Bridging the gap between agent and environment: the missing body

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Abstract. During the last twenty-five years, the embodied mind thesis has had a major influence on Artificial Intelligence research, in opposition to the traditional cognitivist approach. While the computational theory of mind highlights the role of symbol manipulation and central (brain) reasoning, the embodied approach states that mind, body and environment play a role in the cognitive process. MultiAgent Systems (MAS) generally follow a cognitivist approach, because of their very nature : purely software systems.

In this paper, I argue that agent modelling and engineering can benefit from an embodied embedded approach. In the same way as the MAS environment has been shown to be a first-order abstraction, I propose to consider the agent (software, hardware or hybrid) bodies as a major component of the system. I outline how an agent architecture can use this concept to delegate a part of the agent's tasks to its body, and the interfaces between mind, body and environment. I illustrate this paradigm with an emotion computation architecture that takes into account punctual events, temporal dynamics and emotional contagion. Finally, I discuss some open questions raised by the adoption of this approach in the MAS field.

Keywords: Multi-agent Systems, Embodied agent, Environment, Emotions, Architecture

1 Introduction

The works of the Environment for Multiagent Systems (E4MAS) group have widely spread awareness of the importance of all that is "external" to the agents in MAS design. One of the main ideas is to delegate a part of the multiagent system responsibilities to the environment, which embeds mechanisms providing services such as observability and accessibility to shared resources. We can cite for example the ongoing efforts on artifacts for agent coordination, organization and norms [20, 2].

These works have also highlighted the notion of situatedness, even for purely software agents[18], and showed how to derive adaptive intelligent solutions from physically inspired concepts. In [27, 28], the authors show how to distribute tasks to Automatic Guided Vehicles using gradient fields, which combines reactive functioning to an “informed” virtual environment built on top of the real environment. This approach outperforms more classic task assignment through contract-net protocols, which relies on an agent-centered symbolic design.

Offloading a part of the computation costs to the environment and considering it as a first-order component of the system can be linked to the concept of *embodied embedded cognition* (EEC). *Embedded* refers to situatedness, *i.e.* that interaction between the entities and their environment constrain their possible behaviours, which in turn influences their cognitive processes. Taking advantage of this link between the agent and its environment has typically been the core of E4MAS research. The other component of the EEC paradigm is *embodiment*. It relates to the thesis whereby cognition is the product of body processes as well as high level symbolic reasoning. Thus, embodied embedded cognition considers that intelligence arises from a system composed of three elements - mind, body and environment - of which we know well of only two : the mind, through the classical cognitive agent approach based on symbolic reasoning, and the environment, through reactive approaches and E4MAS-related research.

To date there has been very few works on the concept of body in the MAS community. Two works addressing explicitly bodies in the MAS literature are the ELMS model [14] and Soft-Bodies [16]. In these work, the body is considered as controlled by the environment, and encapsulates several responsibilities including observability and accessibility of the public state of the agents. Other works introduce the use of a mediator between agents and environment, such as Interaction Objects [10], which can be viewed as functionally similar to bodies.

In this paper, I argue that (1) embedded embodied cognition is a suitable paradigm for multiagent systems design, and (2) that there is a need for more research on the topic of software bodies, in the same way as was done for the environment to define what are the responsibilities of software bodies, how it interfaces with mind (agent) and environment, and what its status (autonomous, active, separate or embedded) is.

In section 2, I motivate the importance of EEC and introduce two views of embodied cognition, weak EEC and strong EEC. An example of process that can typically be shared between body, mind and environment - emotion computation - is shown in section 3. Then, as a first discussion basis, I outline in section 4 the principles of an embodied agent approach, in terms of system architecture and components. Finally, I discuss in section 5 some open questions such as agent autonomy and operational issues which are raised by the adoption of this approach in the MAS field.

