by Albus [9] and serves as a spatio-temporal short-term memory for a robot [10]. The SES is structured as a geodesic sphere that is centered at a robot's origin and is indexed by azimuth and elevation. In ISAC, the SES is centered between the cameras.

ISAC's LTM is divided into three types: Procedural Memory, Episodic Memory, and Declarative Memory. Like that in a human brain, the LTM stores information such as *skills learned* and *experiences gained* in the long term for future retrieval.

The part of the LTM called the Procedural Memory (PM) [11] holds motion primitives and behaviors needed for movement, such as how to *reach to a point*. Behaviors are derived using the spatio-temporal Isomap method proposed by Jenkins and Mataríc [12].

The Semantic Memory (SM) is a data structure about objects in the environment. It details perceptual and semantic information, and is intended to allow the cognitive systems to reason about and plan with objects, goals, and movements. The EM and SES hold links to SM nodes to represent relevant information.

The Episodic Memory (EM) system holds records of past experiences in a time-indexed format. The purpose of the EM is to allow the cognitive processes to trigger new action, selection, and execution. The Episodic Memory daemon records the contents of the Working Memory System along with salience information from the Emotion Agent for the duration of a single task and posts this information to an EM data unit. EM units decay at a rate related to the output of the emotion agent for the duration of the recorded task.

The Working Memory System (WMS) holds a limited amount of “chunks” of each of the memory types listed above. Each memory system has a different method of populating its section of the WMS; techniques range from an attentional network for the STM-WMS to a direct executive query for the SM-WMS.

III. ISAC'S EPISODIC MEMORY

As stated earlier, the EM system holds records of specific, temporally-based past experiences, or episodes. A single episode is defined as a period of task execution of the robot during which the goal of the robot does not change.

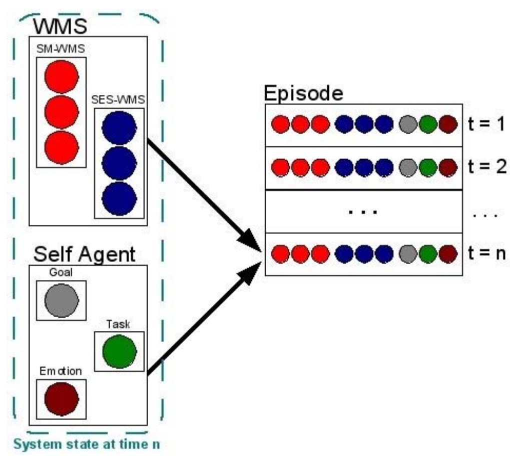

Figure 2: Episodic Memory Formation

As seen in Figure 2, each episode contains links to the entire contents of the Working Memory System and the output of the Emotion Agent for the duration of the task. All constituent links point to Semantic Memory units, so statistics may be calculated about the frequency of use of each SM.

The task of the EM retrieval system is to automatically populate the Episodic Memory Working Memory System (EM-WMS) with the correct episodes for a given situation. The relevance measurement for comparing a given memory with the current situation consists of five major factors:

i. The retrieved memory should contain similar SM units to the current situation.
ii. Recent, commonly accessed episodes are more useful than older, less used episodes.
iii. Novel similarities should score higher than common similarities within episodes.
iv. The executive system should be able to shift attention to certain elements of the cue.
v. Emotionally salient memories should score higher than those producing little emotion.

The first two criteria are obvious: if the cue contains a specific task or object, the resulting memory needs to contain common elements to be relevant to the current situation, and recently formed memories are more likely to contain applicable information. The third selection point is used to enhance the score of cues that are rare over those that are commonly seen. This serves to enhance those aspects of a cue that differentiate it from others. The fourth criterion allows the executive system to weight aspects of a cue that are important to the current context. For example, if the system needed to know the last place it placed a particular object, it would need to heavily weight the memory structure representing that object. Lastly, a machine emotion system may be used to interject personal significance to an episode. If the robot were strongly rewarded after performing a task in a certain manner, it makes sense to recall that episode over a task execution in which little feedback was given.

