Attention in the ASMO Cognitive Architecture

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Abstract. The ASMO Cognitive Architecture has been developed to support key capabilities: attention, awareness and self-modification. In this paper we describe the underlying attention model in ASMO. The ASMO Cognitive Architecture is inspired by a biological attention theory, and offers a mechanism for directing and creating behaviours, beliefs, anticipation, discovery, expectations and changes in a complex system. Thus, our attention based architecture provides an elegant solution to the problem of behaviour development and behaviour selection particularly when the behaviours are mutually incompatible.

Keywords. Cognitive Architecture, Attention, Self-modification, ASMO, Dynamic Behaviour

Introduction

The ASMO Cognitive Architecture [14] is a new project examining the nature of attention, self-modification and awareness in robotic systems, while simultaneously offering pragmatic solutions to the practical challenges that arise during their development. The philosophy behind ASMO (standing for Attentive Self-MOdifying) is that a powerful cognitive architecture can not only enhance the capabilities of autonomous systems, but that a cognitive architecture might also be a more natural and approachable platform for robot programming in the large.

ASMO is under development for two platforms: a custom-built robot bear designed for social human interaction and Aldebaran “Nao” robots used for robot soccer competitions. These two robot platforms have vastly different physical embodiments, operating systems and environments; yet, when developing with either, the same kinds of problems arise. In particular, at each point in time, a robotic agent faces many competing goals, must interpret multiple sources of (unreliable) sensations, and can select from many different actions (with often no objectively “correct” action).

The implementation of a cognitive architecture for these robots is constrained by the practical realities of our research environment. The architecture must be reasonably fast and run on memory-constrained devices, it must be able to support different kinds of robotics problems, it must be easily understood by developers with a variety of skill-sets, it must integrate the efforts of multiple developers and (as is particularly the case with robot soccer – a team based development challenge) it must be able to adapt to changes quickly and under the pressure of competition. However, our goal is not to find a *compromise* between biological inspiration and practice, but instead to translate ideas from cognitive science into an architecture that is *also* practical.

To address the challenge of simultaneously fusing the multiple competing processes on the robot and the competing interests amongst the development team, we drew inspiration from models of human attention as the basis for the attention-driven architecture of ASMO. Human beings are able to operate in complex environments of conflicting goals, noisy and distracting stimuli from external and internal sources, and unbounded options for action. The mind is able to selectively focus on important information and processes, while largely ignoring others. Yet, this focus is not exclusive – the focus may shift when surprising or important patterns occur in those processes that are currently being “ignored”.

Our objectives of creating a self-modifying and self-aware system in ASMO remains a long term project, however the purpose of this paper is to introduce the biologically-inspired attention-based architecture of ASMO. We begin the paper by discussing the underlying attention theory, then we explain how it has been translated into a practical computational system. We conclude with a discussion and comparison with other systems.

Attention Theory

Attention in the human mind is closely related to the brain’s inner life as consciousness and awareness. According to William James [10] (pp. 403-404) attention “is the taking possession by the mind, in clear and vivid form, of one out of what seems like several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence”. Attention plays a key role in cognition by matching internal processing with external demands and it has been studied in animals using techniques from simple psychological introspection to neuroscience brain imaging.

Attention. Anderson [2] considers attention as a mechanism for the allocation of processing and physical resources. This allocated portion changes depending on the demands of the task and the resources available. The attentional demand of the task required to respond to the stimulus is reduced by the consistent mapping between a specific stimulus and particular response, and eventually the response becomes automatic for that specific stimulus [17]. In other words, the process demands attention as long as it has not been served or satisfied.

Selection and Resource Control. Neuman [13] argues that action selection is needed to prevent disorganisation of behaviour because all potential actions might be simultaneously trying to seize control of the body. Action according to Neuman is a “sequence of movements that is controlled by the same internal control structure and that is not a reflex” [13] (p. 375).

McLeod [11] suggests that a process or task will interfere with another process if they are using the same resources. In this case, processes will compete for the same resources, and the winning action gains attention to use these resources. We say the winner has the highest attention for these resources. A winner of a given resource may not be the winner for other resources. Findings in McLeod's experiment show that the same tasks no longer interfere when response modalities change.