2 Cognition is not (only) computation

During the last twenty-five years, the embodied mind thesis has had a major influence on artificial intelligence (AI), emerging from the cognitive science and philosophy fields. The traditional cognitivist approach, or “good old fashioned artificial intelligence" [12], is based on a symbolic representation of the world, logic, and problem solving. As such, it is grounded on a disembodied thinker principle : intelligence arises from the mind, while the body is an imprecise interface to the world - sensor and actuator seen as an input/output device disconnected from the high-level cognitive process.

Originally built in opposition to cognitivism, the embodied cognition approach [31] states that mind, body and environment play a role in the cognitive process. Instead of highlighting the role of symbol manipulation and formal operations, EEC emphasizes that intelligent behaviour emerges from embedded - or *situated* - and embodied minds. Furthermore, the body influences the mind as much as the mind influences the body.

Practical implications of EEC for the instantiation of intelligent systems come from robotics, a major contribution being the work of Rodney Brooks (see e.g. [3]). Brooks argued against the top-down approach of building intelligence from thought and reason, basically because the resources used to build a representation of the world, process it and plan the actions of a robot (1) is very costly in terms of computation resources and (2) this approach does not take into account the dynamics of the world. Observing that intelligence does not equal thought (ant colonies are a well-known MAS example), Brooks proposed to use a sub-symbolic and at least partly reactive approach. The intelligence emerges from the interplay and tight feedback loops between the dynamic environment and the robot, while most of the tasks are not treated symbolically [15]. Current robotics research also include body materials, in order to simplify the control module. Recent progress in robot bipedal walk come from a better design of robot bodies by using the physical properties such as elasticity and shock absorption.

Although the situatedness of the agents has been part of multiagents systems community practice for a long time, it has long been tackled in an *ad hoc* way [30]. Situated agents interacting with their environment have shown the advantages of using the environment for problem solving via indirect interactions such as stigmergy and limited cognitive capabilities of the agents. Works of E4MAS workgroup has then put forward the view of environment as a first-order abstraction for the design of MASs[29]. However, the body / mind differentiation has not received the same attention as the environment role.

It could be argued that since the MAS community deals in a large proportion with purely software agents, embodied cognition is not relevant to our field. While the direct transposition of embodiment does not seem a sound approach, two arguments are in favor of its interest for our community: firstly, many of our approaches are inspired from biological systems. Grounding our models on philosophy and cognitive science does not mean they have to be reproduced exactly, but it is a source of useful concepts, such as extended cognition [17] and enaction [25], which can be adapted to software systems in dynamic environments. Secondly, autonomous agents are facing the same difficulty as robots in terms of design complexity. Drawing a parallel, we could use software bodies to delegate a part of the agents' complexity to a distinct and modular entity, thus simplifying agent design and reducing computation load.

It is thus necessary to distinguish two approaches to embodiment, strong EEC and weak EEC, in a similar fashion to strong AI and weak AI. The *strong* embodied embedded cognition argument is that since human intelligence is deeply embodied, building "real" (or strong) artificial intelligence requires an embodied approach. The *weak* embodied embedded cognition argument is that inspiring our work from the way humans and animals produce intelligent behaviour and diminish their high-level reasoning load offer leads to design - hopefully- smarter systems. Furthermore, the EEC approach may be used for simulation purpose, *i.e.* reproducing and understanding real-world sentient behaviour. In this paper I adopt a weak EEC approach. In order to use concepts from EEC, we have to understand what it means to engineer a triad agent/body/environment and propose a design compatible with it. In particular, defining the role and responsibilities of the body would permit to mainstream the use of embodied agents.

In the following section, we illustrate how this approach can be used to design an architecture for emotion computation.

3 Illustration: Emotion computation

Simulation of increasingly complex biological systems (such as humans or social systems) could gain from the use of an explicit body/mind modelling, for example to simulate emotion computation. Emotions evolve according to three influences [7]: one-off events, temporal dynamics and emotional contagion. Traditionally in multi-agent modelling, all processes are integrated into the architecture of the agent. If the evaluation of the impact of one-off events is necessarily managed by the cognitive process of the agent, it is possible to decentralize the other processes in the software body of the agent and in the environment.

