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Cognitive Computing: A Brief Survey and Open Research Challenges

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***Abstract*—Cognitive computing is a multidisciplinary field of research aiming at devising computational models and decision-making mechanisms based on the neurobiological processes of the brain, cognitive sciences, and psychology. The objective of cognitive computational models is to endow computer systems with the faculties of knowing, thinking, and feeling. The major contributions of this survey include (i) giving insights into cognitive computing by listing and describing its definitions, related fields, and terms; (ii) classifying current research on cognitive computing according to its objectives; (iii) presenting a concise review of cognitive computing approaches; and (iv) identifying the open research issues in the area of cognitive computing.**

Keywords—cognitive computing; computational intelligence; artificial intelligence

I. Introduction

Cognition is a process of mind in charge of creating knowledge [57] and understanding by obtaining an abstract representation of a world [47]. Nevertheless, it should be noted that there is no commonly accepted definition of cognition or of the mind itself [38] despite the extensive research into human cognition (see [3, 8, 51]). Hence, cognitive computing or (cognitive computation [55] as originally coined by Valiant in 1995 [68]) has been defined differently by several researchers across time and contexts.

Valiant [55] defines cognitive computing as "*a discipline that links together neurobiology, cognitive psychology and artificial intelligence*".

Brasil et al. [4] state that cognitive computing is "*a collection of emerging technologies inspired by the biological processing of information in the nervous system, human reasoning, decision making, and natural selection*". However, it is noteworthy that *natural selection*, as defined by Hancock [29], is the process in which desirable inheritable traits of a population predominate over undesirable traits across time, which is very distant from the definition of *cognition* as a process of mind in charge of creating knowledge [57].

Preissl et al. [46] describe cognitive computing as "*the quest for approximating the mind-like function, low power, small volume, and real-time performance of the human brain*".

Szymanski and Hise [52] indicate that cognitive computing is "*an emerging field of inquiry that draws on principles from the behavioral, cognitive, computer, and related sciences*".

Wang defines cognitive computing in terms of *cognitive informatics*, which is a multidisciplinary field that applies how the brain processes information and copes with decision making to information sciences [63]. Then, Wang [61] defines cognitive computing as "*an emerging paradigm of intelligent computing methodologies and systems based on cognitive informatics that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain*".

Modha et al. [38] describe cognitive computing by stating its purpose, which is "*to develop a coherent, unified, universal mechanism inspired by the mind's capabilities*".

Nahamoo [41] defines cognitive computing as "*a fundamentally new computing paradigm for tackling real world problems, exploiting enormous amounts of information using massively parallel machines that interact with humans and other cognitive systems.*" In the same context, Evans et al. [23] state that the focus of cognitive computing is on representing and processing information.

Other researchers have opted to outline cognitive computing by stating its main principles, like Clark [9], who states that in cognitive computing "*there exist suitable ways to abstract detailed behavior, and to talk about goals, plans, constraints and methods at a high level*".

The major contributions of this survey include (i) giving insights into cognitive computing by listing and describing its definitions, related fields, and terms (Sections I-II); (ii) classifying current research on cognitive computing according to its objectives (Section III); (iii) presenting a concise review of cognitive computing approaches (Sections III.A-C); and (iv) identifying the open research issues in the area of cognitive computing (Section IV). Finally, Section V includes some concluding remarks.

II. Cognitive Computing and Related Concepts

In order to gain a better understanding of cognitive computing, defining its related fields and terms is required. Based on the different definitions of cognitive computing [4,

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38, 41, 52, 55, 61, 63] (see Section I), related concepts to cognitive computing are as follows: knowledge, neurobiology, cognitive psychology, artificial intelligence, behavioral sciences, cognitive sciences, computer sciences, biological processing, nervous system, reasoning, decision making, cognitive informatics, human brain and mind, and exploitation of enormous amounts of information, i.e., big data [12].

According to Thornton [53], artificial intelligence and cognitive psychology are members of the cognitive sciences.