The retrieval of episodes is accomplished through an algorithm that takes the currently forming episode and selects several stored episodes for placement in the EM-WMS. As (more generally) stated by Anderson [13], the probability that a memory is relevant is calculated through the combination of two independent factors: a history component and a contextual component.

$$P(A)=P\left(A|H_A\right)*P\left(A|Q\right) \quad (1, [13])$$

The contextual component P(A|Q), or the probability that memory A is suitable given only the cue, is calculated by measuring the importance of each constituent SM unit in the formative EM and comparing it with the relative importance of the same SM in the candidate EM units. Importance is defined as the percentage of time that each SM spends in the Episodic Memory divided by the total size of the EM and the access count for the SM in question, and may be calculated for candidate EM units by a simple count. This definition is derived from the role of the WMS: to hold the most relevant task-related information in the current context.

The retrieved episodes are used to generate future actions through a planning system. Because the size of the EM-WMS is relatively small, episodes can be linked together to chain behaviors in a tractable fashion. The EM-WMS is populated continuously, so the episodes available to the planner change as new situations arise. This allows the system to generate plans as new problems are encountered.

The search is performed in a top-down manner – the list of SM units in the search cue are ordered by importance. EM units containing each SM unit are found through the use of a hash, and each candidate EM unit is assigned a score by multiplying the importance of the SM unit to the candidate unit with the importance of the SM unit to the cue. The list of SM units in the cue is traversed, and candidate EM units are pruned as it is no longer possible for them to enter the list. When the list of candidate units equals the size of the EM-WMS, the search is successful.

This search method has several characteristics that are advantageous to its application in ISAC's cognitive system:

- It prunes irrelevant information from memory during the course of a search, reducing memory requirements.
- It weights less common DM units more than others, so the search space is naturally constrained.
- It requires only a 1-level hash, reducing resources needed for complex data structures.
- A tolerance value may be set after system experience to further prune search space.
- Temporal information is discarded, which immensely reduces the complexity of comparison of time-based memory units.
- The search will return the best possible results at any given time during execution.

The history component of Equation 1 is calculated by the equation [13]:

$$P\left(A|HA\right)=\frac{\mathrm{v}+\mathrm{n}}{M\left(t\right)+\mathrm{b}}*r\left(t\right) \quad (2)$$

In Equation 2, v and b are constant and shape the decay curve and are set to 1 and 3 by [AND], M(t) represents the integral of the decay function r(t), and n is the number of times that particular EM unit has been accessed and brought into the EM-WMS.

$$r\left(t\right)=\alpha e^{-\alpha*t} \quad (3)$$

Equation 3 shows the decay function of the EM unit, where alpha represents the emotional salience of the EM unit (adapted from [13]).

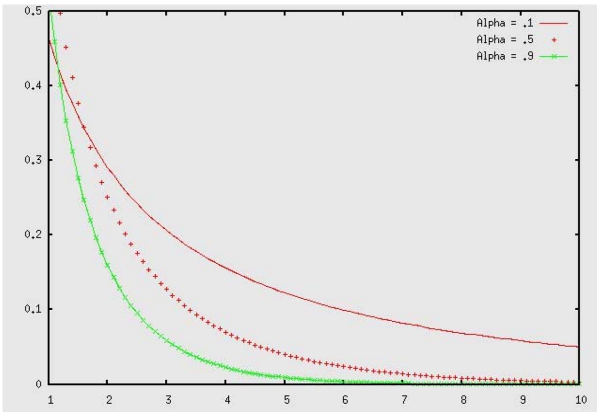

Figure 3: Sample decay curves for various alpha

Figure 3 shows sample decay curves for several emotional saliences. Those memories stored with lower alpha coefficients do not decay as quickly as those with higher alpha. The alpha is therefore set to be inversely proportional to the salience of a given memory term. The salience term is important for the selection of correct memory units – the robot should strongly retrieve episodes that resulted in extreme reward or punishment, and it should remember those highly salient episodes well into the future.