Although there is no consensus on the way emotions are processed in biological systems, many computational models have been proposed. In the following, we base our modelling on the thesis whereby the computation of emotions is the result of an intuitive (*appraisal*) and cognitive dual process[21]. The first is semi-automatic and often unconscious. It represents the change resulting from an immediate emotional percept, it concerns the so-called primary emotions (such as joy or amusement). The second is a cognitive evaluation, which derives from the consistency between beliefs, goals, and percepts of the agent and the emotions he feels, with emotions both primary and secondary (such as shame). Furthermore, emotional contagion is necessary to the emergence of consistent collective behaviour. Hatfield *et al.* [11] showed that emotional contagion takes place at a significantly lower level of consciousness than empathy, via uncontrolled automatic processes. These uncontrolled automatic process also contain mimicry behaviour, which is an important part of social norm in dialogues.

These kind of mechanisms are typically candidates to delegation, since they are not controlled by the mind in biological systems. In order to propose an adequate architecture for emotion contagion, an embodied cognition inspired MAS relies on two concepts: the active environment and the body/mind separation. As mentioned in introduction, the notion of explicit environment has long

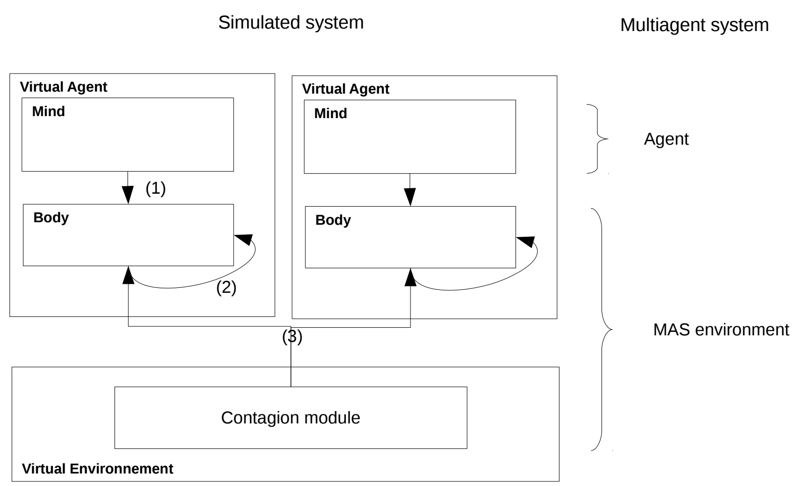

Fig. 1. Mind, body and environment in an architecture for emotion computation.

been associated with the reactive agent paradigm, but recent works [29] have shown the benefits of the use of this abstraction in the general framework of MASs. These studies highlight the interest to delegate some responsibilities of the agents to the environment. In particular, it may be in charge of accessing and spreading a part of the agent states. In the context of emotion modelling, the environment can get the agents emotional states and compute the emotional contagion instead of the agents.

In the same logical way, we can consider that the agent consists of two parts: its mind and its body (which may possibly be a software body) [16]. In this embodied agent framework, the mind contains the decision process of the agent and is autonomous, and the body is influenced by the mind, but controlled by the environment. This corresponds to human functioning: although the mind may take any arbitrary decision, the limits to the realization of these decisions are imposed by both the body capacities and its environment rules. In practice, our proposal implies that the body states of the agent are observable and that access to them is controlled by the environment, including for the agent itself. For the calculation of emotions (Fig 1), the result of events perception (1) is then the responsibility of the mind of the agent, the temporal dynamics (2) is managed by the body and the emotional contagion (3) by the environment. More details on this architecture can be found in [23].