Artificial intelligence is concerned with reasoning and its underlying processes of thought in order to build intelligent systems that (i) act and/or think like humans and (ii) think and/or act rationally [49]. Reasoning is a series of steps that allows obtaining conclusions (i.e., knowledge) from some initial premises [58]. Knowledge can be defined as the understanding of a subject obtained through study and/or experience [6]. Big data focuses on gaining knowledge from enormous volumes of data [48], which can be used to support decision-making. Decision-making is defined as the process of evaluating and selecting, based on a given criteria, the best alternative from a set of two or more possible choices [44] in order to reach a goal.

Cognitive psychology deals with how the brain perceives and interprets external impressions [39]. Neurobiology studies how connections among neurons influence the behavior of an individual [33]. The nervous system, composed of neurons, reacts to physical stimuli (e.g., external impressions) and exchanges electrochemical signals among neurons to coordinate body's (re)actions. A biological process is a chemical process in which a series of molecular-level events [50] interact among each other to attain a biological goal (e.g., metabolism) [14].

According to [18, 27], the behavioral sciences include biology, sociology, anthropology, and psychology. Biology (as the scientific study of body and cells) is highly and inherently related to cognitive computing. In a similar manner, sociology, anthropology, and psychology hold a high-level relationship with cognitive computing due to their focus on the study of human behavior either as an individual or as a society.

It is noteworthy that both *brain* and *mind* are commonly included in definitions of cognitive computing (see [61] and [38], respectively) and also commonly used interchangeably (see [40, 42, 56]). However, *mind* and *brain* are different. *Mind* refers to a set of activities that enable a human being to feel, think, and know, whereas the *brain* is an organ that endows human beings with the faculties of feeling, thinking, and knowing [31]. Hence, the focus of cognitive computing should be on mimicking the mechanisms of the brain to endow computer systems with the faculties of feeling, thinking and knowing.

In conclusion, cognitive computing is a multidisciplinary field of research aiming at devising computational models and decision-making mechanisms based on the neurobiological processes of the brain, cognitive sciences, and psychology to endow computer systems with the faculties of knowing, thinking, and feeling. In addition, it is noteworthy that

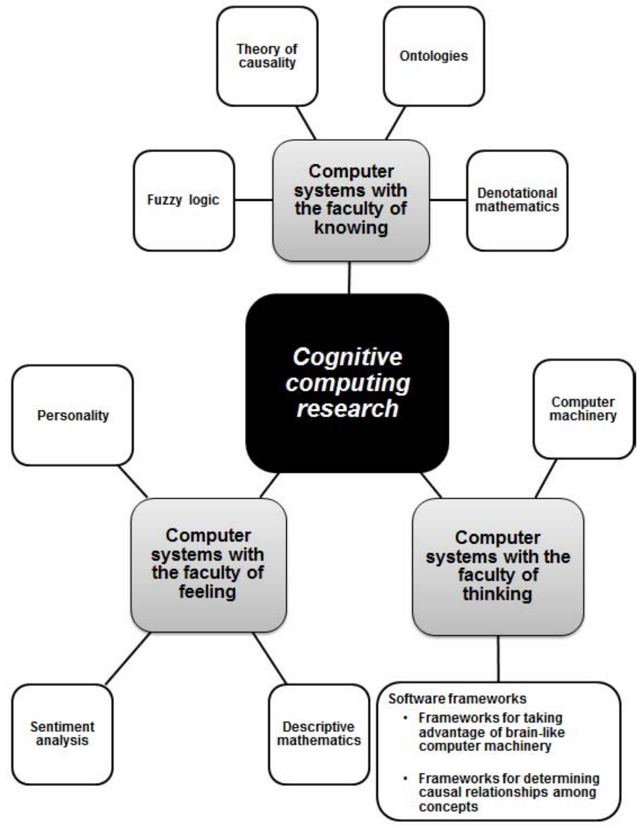

Fig. 1. A coarse taxonomy of cognitive computing research areas.

cognitive computing models can be supported by big data; for instance, see the automatic knowledge extraction mechanism [24] of IBM Watson [25].

III. Current Research on Cognitive Computing

In this survey, we categorize current research on cognitive computing according to its objectives into those providing a computer system with the faculties of (i) knowing, (ii) thinking or (iii) feeling. See Fig. 1 for a coarse taxonomy of cognitive computing research areas, which are analyzed in Sections III.A-C.

