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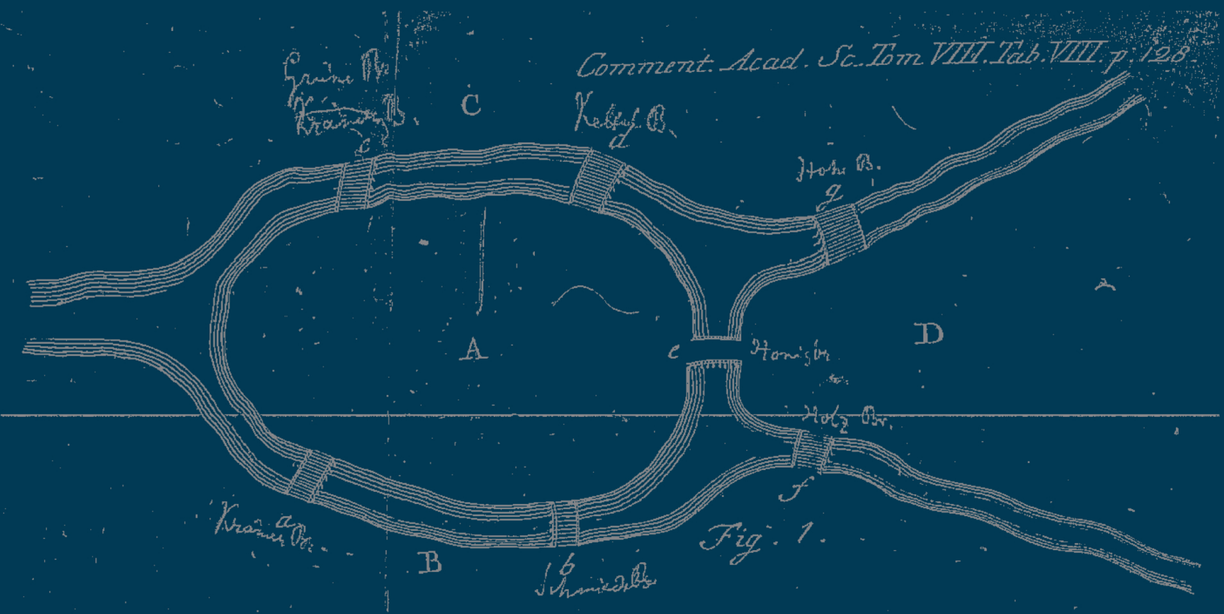

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Chapter 30
Time in robot cognition: An emerging research branch

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Abstract: The long-term goal of robotic research is the implementation of intelligent and social artificial agents capable of interacting in human terms. Besides the significant progress in the field during the last decades, even state of the art robots exhibit poor social competencies when compared to humans or animals. An important reason for that is the lacking ability of robots to experience the flow of time, which in turn prevents artificial agents from sufficiently considering time in their perceptual, behavioral, cognitive, emotional and communicative processes. Given that time is an important dimension of human-human daily interactions, any machine that aims to be seamlessly integrated into human environments is expected to have mature time processing abilities. Based on the above, we put forward temporal cognition as a vital capacity of intelligent and social artifacts. In the present paper we will provide examples of the current robots' time processing insufficiency, we will discuss possible approaches for implementing artificial temporal cognition taking inspiration from the human time processing skills, and we will point out the significant impact that this new research branch is expected to have in the future of robotic research.

Keywords: artificial sense of time, bio-inspired robotics, temporal cognition.

Introduction

The ability to experience and process time is directly involved in most of the daily human activities. Consider for example how we are able to direct attention on a specific past period, how we weight alternative choices to minimize future risk with our decisions, how we select the objects that we put in our luggage before a trip, or how we coordinate our free time with the activities of friends. All these daily actions depend on our time processing capacity and the ability to mentally move back and forth in time. That is, intelligent human behaviors are not reactive but encompasses a lot of information regarding our previous experiences and future prospects.