Beyond the physical aspects

In this emotion computation example, a low-level form of embodied cognition is emphasized, since we consider the body to have only two properties: internal dynamics (delegated by the mind) and access/modification rules (delegated by the environment). As such, we have shown in [23] that it enables (1) to propose a modular model with separate responsibilities for each component and (2) to reduce the overall computation load.

However, the embodied cognition thesis [31] argues that the whole cognitive process emerges from the interaction between mind, body and environment. Two examples of such embodied processes are task realisation and planning.

In [1], Ballard *et al.* study the strategies used by humans to reproduce coloured blocks patterns under time pressure. Instead of memorizing the pattern, the subjects used repeated reference (through perception, detected thanks to eye-tracking) to the blocks in the model pattern at strategic moments to get partial information as needed, *e.g.* firstly the colour of the block and then its precise location. In this way, humans use a minimal memory strategy, using the world as its best model.

In [24], the authors propose the use of a graph of sensory information to encode a robot's navigation information. This graph is built during exploration. In order to manage unknown locations, they provide false sensory information to complete the graph of known location, instead of providing an allocentric map. Planning is then done through auto-simulation.

4 Embodied agents - Principles

In this section, I propose a tentative definition of body responsibilities, then show its impact in terms of MAS architecture. The main difficulty comes from the particular place of the body, whose states and capabilities depend on both mind and environment. This proposal derives from the work of Platon *et al.* [16] on softbodies, the ELMS [14] and MIC* [10] models, and influence/reaction models such as [13]. In these works, the effects of agent actions is calculated by the environment in order to verify the environment integrity and model action uncertainty. Two other key points have guided this proposal: firstly, uncertainty in action necessitates feedback loops for the agent to control and if necessary modify its future action selection; secondly the body has its own rule set. In the influence/reaction model, influences represent the microscopic level, while the reaction represent the macroscopic level. However, both individual and global rules must be applied to the agent influences, and individual rules may differ among agents. Hence, encapsulating local rules in local entities (bodies) enables to modularize the design of environment dynamics.

4.1 Body Responsibilities

The agent soft body encapsulates the following responsibilities:

1. **Access to resources and observation** : the body mediates the access to resources in the environment, and the perception process. It provides the means to focus the perception via sensors, both in a top-down (active

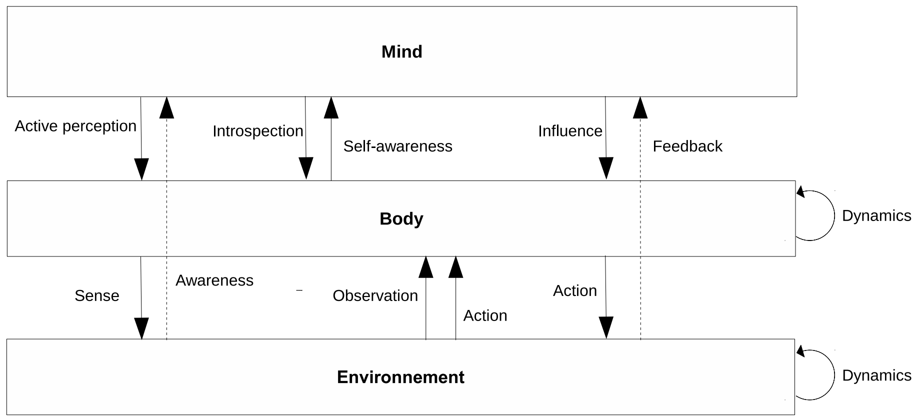

Fig. 2. Mind, body and environment interactions.

perception) and in a bottom-up process (awareness). It also encapsulates the action capabilities of the agent, through influences.

2. **Access / observation of agent** :
   – towards the mind, the body enables introspection, i.e. a sensing of the body states and processes by the mind;
   – towards the environment, the body provides observability of the public state of the agent, and an interface to take into account external influences
3. **Own set of dynamics and rules**: the body regulates and controls the previous processes, and can possess its own dynamics, independent or in reaction to environment or mind influences.