A. Endowing Computer Systems with the Faculty of Knowing

Provided that the result of cognition is knowledge [57], several research efforts have been conducted to formally define knowledge from a cognitive computing's perspective.

Tian et al. [54] formalize knowledge by making use of concept algebra [64] and real-time process algebra [67]. Concept algebra is a mathematical framework supported by the *object-attribute-relation* theory for knowledge manipulation [64]. Abstract concepts can be defined, related to each other, compared and composed in order to create a network of concepts that formalizes knowledge. Real-time process algebra is a mathematical notation system capable of describing system architectures as well as the dynamic and static behaviors of their components [67]. Tian et al. [54] combine concept algebra with real-time process algebra to devise a knowledge representation system capable of acquiring and manipulating knowledge.

Similar to Tian et al. [54], ElBedwehy et al. [21] also make use of real-time process algebra [67] to design a cognitive semantic model of knowledge consisting of four stages. In the first stage, a prototype of knowledge is created. The second stage consists of discriminating between relevant and irrelevant knowledge. In the third stage, knowledge is generalized, and finally, the fourth stage consists of developing an algorithm composed of a set of symbolic rules derived from the previous stages. As in [21], Xiao and Lan [69] also emphasize the need for knowledge reduction, i.e., obtaining a sufficient number of attributes to describe an object or concept in order to simplify the cognition process.

Peña-Ayala and Mizoguchi [45] model knowledge by using causal reasoning [30] and fuzzy logic [71]. Concepts and their relationships are formalized by means of ontologies. Then, causal relationships (expressed as fuzzy rules) are defined for the concepts, which are integrated into a cognitive map, i.e., a model of cognition [19]. The cognitive map represents the final model of knowledge.

Wang [60, 62] proposes inference algebra, a denotational mathematics to formally define causation and different types of inferences, which are as follows: conditional, causal, numerical, event-driven, time-driven, logical, and fuzzy inferences. In addition, Wang also proposes a set of operators to manipulate inferences, which are used to represent knowledge.

IBM Watson [25] makes use of semantic technologies, which led IBM Watson to outperform top-ranked human players at Jeopardy, a *question and answer* TV show [28]. The semantic technologies of IBM Watson consists of more than 100 natural language processing techniques [26, 28], which are mostly probabilistic reasoning approaches [26]. To represent knowledge, IBM Watson uses both semi-structured (e.g., taxonomies) and structured approaches (e.g., ontologies). However, in order to answer open-domain questions, IBM Watson is endowed with an automatic knowledge extraction mechanism [24]. This mechanism is capable of conducting a lexical analysis on a large collection of web documents. The analysis results in a set of objects (i.e., concepts) and the relationships among them.

B. Endowing Computer Systems with the Faculty of Thinking

Once knowledge has been formally modeled, cognitive computing systems are able to solve problems autonomously by interpreting the causal relationships and concepts of a given domain knowledge base. In this regard, scientific research efforts aiming at endowing computer systems with the faculty of thinking can be categorized into (i) low level computer machinery (see for instance [2, 32, 37]) and (ii) high level software frameworks (see for instance [1, 34, 59]).

Computer machinery to enable thinking. Hardware has been designed and implemented in order to attempt to recreate the human brain.

Imam et al. [32] and Arthur et al. [2] propose an event-driven digital neurosynaptic core, which is composed of 256 neurons, 1,024 axons and 262,144 synapses (i.e., the junction between two given neurons). There are three types of synapses: strong excitatory, weak excitatory and inhibitory. Imam et al. argue that the neuromorphic chip (i) is relatively compact occupying only 4.2mm^2 of silicon and (ii) requires low energy consumption, namely, 45 pJ per spike [37]. Arthur et al. empirically demonstrated that the neurosynaptic core is highly configurable (due to its large number of potential connections among neurons) by using four test cases: robot navigation, implementation of a virtual player of pong, digit recognition, and an associative memory. In addition, Esser et al. [22] designed and implemented many other algorithms that take full advantage of networks of neurosynaptic cores. Among these new algorithms [22] are music recognition and eye detection.