However, current research in robot perception and action has mainly concentrated on the spatial properties of the environment, largely disregarding the temporal information that accompanies real world phenomena (Maniadakis et al., 2009; Maniadakis & Trahanias, 2011). Such a cognitive approach isolates artificial agents from the past and the future of the world, resulting in systems that are "stuck in time" (borrowed from Roberts, 2002), a characterization that is often attributed to animals or autistic children. In other words, for artificial agents there is no concept of a time that extends into past and future. Existing robots operate mainly in the "now" of their environment, without being aware of the long and short term changes occurring in the dynamic world.

Despite the fundamental role of time in natural cognition, current endeavors in the development of robotic intelligence are by no means directed towards encompassing time processing in the systems' repertoire of capacities. This is really surprising given the extensive inspiration that robotic community has taken from the cognitive modalities of the brain during the last decade. Even if robotic capacities are surprisingly efficient in accomplishing behavioral tasks such as navigate following complex maps, grasp and manipulate objects, etc., artificial agents lack the ability to place their behaviors in a more general context seamlessly integrated with human activities.

The present work aims to reveal the lack of time processing skills in artificial cognitive systems, to discuss the fundamental role of time in developing intelligent and social behaviors, as well as to direct research attention on furnishing artificial cognitive systems with the ability to experience and process time.

Temporal Cognition

For humans and animals, sensing and knowing the world arises through spatiotemporal experiences and interpretations. This means that not only spatial information but also time has a crucial role in cognition. In the present article, we use Temporal Cognition as an umbrella term describing the set of cognitive functions that support the broad range of our time experiences. Formally speaking, we define TC as follows:

> ***Definition.*** *Temporal Cognition encompasses the set of brain functions that enable experiencing the flow of time and processing the temporal characteristics of real world phenomena, accomplishing (i) the perception of synchrony and ordering of events, (ii) the formation of the experienced present, (iii) the perception of different temporal granularities, (iv) the conceptual abstraction and processing of durations, (v) the mental travelling in future and past time, (vi) the social sharing of temporal views about the world.*

The above definition indicates that what is important for artificial systems is the holistic exploration of time-relevant cognitive processes. Despite the fact that existing works in cognitive science and neuroscience have mainly followed a decomposing approach considering separately what is the role of time in memory, how we perceive temporal orientation, how time is represented in the brain, what is the role of different temporal granularities, etc., investigating time perception in the context of artificial systems requires a synthetic approach, with the holistic consideration of all TC branches. This is because any implementation decision that will be taken for each of the afore mentioned TC aspects is likely to additionally affect procedures in the other aspects as well.

Interestingly, the newly developed sense of time will provide added value to the existing cognitive capacities of artificial agents enabling them to expand in the "new" time dimension (e.g. attention will shift not only in space but also in time, learning may be more efficient after considering past, etc.).

Time as a perceivable physical entity

Discussions of the nature of time, have frequently attracted scientific interest throughout the years, from Aristoteles, Newton and Einstein, to many other modern philosophers and researchers. There are now many (complementary) definitions of what is time, and providing yet another definition, is out of the scope of the present article. What is important here to note, is the fact that time is a unique physical entity that is perceived by living organisms. Time provides the framework to sense and record changes in the environment, as well as to act on the world in order to affect its state. Along this line, considering time provides a practical convenience in modern human societies with numerous time-relevant standards being set up, allowing people to keep their lives running smoothly.

Moreover, time is considered one of the fundamental quantities used to perceive and measure world states in the International System of Units. As a result, to adequately perceive and understand our physical world, intelligent artificial systems should able to monitor the flow of time and integrate it with their perceptions and actions.

Of course, time is not what clock measures. This is because clocks do not implement time, but they just provide a means to measure it. The flow of time will certainly continue being a key parameter in the evolution of our world, even if we break all clocks existing on earth. Therefore, the equipment of artificial systems with a clock is not enough for perceiving and processing time in a way comparable to humans. A specialized cognitive capacity is required to provide meaning on the sequence of time measures and combine them with the observed changes on the world. This capacity is described with the term Temporal Cognition in the present document.