4.2 MAS viewpoint (architecture overview)

Considering embodied cognition implies to shift the architecture focus to an environment / body / mind holistic approach. Figure 2 shows the different interactions between body, mind and environment. Embedded embodied agents are firstly situated in an environment, which contains the MAS resources, environmental laws and dynamics, and provide accessibility and observability. The body mediates all interaction between mind and environment. Furthermore, it is a dynamic entity, in the sense that it encapsulates automatic processes, and a regulation entity that contains its own rules. In this way, both environment and body are active, but only the mind / agent is autonomous (proactive towards its goals).

In the objective of improving modularity, and since in embodied cognition the mind does not have the full control of its body, the presence of tight feedbacks enable the agent to adapt to its body. Modular minds must learn how to use their bodies, what they can and cannot do.

Body and environment rules should be compatible. In the current situated agent approach, the environment rules encapsulate both rules related to the individual (bodily capabilities) and environmental rules (e.g. physical rules or norms), *e.g.* in [22]. In this approach, the two kinds of rules are separated since they are semantically distinct.

5 Discussion and perspectives

Control issue

Introducing bodies in agents and MASs design opens the question of body control. Although the virtual entity previously named agent contains conceptually mind and body, for example in the case of simulation, practical software engineering can materialize this in three different ways: the body can be autonomous, controlled by the mind or controlled by the environment. Although all these solutions are better than integrating all the processes in the agents in term of modularity and complexity, a mixed approach that fits the conceptual principles of embodied cognition such as proposed in the previous section is the most suited: the body is not autonomous, but influenced by the mind (with more or less success) and regulated by the environment.

The bodies of the agents can be controlled by the environment, whose services are generally materialized in the MAS platform. Some authors propose to create software bodies which are not part of the environment, e.g. in [26] to control the animation of conversational agents. The idea of using the mind to generate high-level decision and delegate the implementation to the body is indeed at the heart of computational embodied cognition.

Operational issues

Directly linked to the control issue is the operationalization of the approach. Let us note that the MAS environment and the agent bodies are functional components. Hence, a functional centralization of the control of the body by the environment does not necessarily mean that the environment itself is centralized.

The virtual agents community has claimed the use of the term "embodied agent". With respect to this field, it means that the agent has a visual representation which is used as an interface with the user. However, this visual representation does not mean that the body is a distinct component, nor that the symbolist approach is not used. Hence, we have to separate two different kinds of embodiment: representative or conceptual. Indeed, an agent may be neither, either or both. For example, as mentioned before, researchers have proposed a software body [26] in order to control the animation of conversational agents and thus off-load a part of the mental process of the agent. In this case, although the body is only used to offload the motor part and not the perception, conceptual and representative bodies are used.

To the best of our knowledge, there is no generic model of bodies for software agents. However, inspiration sources can be found in the literature on environments.

Platon et al. [16] have introduced the concept of over-sensing: agents have soft-bodies that have public states, which are mediated (both for visibility and accessibility) by the environment. The information on modifications to the public states is spread throughout the environment. Nevertheless, the model is designed for observability and not action. The ELMS model [14] propose to consider the agent body as embedding the physical aspects of the agents: this models adds action capabilities and perception constraints to the external observability role. Artifacts [19] can be a way to implement an embodied agent approach, by programming the body and environment responsibilities as reactions and dynamics. MIC* [10] defines Interaction Objects as means to interact with other agents and with the environment while preserving the autonomy - Internal Integrity - of the agent. Electronic institutions often mix social norms and local control. These local laws (see e.g. [32]) could be assimilated to and enforced through soft-bodies via the MAS platform.