In the same vein as [2, 32, 37], Preissl et al. [46] propose Compass, a multi-threaded engine that simulates TrueNorth [36], a brain-inspired digital chip with 4,096 neurosynaptic cores [2, 32, 37]. Compass is a massively scalable simulator capable of attaining near-optimal scaling performance. The cognitive architecture of Compass is composed of a number of neurons comparable to that of the human brain. In addition, Compass is provided with novel PGAS [70] communication primitives that allow for efficient communication between neurons.

Software frameworks to enable thinking. Advances in cognitive software to enable thinking have focused on either:

1) *Taking advantage of brain-like computer machinery, or*

2) *Determining causal relationships among concepts of a given domain knowledge base.*

To take advantage of the brain-like computer machinery proposed in [2, 32, 37], Amir et al. [1] designed a programming language for TrueNorth [36]. Amir et al. argue that hardware architectures mimicking the human brain composed of a set of interconnected neurosynaptic cores require a different programming approach to efficiently execute tasks. Hence, Amir et al. devised an object-oriented programming language called *Corelet*. A program written in *Corelet* requires an abstract representation of the network of neurosynaptic cores, along with well-defined interfaces consisting of inputs and outputs (of the network), which receive and send spikes, respectively. *Corelet* enables programmers to construct and compose a high-level network of networks of neurosynaptic cores. Amir et al. also contribute a repository of more than 100 *Corelet* algorithms, which can be used to create new programs.

Djurfeldt [15, 16] proposes a formal language called connection-set algebra for structural connections of parallel neural networks similar to *Corelet* [1]. Connection-set algebra consists of a group of connection operators based on set algebra and matrix algebra, which create a graph representation of the neural network, e.g., an adjacency matrix. However, connection-set algebra is a high-level formalism focused on defining declarative connection patterns among neural networks, and hence it does not take into account brain-like hardware architecture.

In order to determine causal relationships among concepts of a given domain knowledge base, Wang [59] proposes a model of human attention (as a cognitive process) formalized by means of denotational mathematics [60, 62]. According to Wang, attention is both a conscious and a subconscious cognitive process that allows perceiving external events and reacting accordingly. Attention supports sensory processes, memory processes, perception processes and action intelligence, which are among the functions of the cerebellum and some cerebral cortexes. In addition, Wang [59] states that the brain can be seen as a real-time, parallel system with multiple threads of thought, which are interrupted and switched based on an attention engine. Thus, attention allows cognitive computational systems to select and focus on a set of parallel cognitive processes according to external stimuli.

Lawniczak and Di Stefano [34] propose a hierarchical 5-layer architecture for cognitive agents composed of a perceptual layer, a reasoning layer, a judging layer, a response layer, and a learning layer. The perceptual layer is in charge of modeling sensors and creating an abstract representation of the external world. The reasoning layer receives as input (i) a model of the world and (ii) sensors' outputs. Then, by using fuzzy inference mechanisms, cognitive agents can obtain the logical rules of the world. The judgment layer uses the fuzzy rules provided by the reasoning layer in order to (i) extract features from available data, (ii) create a rule-based model for decision-making, and (iii) obtain estimations in the presence of uncertainty. The response layer consists of a collection of automata, which define agents' actions over the environment. Finally, the learning layer implements a feedback loop to generate new knowledge from the interaction of agents with their environment.

C. Endowing Computer Systems with the Faculty of Feeling

As stated by Hoffman [31], the brain endows human beings with the faculty of feeling. In this regard, within the cognitive computing community, there are several research efforts oriented toward devising computational models of feelings (or emotions), which are as follows.

Orozco et al. [43] propose an emotional intelligence model supported by the emotional competence framework, which is composed of three components: self-consciousness, social awareness, and self-regulation. Orozco et al. devised (i) a knowledge base ontology for self-consciousness, (ii) a facial expression classifier for social awareness, and (iii) a computational model that combines personality, emotions and moods for self-regulation. Self-regulation is supported by (i) the OCEAN model of personality [10] consisting of five dimensions: *openness*, *conscientiousness*, *extroversion*, *agreeableness*, and *neuroticism*; (ii) the universal emotions [20]: *anger*, *disgust*, *fear*, *happiness*, *sadness,* and *surprise*; and (iii) three basic moods: *good*, *neutral,* and *bad*. The values for each personality dimension, emotion, or mood, range between 1 and -1 (representing the intensity level of a given component). Finally, Orozco et al. designed a set of matrix operations that evolve (over time) self-regulation of avatars by taking into account the vector of personality traits, the vector of universal emotions, and the vector of basic moods. The resultant emotional intelligence model allows virtual avatars to show empathy for humans' emotional situations.