Time as a regulator of cognition

All cognitive processes are integrated with a critical when factor. In other words they are entimed on a particular time period that accompanies their validity. Outside this period, they are not valid any more. Besides the validity of specific statements, cognitive processes that regard multiple asynchronous events/processes require a framework that enables examining associative relationships.

All our perceptions and actions make key associations with temporal features that affect our cognition. This means, our behaviors are modulated by the temporal properties of the world and it is very likely that our behaviors would be different if these temporal properties were also different. As it is commented by Wilson, time pressure plays a key role in choosing and expressing a given action (Wilson, 2002). If there was no pressure we may have selected a different behavior, or we may have executed the same action differently. This highlights how our instant experiences modulate our thinking.

Of course, cognition is not only related to the here and now of the world but can also span in multiple points or periods of time. Similar to the well known "embodiment" (Pfeifer & Scheier, 1999) that highlight how situatedness – i.e. the experience of the current world state – affects cognition, we use the term "entiment" to describe how the association of cognitive processes with different moments in the past, present and future, plays a key role in shaping cognition. For example, by taking a particular strategic decision, we expect the occurrence of specific events at specific times in the future. This expands the entiment of our current decision not only in the present but also in the future.

The entiment of cognitive processes is also important for organizing our social life. Consider for example a discussion that we may have with friends about the political events and the music of 60s. In such a scenario, we and our friends mentally travel back in time, focusing on a particular time period (i.e. our attention is shifted not only in space, but also in time). All persons participating in the discussion need to develop a common understanding about the period we are talking about. If someone will mention (by mistake) an event of 70s, we will most likely identify this conflict, correcting our partner that his mind has moved outside the period of interest (i.e. outside of the 60s decade). Therefore, we not only situate our personal thoughts in time, but in order to efficiently communicate and socialize we perceive how others entime their thoughts and activities. Another common example that reveals the fundamental role of time in the organization of social life regards our ability to make plans accomplishing to coordinate our own free time with the free time of our friends.

Interestingly our last examples show that, when implementing sophisticated thoughts, parts of our cognitive processes may be entimed differently on the time-line (e.g. while discussing in the present we recall and keep track of past events). This feature is particularly important for implementing high level cognitive skills that are typically less related with the here and now of the world. Temporal cognition provides the framework that enables the association of time-distant percepts, behaviors and emotions and thus provides the basis for implementing particularly complex and sophisticated thoughts.

Overall, the entiment of cognitive processes is a key ingredient for human intelligence and thus, if we are going to ever implement intelligent robots seamlessly interacting with humans, such robots will be equipped with advanced, human-like TC.

Temporal Cognition Brain Mechanisms

The different aspects of TC listed in the above definition develop gradually in humans starting from the late infancy (at about the age of 12 months) when primitive ability to experience the flow of time is obtained (Arterbery, 1993), continue during childhood implementing the ability to think of future at about the age of 4 (Atance and Jackson, 2009), and become fully mature to adult-like levels by the age of 12 (Droit-Volet et al., 2006). Interestingly, TC capacity has been reported to migrate in our brain during development. More specifically, (Smith et al., 2011) has demonstrated age-dependent developmentally disassociated neural networks for time discrimination.