The plots in Figure 3 show the decay of memories that are not accessed. When a memory is accessed, its history probability increases because of "n" in equation 2. This helps offset the decay for a memory that proves to be useful in several situations.

Humans may be seen to exhibit this quality of remembering emotionally salient events as well in what are called "flashbulb memories". In ISAC, the salience of a memory is calculated through a transformation of the emotional salience scalar that is output from the emotion agent during that memory's formation.

IV. The Emotion Agent

Clearly, the cognitive system needs a way of representing and evaluating emotion. We propose a design using Haikonen's System Reactions Theory of Emotions (SRTE).

The SRTE states that "emotions could be considered as interactive combinations of perceivable basic system reactions…" The basic system reactions are simple, automatic responses to the elementary sensations (ES) [14]. Haikonen proposes the elementary sensations to be Good, Bad, Pain, Pleasure, and Match/Mismatch/Novelty (MMN).

First, the elementary sensations must be defined for ISAC: Good, Bad, Pain and Pleasure. ISAC does not have elementary sensors for pain, pleasure, or taste/smell. Table 1 shows the relationship between elementary sensations and the reactions of the system to those sensations.

Elem. Sensation	System Reaction
Good; taste, smell	Accept, approach
Bad; taste, smell	Reject, withdraw
Pain; self-inflicted	Withdraw, discontinue
Pain; due to ext. agent	Aggression
Pain; overpowering	Submission
Pleasure	Sustain, approach
Match	Sustain attention
Mismatch	Refocus attention
Novelty	Focus attention

Table 1: Elementary sensations with corresponding system reactions [14]

The pain could be implemented programmatically. For example, when the joint angles of any of the joints approaches the limit, a "pain flag" is raised. This flag will increase its weight as the angle gets closer to the limit, reaching a maximum at the limit of the angle.

A similar approach can be used with the intensity of the light perceived by the cameras in ISAC or level of sound in the microphones. Other pain thresholds can be imagined, for example, internal pain caused by the long absence of interaction with humans.

The pleasure elementary sensation could be generated when there is good light for perception in the visual sensors or when there is a realization of an expectation. For example, when ISAC recognizes and greets the person with whom it just started to interact, if this person answers positively it will cause ISAC to feel pleasure.

In other words, the realization of any expectation would raise the "pleasure flag" in ISAC. Of course the opposite is also true, that is, the absence of the realization of an expectation will cause internal pain or discomfort. The pleasure flag could be generated in many other cases, for example when ISAC hears praise.

Good and bad seems easier to implement. ISAC will consider something is good when the word "good" given by the experimenter is associated with something, an object for example. Good could also be a positive outcome of an interaction or several other situations that would be added to ISAC's repertoire as the emotion agent gets more robust and experienced.

Having defined these basic elementary sensations and the corresponding system reactions, we proceed to define ISAC's emotions as the combination of them. For example, the ES of Pain if self-inflicted would generate the SR of withdrawal, and the ES of novelty would generate the SR of focusing attention. If these two SR appear together, then the emotion "caution" is evoked. Figure 4 shows the flow of information from ES onward:

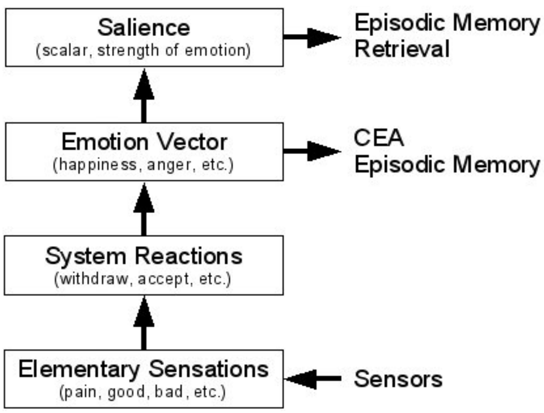

Figure 4: Emotion information flow

The ES, SR and obtained emotions should have continuous values ranging between a minimum and a maximum, say between one and minus one. The emotion agent constructed as described would generate a vector of emotions describing the current emotional state, or current mood. This vector would be attached to the associated episode stored in the episodic memory, giving emotional significance to any episode, task or interaction and may be used for any decision making. A measurement of the magnitude of the emotion vector is used to measure the salience, or strength, of the emotion.