Automaticity. When a stimulus-response mapping receives positive feedback, the priority of the mapping increases to strengthen the connection between the stimulus and the response [18]. Extensive practice can make this connection stronger and complex behaviours can become more and more automatic provided that the response is consistently associated with particular stimuli. Automatic processes/actions do not develop if the mapping between stimuli and responses is not consistent [16]. Once a process has been learned and encoded as an automatic response, it is difficult to unlearn or change, and effort is required to deliberately modify the response. Automatic processes require little or no attention to monitor them, only to initiate them [15].

Design and Implementation

The attention-based architecture of ASMO is a practical and agile software design inspired by attention theory. In ASMO, a robot's mind is comprised of a set of autonomous independent processes (c.f. a "society of mind" [12]), that are orchestrated by the allocation of "attention value" which could be determined by the systems designer directly, automatically using machine learning techniques or as a result of the robot's direct experience [19].

In ASMO, processes are self-contained units of activity which can be enacted as an action or skill. While behaviours are emergent from the interaction of several processes, a robot with just a single process is still capable of at least one meaningful action or skill. For example, in robot soccer, one process might be "search for ball" . Even though a soccer playing robot requires many skills, in ASMO the "search for ball" process can be observed and tested in isolation by loading it as the sole process on the robot.

Processes are implemented as sequential call-back functions that are automatically detected in modules in the robot's file-system (memory). The robot's top-level control cycle then simply iterates over the set of processes in the system, invoking and enacting each in turn. Pseudo-code of a simplified model of ASMO appears in Figure 1. It introduces supervisors and reflexes and we explain their role in managing attention below. Note that processes may also be implemented using multiple threads (as is the case on our robot bear, where we use lightweight threads in the distributed Erlang programming language).

Attention. In ASMO, attention is modelled simply by the addition of an "attention" attribute to each process. The attention attribute captures the degree of attention the process seeks on the basis of sensations and perceptions. In the current implementation, the attention attribute of a process is an abstract numerical value (e.g., an integer) that can be set and read by the process. Under ordinary operation, attention values are (by convention) bounded between 0 and 100. Processes with attention values of 0 or less are given no attention. A value of 100 (or more) is a process that demands full attention. Attention values are used to mediate access to limited resources, but may also be used within a process to modify the character of its actions according to urgency.

```
reflexes = autoDetectReflexModules()
supervisors = autoDetectSupervisorModules()
processes = autoDetectProcessModules()
while True:
 inner.sensations = body.sense()
 reflexHappened = False
 for reflex in reflexes:
    if reflex.run(inner) == True:
       reflexHappened = True
       break
 if not reflexHappened:
    for supervisor in supervisors: supervisor.run(inner)
    for process in processes: process.run(inner)
    body.do(inner.getActuationWinner())
```

Figure 1. ASMO main loop

The attention value varies over time in accordance with the environment and the agent's intention, motivation, goals and experiences. A process demands attention to respond to stimuli from the environment, hence the process modifies its own attention values (e.g. can be a simple increment of 1 or a function) in order to win over the current winner process. Although programmers can set default attention values at initialisation, these values are not used because they are updated as soon as the agent interacts with the environment.

For example, a process called "search for ball" may currently win the attention to access the robot to search for the ball while a process called "search for goal posts" increases its attention value by a small amount with each clock tick for which it has not seen a goal post. Over time, the attention value of "search for goal posts" process will become sufficiently high that the robot enacts it in preference to all other processes including "search for ball" process, thus no longer allow the robot to search for the ball.

Attention values are also affected by the agent's intention, motivation, goals and experiences which are represented by another class of processes that we refer to as *supervisors*. In ASMO, supervisors are like ordinary processes, except that they are enacted before those processes. By convention, while any process may update its own attention value, only a supervisor is allowed to inspect or update the attention values of other processes. Supervisors can on the fly enhance a process' attention value (e.g. increase by 10) when the process is not conflicting with the agent's intention and motivation (i.e. help the process to win the attention faster) or reduce the attention value respectively when the process is conflicting.