The investigation of the brain mechanisms involved in the perception and processing of time has attracted significant research interest in brain science during the last decade. Contemporary review papers and special journal issues have summarized the new and burgeoning scientific findings in the field (Meck, 2005; Crystal, 2007; Ivry & Schlerf, 2008; Wittmann & van Wassenhove, 2009). It is now well established that, despite the fundamental role of time in our life, there is no region in our brain that is solely devoted to the sense of time (this contrasts to the exclusive representation of audition, vision, touch, proprioception, taste, and other senses in specific cortical regions). However, over the past decade, a number of different brain areas have been implicated to contribute in time-experiencing including (among others),the cerebellum, right posterior parietal cortex, right prefrontal cortex, fronto-striatal circuits, and insular cortex for duration perception (Lewis & Miall, 2003; Hinton & Meck, 2004; Bueti et al., 2008; Ivry & Schlerf, 2008; Wittmann, 2009), the inferior frontal and superior temporal lobes, hippocampus, medial prefrontal, medial parietal and posterior cingulated cortex for past–future distinction, and mental time travel (Botzung et al., 2008; Suddendorf et al., 2009; Viard et al., 2011), the prefrontal, inferior parietal cortex, superior colliculus and insular cortex for synchronous, and asynchronous event distinction (Dhamala et al., 2007; Kavounoudias et al., 2008), the posterior sylvian regions, posterior parietal, and temporo-parietal networks for temporal order judgment (Woo et al., 2009; Bernasconi et al., 2010; Kimura et al., 2010). The involvement of many brain areas in TC is explained by the significant contribution of multiple cognitive processes such as attention, working-memory, decision making, emotions, etc., in experiencing and processing time (Livesey et al., 2007). Therefore, slight perturbations on these processes may affect our time experiences, explaining why subjective time (how each one of us is perceiving the flow of time) is in principle different than the objective, physical time (Searle, 1992). The aforementioned highly distributed network of brain areas that supports TC suggests that the sense of time relies on, and possibly emerges from, multi-modal cortical interactions. In-line with this, it has been recently suggested that time perception plays an important role in the fusion of perceptuo-motor information throughout the cortex, and the accomplishment of complex cognitive tasks (van Wassenhove, 2009).

A new generation of robotic systems

In order to achieve natural human-like performance, robotic systems need to incorporate the fundamental cognitive skills of biological agents. It is now known that apart from humans, many animals such as monkeys (Medina et al., 2005), rats (Guilhardi et al., 2005), and even zebra-fish (Sumbre et al., 2008), are capable of processing time. Therefore, it seems likely that time perception is a prerequisite for intelligent behavior and it is now high time to direct the attention of the robotics researchers on the investigation of artificial TC (Maniadakis et al. 2009, Maniadakis & Trahanias, 2011, Maniadakis & Trahanias, 2012).

In practical terms, we can identify at least three dimensions in which TC can improve robotic cognition:

- Advance internal cognitive processes: There are many mechanisms with an important role in shaping cognitive dynamics, such as learning, memorization, forgetting, attention, association, and others, that can significantly benefit by considering temporal information. For example, new learning algorithms may be implemented that consider the details of past events when adjusting decision making procedures, time-based association mechanisms may be used to enable future conflict prediction, while directing attention on a particular time period in the past will enable considering relations between a specific set of events.
- Develop skills dealing with the manipulation of time: Artificial TC will provide robotic agents with the capacity to process all different aspects that time is involved in our daily life, accomplishing tasks which are currently out of their scope. For example,

robots may be capable of (i) synchronizing with natural human actions (currently humans are mainly synchronized to robots); (ii) abstracting and categorizing the time scales required for the evolution of different processes; (iii) being aware of the temporal order of their own experiences; (iv) considering the causal relationship linking the present and future with past events that may have occurred many hours or days ago, and others.

- Develop skills that implicitly involve time processing : Time is an important parameter for many low and high-level skills. This is because even simple actions (e.g., object grasping) include a critical "when" component (Battelli et al., 2008) that links a given behavior with the ongoing real world processes. Moreover, high-level cognition that is typically less related with the here and now of the world, requires the association and reasoning on events that occurred, or will occur at different times (e.g., mind reading links past knowledge with future actions). Therefore, both low and high-level cognitive skills can gain significant efficiency through artificial TC.

Implementing artificial temporal cognition

Addressing artificial TC for robotic systems is a most challenging research endeavor. This is partly due to the fact that the capacity to experience and process time has to be seamlessly and effectively integrated with the already implemented robotic skills. Undoubtedly, the latter is affected by the computational approach adopted for implementing TC, which is critical for maximizing the benefits that cognitive systems will gain from this new computational modality. Broadly speaking we can identify two main approaches for equipping robots with TC.