V. Experiment

An experiment is proposed where the Episodic Memory system uses the history component (which conveys the emotional content of an episode) to return a highly emotionally salient episode. This experiment demonstrates how the episodic memory system selects highly salient episodes over episodes that are less salient.

The cognitive control experiment as discussed in [10] can be summarized as follows. ISAC performs a simple task (such as following a moving object around the room with its cameras). A person enters the room, and yells "Fire!". ISAC must retrieve the episode associating the current situation with a highly emotionally salient past experience, and must then switch tasks to warn the experimenters to leave the room based on this past experience.

The specific question to be answered by the segment of this cognitive control experiment detailed in this section is: "How does the Episodic Memory system know to retrieve the correct, highly salient episode, and how does the salience of the appropriate episode change over time?" In other words, this experiment is intended to show how the emotional salience of a memory influences its retrieval process, and how the salience could be important to selecting the appropriate memory for a given context.

As a precondition of the experiment, ISAC's Episodic Memory banks are loaded with a number of episodes, both salient and non-salient, relevant and non-relevant. These Episodes will approximate tasks that ISAC might actually come across, such as locating or learning an object, playing a game with a human experimenter, learning new movement commands or tasks, or greeting humans. Thirty-three sample episodes are stored in ISAC's EM system, and the task of the EM-WM system is to select the three most relevant episodes to the current situation. The target episode will be a previous encounter with the "Fire!" stimulus, in which ISAC was taught with high emotional salience that humans should leave the room.

ISAC's task is then to retrieve the target episode based on the contextual relevance supplied by the relatively rare "Fire!" stimulus augmented by the strong emotional salience associated with the target stimulus.

The first step in this memory retrieval experiment is to populate the Episodic Memory with multiple candidate episodes that might be recorded during the robot's normal operation. ISAC recognizes four objects and four people in its semantic memory. Episodes are designed to use a variety of semantic memory units to simulate different sorts of simulations that ISAC might encounter during normal operation. For the purposes of this experiment, these episodes are directly entered into the system by a human operator and are distributed by task. Tasks cover subjects like placing objects in a certain configuration, greeting humans, and identifying objects.

Other than the "Fire!" experience, each of the episodes is recorded four times per sample task (once for each object or person), ensuring a distribution of each Semantic Memory unit among several episodes. The "Fire!" episode is recorded once.

The cue for the memory consists of a simulated episode in which ISAC performs a task and is interrupted by a person giving the "Fire!" stimulus. The fingerprint produced by the cue shows how the system operates to retrieve the target memory. Even though the "Fire!" stimulus represents a small fraction of the forming EM unit, its rarity causes it to be weighted more than the other constituent SM units because the fingerprint weight of a given SM unit decreases as its usage increases. The strength of the “Fire!” stimulus in the cue is then enhanced because of the strong emotion displayed during the previous exposure to “Fire!”.

This scenario shows how the system is able to draw attention to information that is both novel and salient. If the target EM had been formed with a low amount of emotion, it would have decayed quickly by Equation 2 and would not be retrieved. The emotional information therefore allows the system to remember both recent information that was not very salient but was recently formed and information in the distant past that was extremely salient. This characteristic could be useful for both locating a recently seen object or retrieving old but important information.

Following retrieval, the cognitive system could use the episode to switch goals to removing all humans from the room. To accomplish this it would use the planning system mentioned in Section 3.

VI. Conclusion

The development of an Episodic Memory system for the cognitive robot ISAC was detailed. A scenario has been described that uses a combination of emotional salience and statistical information to retrieve the “correct” episode. This retrieval would not be possible without using the information detailed in the retrieval algorithm.

Future work includes fine-tuning of the system parameters (such as the decay coefficients of EM units) for the daily operation of ISAC. The planning system mentioned in Section 3 must also be developed more fully.

VII. Acknowledgment

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