Supervisors can also be use to manage attention values for tactical orchestration of multiple processes. For example, a defensive mode of game play might be enacted by increasing the attention value of "homing", "blocking" and "passing" processes, rather than "chasing" and "kicking".

Selection and Resource Control. The allocation of attention values to processes is not a meaningless or arbitrary accounting task – the attention value of a process is used to mediate control of the limited resources of a system. In particular, attention plays the greatest importance in sharing access to the robot's actuators (obviously a robot's motors can only do one thing at a time safely!).

In ASMO, access to the motors is mediated by an "attention election". Each process votes for what it would like the robot body to perform ("inner.voteFor(action)") and attention is considered when deciding the winner ("inner.getActuationWinner()"). On our soccer robots, the process with the highest attention value always wins, but other vote counting strategies (e.g., weighted majority rule) may be used [3,7,8]. In fact, multiple elections may also be used if groups of actuators can be safely moved independently (e.g., the head can often search for objects independently of the body's locomotion).

In the case there are multiple processes with equal attention values, ASMO simply chooses one process as the winner. The second process would then become the winner in the next clock tick because the first winner has been satiated and therefore its attentional demand is reduced, unless another process has a higher attention value than the past winners at that current clock tick. This activity is repeated for every clock tick and ASMO continues serving the highest attention value. The past winner could also become the new winner after a few clock ticks. In this situation where the winner is not consistent enough to produce a meaningful action, we say that the agent is confused, just like a person who sometimes becomes confused when there are overwhelmed by perceptual stimuli and goals.

Automaticity. ASMO includes support for two types of automaticity which are the *boosted process* and *reflex*.

Processes may be made to behave more "innately" or "involuntarily" using *attention boost*. Attention boost is represented as a numerical value that can influence an agent's attention. Like "attention value", this numerical value (i.e. scalar) is just a type of representation which can be formed by a complex non-linear function, non-scalar value or other representations. Attention boost has no effect on the ordinary operation of a process, however it is implicitly added to attention in an election. Thus, high values of attention boost can be used to make a process become as dominant as reflexes if required while ensuring that its particular behaviour is unchanged.

Processes which have consistent mappings between stimuli and their responses will increase their attention boost value over time. This mapping connection is strengthened when the process receives positive feedback (e.g. responses accordant with the agent's intention and motivation). The higher the boost value, the less the attention value needed to win the attention election and the more automatic the process. There is no discrete separation of automaticity in ASMO, instead it is a continuum line and a degree of how automatic a process is.

A process which we said to be more automatic (we would call "automatic process" for clarity of this paper) does not decrease its attention value to indicate it demands less attention than an ordinary process. Instead, it keeps competing for attention, but has a higher boost value which is counted at election time. When the attention boost is sufficiently high, this automatic process normally wins the attention election even though it has a zero or a small amount of attention value which indicates that the process requires little or no attention.

Once a process has learnt to become more automatic (i.e. has a high attention boost value), it is difficult to unlearn and against this process and deliberate effort is needed to let an ordinary process wins the attention to perform a different action. This deliberation can come from the agent's intention and motivation represented as the supervisors. A supervisor helps to contribute to an ordinary process' attention value to achieve the agent's intention and motivation which its total attention value may be greater than the automatic process' total attention value (i.e. attention value plus attention boost).

Another type of automaticity is a reflex. Reflexes form direct connections between sensors and motors just like in human. They can be implemented at the body-level (hardware), outside the ASMO main loop for which different body has different type of reflexes. These reflexes are assumed to be unique, therefore there is no conflict to take control of the resources. In the computing world, it is more flexible to implement processes at the software-level than the hardware-level, thus we include reflexes inside the ASMO loop and ensure they behave like hardware-level reflexes.

In ASMO, reflexes do not have an attention value attribute and an attention boost. They are enacted before supervisors and ordinary processes in order to allow them to take immediate control of any resource. This ensures that highly critical behaviours (such as recovering from a fall or avoiding battery failure) can dominate behaviour when necessary, without those processes needing sufficiently high attention value and to compete with other processes at the critical time.