These works provide hindsights on the modelling of situated embodied agents that interact with their environment. However, they do not consider the interface between the mind and body with the same attention. As highlighted before, the body also plays a role in the cognitive process of the agent, by providing feedbacks, introspection and self-awareness capabilities. Furthermore, as in biological systems, the body may encapsulate *translation* capacities, *i.e.* means to ground symbols on sensory and motor systems through experience. In order to model this process, works such as [6] propose to include a layer between the "reality" and the "mind" models that contain the conceptual model of the world, hence filtering percepts into shared semantic information thanks to an ontology.

Let us remark that body and environment have to be distinguished: they provide different services, mainly differentiated by the level at which they are applied. Body responsibilities are dedicated to the mind it is attached to, while the environment manages social interactions and outside resources.

Agent autonomy

To evaluate agents autonomy in the framework of our proposal, we take Castelfranchi 's definition of the autonomy [5], which considers autonomy as the dependence of an agent towards other elements of the system in accordance with a purpose, a function, or an action:

- *Non-social autonomy*, *i.e.* agent autonomy towards the environment: the agent is autonomous in terms of management and generation of internal states and goals. It is also autonomous in the sense that it can direct its attention within the environment. However, it is dependent on the environment for an unconscious / automatic part of its emotional process, and for the state of its body software. For example, insofar as the human being has only limited control over its own emotions because of their automatic aspect

[11], we consider that the environment regulates access to the emotional state of the agent in the same way that the body automatically maintains a temporal dynamic and physiological responses to the status of other agents. The agent is also dependent on the environment for the activities it attempts to perform. This notion is classical for situated agents: the agents influence their environment, but the environment is the one to decide whether and to what extent their actions are successful based on a set of functional rules. For example, an agent cannot defy gravity.
- *Social autonomy*, *i.e.* agent autonomy towards other agents, the agents retain their full autonomy in our representation.

Considering the autonomy as being the internal integrity of the agents [10], "*a programming constraint that considers an autonomous agent as a bounded system which internal dynamics and structure are neither controllable nor observable directly by an external entity*", the body is a suitable concept to ensure the autonomy of the mind. The body encapsulates the action and perception mechanisms, hence creating a buffer that is observable and accessible without modifying the state of the agent.

Design shift

The biggest challenge is to change the community's view on embodiment. Embodied cognition is not a make-up for the reuse of previous concepts, but a holistic approach of intelligence. Hence, a real design shift is called for. Inspired from the robotics experience, the main objectives are (1) to reduce the reliance on symbolism to what it's done for, e.g. off-line cognition (such as memory use or long-term planning), while relying on quick adaptive solutions for situated cognition; (2) to improve modularity and reduce complexity by conceptually separating each cognitive part's responsibilities; and (3) to find new inspirations from biological systems. This last point is an important challenge. Piaget's developmental psychology (outlined in [8]) emphasizes the importance of learned automatisms in intelligent adult behaviour. Deeply grounded sensory-motor circuits enable to off-load the mind. In agents systems, these means that feedback loops should be used to enable the agent to acquire a body intelligence, i.e. patterns of good use of its capabilities in cognitive tasks.

The objective of this article is not to oppose symbolic AI and embodied AI. Indeed, symbolic AI has proved efficient for the design of many intelligent systems [9]. The main difficulty in effectively taking advantage from embodied embedded cognition is not designing efficient reactive systems (such as ant-based algorithms and AGV [27]), nor AI systems that work (such as Deep Blue [4]). It is designing flexible solutions to high level problems, which are adaptive to environment changes (hence needing awareness of these changes and relying on perception instead of offline computation) and provide non trivial / cognitive answers. It is also designing once the mind for several modalities (bodies), which implies learning or adaptive minds.

Finally, the approach based on embodied agents, in which the relationship between mind, body and environment are strictly formalized should facilitate the modelling of human or human-inspired processes. In particular, the choice of removing from the control module (*i.e.* from the mind / autonomous agent) some low level calculations, such as emotional contagion or the physical aspects, can help to simplify its design. More research is needed to better understand how MAS designers can apply this principle to all cases where the agents are situated and can therefore interact with an environment, and propose an adequate methodology.

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