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Simulation within simulation for agent decision-making: Theoretical foundations from cognitive science to operational computer model

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Abstract

This article deals with artificial intelligence models inspired from cognitive science. The scope of this paper is the simulation of the decision-making process for virtual entities. The theoretical framework consists of concepts from the use of internal behavioral simulation for human decision-making. Inspired from such cognitive concepts, the contribution consists in a computational framework that enables a virtual entity to possess an autonomous world of simulation within the simulation. It can simulate itself (using its own model of behavior) and simulate its environment (using its representation of other entities). The entity has the ability to anticipate using internal simulations, in complex environments where it would be extremely difficult to use formal proof methods. Comparing the prediction and the original simulation, its predictive models are improved through a learning process. Illustrations of this model are provided through two implementations. First illustration is an example showing a shepherd, his herd and dogs. The dog simulates the sheep's behavior in order to make predictions testing different strategies. Second, an artificial 3D juggler plays in interaction with virtual jugglers, humans and robots. For this application, the juggler predicts the behavior of balls in the air and uses prediction to coordinate its behavior in order to juggle.
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1. Introduction

For many years, researchers have tended to create virtual environments that provide the opportunity for a human to evolve while interacting with virtual entities. For these virtual worlds to be believable, each entity controlled by the computer must exhibit a behavior giving the illusion of being controlled by another human. This raises the following question: how can an entity be equipped with believable autonomous behavior in a complex virtual environment in which humans participate?

Traditional symbolic artificial intelligence techniques have been applied to define these behaviors. However, these techniques have limitations as they are mainly based on predetermined rules of behavior chosen by the designer. Indeed, in complex (open simulation, heterogeneous and participatory) virtual worlds, entities may have unpredictable behavior (behavioral variability of autonomous entities, free will of human users), thus creating new situations. When faced with situations unforeseen by the programmer, entities may display unsuitable behaviors.

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In this paper, virtual entities are considered at the same level as human, by integrating human characteristics that are currently lacking in existing artificial intelligence mechanisms. To address this issue, we were inspired by ideas and concepts from cognitive science in defining human decision-making. More precisely, our focus is on finding a computational approach to reproduce adaptive behavior in an intelligent agent, inspired from the human's anticipation ability and capacity to adapt while interacting. We will then be able to examine the use of such concepts into an artificial entity's decision-making process.

This paper is organized as follows. After presenting the concepts from cognitive science which highlight simulation as being an essential aspect of cognition and from which the presented approach is inspired, Section 2 analyzes related works in computational models. Although studies from cognitive science suggest that mental simulation is central to decision making and arguably other important aspects of reasoning, existing approaches do not offer a generic computational model of this paradigm.

To address this issue, in this paper we present a generic computational model of mental simulation. Thus Section 3 describes a conceptual framework where the entity possesses an autonomous world of simulation within the simulation. In this internal world, the entity is able to simulate itself (using its own model of behavior) and also simulate its environment (using its representation of other entities). The entity also has the ability to anticipate and to learn using internal simulations. In our previous works, the concept of internal simulation has been studied, for test purposes, in two applications described in previous publications (Buche, Chevaillier, Nédélec, Parenthoën, & Tisseau, 2010; Buche & De Loor, 2013; Buche, Jeannin-Girardon, & De Loor, 2011). These applications illustrated the applicability of mental simulation paradigm to decision-making, but connections between decision/anticipation/learning were *ad hoc* for each specific application and required complete architectural modifications to be applied to a new domain.

To test the genericity of the computational model, we have reused these examples in Section 4. The key idea is to show that it is possible, using our architecture, to switch from one domain to the other without making changes to processes binding decision/anticipation/learning. First, we illustrate our approach through an example that simulates dogs gathering sheep. To simulate sheep behavior, the dog uses fuzzy cognitive maps (FCM) of prey. The dog can therefore simulate the sheep's motion in order to make predictions and to test different strategies. Without changing the architecture, we illustrate our proposal by an artificial 3D juggler playing with virtual jugglers, humans and robots. For this application, the juggler predicts the behavior of balls in the air and coordinates its own behavior accordingly, in order to juggle. The virtual juggler uses neural networks to simulate ball motion. The proposed architecture allows the agent to adapt to changes introduced by adding other agents and human users to launch balls that the virtual juggler can catch while juggling, which was not the case in the original application described in Buche and De Loor (2013). Without changing the architecture, we were able to switch from FCMs to neural networks as a controller for the prediction process. Finally, Section 5 concludes and introduces future work.

2. Context

2.1. Cognitive science toward artificial intelligence

There is a growing body of literature in cognitive science advocating the simulation process as being central in cognition (Decety & Grèzes, 2006; Hesslow, 2002, 2012; Pezzulo, Candidi, Dindo, & Barca, 2013). Contrary to the classical cognitive approach, in these simulative theories, perceptual, cognitive and motor process are not considered as being part of separate domains but rather that sensorimotor processes are fundamental to cognitive activities.

Despite different views of the concept of simulation, one central common point is that simulation corresponds to the reactivation of actions that were formerly executed and stored in memory (Decety & Grèzes, 2006). For example, in his simulation theory (ST), Hesslow (2012) proposed three main assumptions: (1) simulation of action, (2) simulation of perception and (3) anticipation.

The simulation of action (1) implies that brain areas recruited when performing an action are similar to the ones activated when covertly (i.e., when the action is not executed) reactivating the action. In this way, one can consider that a simulated action corresponds to an unexecuted action. The second statement (2) means that perceptual activity may occur in absence of external stimuli. Like during the simulation of action, activation in the brain is similar when perceiving external information and when imaging perceiving this information. Finally (3), Hesslow (2012) proposed the existence of some associative mechanisms allowing both behavioral and perceptual activity that could produce activation in the sensory areas of the brain. The direct consequence is the possibility to generate perceptual activation from simulated action similarly to obtaining this activation from the actual execution of the real action.

In sum, one can simulate both action and perception. When doing so, the recruited brain areas are the same as the ones activated when actually performing the action or actually perceiving external information. Moreover, action simulation can elicit perceptual activity similar to the one which would have occurred if the action were actually performed. The benefit of this anticipation mechanism is twofold. First, one can be prepared to respond to the consequence of one's own action. Second, one can evaluate in advance the consequence of an action and thus select the most appropriate behavior to achieve the indented goal (Hesslow, 2002; Pezzulo et al., 2013).

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