In order for computers to feel, they need to perceive its environment [65]. Wang [65] proposes an automatic perception engine, along with a formal inference engine, which allow computers to perceive through their behaviors and experiences. Both the perception engine and the inference engine are formalized by using descriptive mathematics [64, 66, 67].

Provided that emotions (i.e., strong feelings) are a central element for decision-making [5], Cambria et al. [5] combine an opinion mining engine and a facial expression classifier in order to determine the emotions of humans. By using a conversational avatar capable of perceiving and fusing information from user-generated written texts, voice, and video, the affective state of a human (interacting with the avatar) is extracted. Then, the avatar makes use of a facial expression generator, a speech generator and a body gestures generator in order to create an empathic response.

IV. Research Agenda

Based on the overview and analysis of current research on cognitive computing (see Section III), we have identified three main research opportunities in the area. The first opportunity is to bridge the gap among cognitive approaches designed to endow computer systems with the faculties of knowing, thinking and feeling (Section IV.A). The second opportunity consists of integrating software-based cognitive approaches and brain-like computer machinery (Section IV.B). The third opportunity is to devise computational models for social cognitive agents (see Section IV.C for details).

A. Bridging the Gap among Knowing, Thinking and Feeling

A myriad of cognitive approaches have been proposed to capture and model knowledge. Both computer machinery and software frameworks aiming at endowing computer systems with the faculty of thinking have been designed. Mathematical, psychological and data-oriented models of feelings have been devised. However, it is noteworthy that even though the faculties of knowing, thinking and feeling are interconnected [35], there is little work on integral cognitive architectures that take all of them into account. The relationship between knowledge and thinking has been somewhat studied. Nevertheless, to the best of our knowledge, the relationship between knowledge and feelings has not been established. Cognitive computational models taking into account this relationship may provide insights into how feelings should influence decision-making or vice versa.

B. Integration of Software-based Cognitive Approaches and Brain-like Computer Machinery

Software-based cognitive approaches focused either on representing knowledge, designing thinking or feeling capabilities are detached from brain-like computer machinery. Networks of neurosynaptic cores are designed to efficiently compute a large number of machine instructions. However, the network of neurosynaptic cores does not explain (i) how domain-specific knowledge is represented in the brain [7] or (ii) the neurological relationship between reasoning and feelings [13]. On the one hand, there is a need for specialized neurosynaptic cores not only focused on efficient computations but also focused on capturing knowledge and feelings. On the other hand, there is a need for integration of cognitive software focused on representing knowledge and modeling feelings into brain-like computer machinery.

C. *Social Cognitive Computing*

There is scientific evidence in support of the development of the brain due to the influence of complex social activities, not only in human societies [11] but also in primate societies [17]. Hence, there is a need for social computational models capable of evolving cognitive capabilities of agents. Cognitive agents interacting with each other not only should be capable of evolving their feelings and knowledge but also should be capable of improving their thinking skills.

Recalling that Brasil et al. [4] indicated that cognitive computing is inspired by *natural selection*, improving thinking skills of a society of cognitive computing systems may be achieved by using natural selection mechanisms in which desirable inheritable traits of a population predominate over undesirable traits across time.

V. Conclusion

The intent of this survey is to promote further research on cognitive computing by presenting a concise review of literature on cognitive computing and identifying the open research issues in the area. In addition, we also contribute a taxonomy that categorizes cognitive computing research according to its objectives into those providing a computer system with the faculties of knowing, thinking or feeling. Moreover, we provide a general characterization of cognitive computing by discussing its multiple definitions and describing their related fields and terms.

Research on cognitive computing has had outstanding advances in the last decade either on endowing computer systems with the faculties of knowing, thinking or feeling. However, there is still a long journey ahead before fully mimicking how brain processes information, generates knowledge, makes decisions and creates feelings.

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