Discussion

While biologically-inspired and motivated by cognitive science, the ASMO architecture is ultimately intended as a practical platform for real robotic systems development. Our most compelling evidence for the novelty and contribution of the attention architecture of ASMO comes from our experiments at RoboCup 2010 [1]. In 2010, we had three months to implement a fully functional robot soccer system from scratch for competition in Singapore on brand new Nao humanoid robots. This was a significant and challenging undertaking within a severely limited time-frame; especially given that most of the other 24 teams in the league had an existing robot soccer system (vision, locomotion, localisation, and behaviour), several years of experience with the robots and significantly greater resources.

The architecture required a challenging change in mindset from the traditional state-based paradigm of mainstream robotics to a process-oriented perspective. However, once this perspective was understood, development in ASMO became much less challenging than state-based systems development. Moreover, ASMO offered further considerable benefits in our RoboCup experience:

- The self-contained processes of ASMO accelerated the development of skills, by allowing actions and complex behaviours to be developed and tested in isolation.
- The self-contained processes of ASMO allowed strategies and techniques to be tested simply by changing the mix of the attention values and/or attention boost of processes as the means to improve system performance.
- Buggy processes did not crash the robots because non-responsiveness resulted in a loss of attention and, therefore, a loss of control over the system resources. Poorly designed processes tended to lose attention value and not be enacted or reinforced.
- The isolation of behaviours into autonomous processes assisted with the distribution of work across a team. The attention based architecture supported a wider diversity of behaviours which were generated by the subjective experience of the each robot player.

Comparison with other Systems

In this section we highlight the novelty in ASMO by comparison with three key related cognitive architectures: the Subsumption Architecture [6], ISAC [9] and Global Workspace Theory [4].

The Subsumption Architecture [6] comprises reactive processes which could be said to compete for access to an agent's control. Each process has inputs which can be suppressed and outputs which can be inhibited. A coherent behaviour is produced by fixed connections for suppression and inhibition among processes. Thus, the behaviour produced is monotone because the connection cannot change on the fly. ASMO provides a similar architecture to the Subsumption Architecture, however the connections are made implicit and emergent through the use of attention which can be modified on the fly. This simplifies the effort involved in identifying and establishing connections between processes, and allows for more dynamic and intelligent behaviour even in unforeseen and surprising situations. For example, planners can be used in ASMO to influence the processes' attention values in order to produce actions which are different to the responses of the stimuli (which is the case of behaviour-based robotics).

The ISAC robot is modelled by an attention network [9]. This attention network selects the most salient event in the environment, which is measured by its incidence, task-relevancy, and regularity. The incidence evaluation increases salience of an event for its unexpectedness provided this event is related to the robot's task [9] (p. 46). In ASMO, the unexpected event would still gain attention even though it is not task-related, since it could turn to be more important than the current task (e.g. the robot's legs were hit when its task is to grab an object by its arms).

The ASMO attention architecture shares some important similarities with Global Workspace Theory (GWT) [4]. GWT is a simple blackboard design that connects pairs of "conscious" and "unconscious" processes. In ASMO, attention acts like a global blackboard and supervisors manage and connect processes. Agents based on GWT need not be attention based, however the idea of processes jostling for execution control on a global workspace that results in action selection holds some similarity to the ASMO architecture. Importantly, the similarity of ASMO with GWT does not mean ASMO adheres to the *Mind as a Theatre* metaphor, on the contrary, the attention architecture in ASMO aligns more with the view that consciousness is a grand illusion [5], i.e. an epiphenomena that emerges from distributed attention control of high level supervisors, low level processes and reflexes, and perception (e.g. vision, motor feedback).

Conclusion

In this paper we have outlined an attention model, and its translation into a practical and workable architecture for intelligent agents. The resulting architecture is highly innovative compared to mainstream robotics architectures and requires a conceptual leap in design for its effective use. Thus, without looking at the human mind for inspiration, we would not have otherwise developed the architecture. Nevertheless, our practical experience is that the ASMO architecture is superior to traditional techniques in the competitive and social robotics for which it has been tested and evaluated.

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