The first approach relies on artificial intelligence (AI) methods that accomplish time-dedicated processing, e.g., temporal logic, or event calculus (Brandano, 2001; Fisher et al., 2005). Noticeably, despite the extensive experience that exists with such systems, the latter are rarely employed in robot implementations, which is because the robotics community has not adequately appreciated the role of time in cognition. Typically AI approaches treat time as an isolated piece of information that can be directly obtained by computer clocks for labeling events and subsequently processed through dedicated mathematical procedures. A significant advantage for the underlying approach is the extensive know-how already obtained, which can be readily employed to facilitate the processing of time. However, getting a bunch of measurements from a robots clock is far from efficiently incorporating time in the cognitive loop of artificial agents. This is because AI approaches result in compact implementations, meaning that TC will operate as a rather separate module of the overall cognitive system, being minimally affected by other cognitive processes. Clearly, such a module for experiencing, representing and processing time can hardly parallelize with the known TC brain processes where there is no time-dedicated region and time-experiencing emerges from the interaction of sensory, motor, cognitive, and emotional modalities (Wittmann & van Wassenhove, 2009). Moreover, the use of clocks, is only one aspect of time processing that does not guarantee TC capacity (in fact, humans develop TC before being capable to use clocks, while animals that also perceive and process time cannot of course use clocks at all!). In a broader sense, we note here that the "good old fashioned AI" approaches have been criticized in many ways by the robotics community

(Wilson, 2002; Steels, 2003). It is now widely accepted that temporal and other logics can deal with only a limited set of real world circumstances (Pfeifer and Scheier, 1999), and it seems unlikely that they can support the development of near-natural intelligence in artificial systems.

The second alternative approach aims at the computational replication of the TC working principles of the human brain. Such an approach assumes collaboration between robotic and brain science communities to abstract the neural mechanisms accomplishing TC and implement their computational counterparts in artificial cognitive systems. Evidently, the brain-inspired approach has high potential to result into artificial cognitive systems equipped with human competent TC. At the same time, due to the complexity and the highly distributed nature of biological TC mechanisms, this approach fosters the revealing of the brain working principles. Extensive testing of the implemented models may facilitate the in silico investigation of TC processes, providing valuable feedback to brain science regarding time processing functions and their role in cognition (e.g., by offering a valid computational test-bed where alternative theories may be evaluated).

To simulate the highly distributed network of brain areas supporting TC, computational modules having both temporal and other cognitive functional responsibilities need to be implemented. The connectivity of such modules that will assimilate the connectivity of brain areas will base on transfer components that should monitor, extract and forward either temporal or other ordinary cognitive information. The implementation of a large scale brain-inspired system will exploit the interaction between cognitive modalities accomplishing the fusion of sensory information and the temporal association of knowledge items, therefore providing added value to the already implemented perceptual, motor, cognitive, and emotional robotic capacities. This type of "entiment" of cognitive processes (i.e. their placement in time) will facilitate the association of past, present and future events, enabling the administration of particularly complex thoughts. Interestingly, due to the crucial role of time in many high-level and social cognitive skills, such as cause attribution, prospective memory, executive control, mind reading, multi-agent planning, and others, the equipment of artificial systems with TC will enable the aforementioned skills to develop in robotic agents.

Conclusions

As it is argued throughout the paper, temporal cognition is not an optional extra but a necessity towards the development of truly autonomous and intelligent machines. Temporal cognition is a vital capacity that enables the processing of the well defined physical concept of time and additionally the entiment of other cognitive modalities into the real world. The latter facilitates the binding of cognitive modalities into a complex whole that effectively accomplishes high-level cognition.

Still, in the field of robotics, the key role of time in cognition is not adequately considered in contemporary research. Without any doubt, it is now high time to direct research efforts on the exploration of robotic time perception and processing abilities. This will be a significant milestone in bridging the gap between human and artificial cognition.

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