A Cognitive Informatics Reference Model of Autonomous Agent Systems (AAS)

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ABSTRACT

Despite the fact that the origin of software agent systems has been rooted in autonomous artificial intelligence and cognitive psychology, their implementations are still based on conventional imperative computing techniques rather than autonomous computational intelligence. This paper presents a cognitive informatics perspective on autonomous agent systems (AAS’s). A hierarchical reference model of AAS’s is developed, which reveals that an autonomous agent possesses intelligent behaviors at three layers known as those of imperative, autonomic, and autonomous from the bottom up. The theoretical framework of AAS’s is described from the facets of cognitive informatics, computational intelligence, and denotational mathematics. According to Wang’s abstract intelligence theory, an autonomous software agent is supposed to be called as an intelligent-ware, shortly, an intelware, parallel to hardware and software in computing, information science, and artificial intelligence.

Keywords: AI; abstract intelligence; agent systems; autonomic computing; behavioral models; cognitive model; computational intelligence; denotational mathematics; intelligence models; intelware; LRMB; mathematical models; multi-agent; RMAAS; software agent; system behaviors; tonomous agent

INTRODUCTION

A software agent is an intelligent software system that autonomously carries out robotic and interactive applications based on goal-driven cognitive mechanisms. The studies on software agent are rooted in the essences of computing science and cognitive science such as automata theory [von Neumann, 1946, 1958, 1963, 1966; Shannon, 1956], Turing machines [Turing, 1950], cognitive psychology [Newell, 1990; Sternberg, 1997; Anderson and Rosenfeld, 1998; Matlin, 1998], artificial intelligence [McCarthy, 1955, 1963; McCulloch, 1943, 1965; Barr and Feigenbaum, 1981], computational intelligence [Poole et al., 1997; Wang, 2008a], and decision theories [Wald, 1950; Newell and Simon, 1972; Berger et al., 1990; Bronson and Naadimuthu, 1997; Wang and Ruhe, 2007; Wang, 2008b].
The history towards software agents may be traced back to the work as early as in the 1940s. J. McCarthy, W. McCulloch, M.L. Minsky, N. Rochester, and C.E. Shannon proposed the term Artificial Intelligence (AI) [McCarthy, 1955, 1963; McCulloch, 1943, 1965]. S.C. Kleene analyzed the relations of automata and nerve nets [Kleene, 1956]. Then, Bernard Widrow developed the technology of artificial neural networks in the 1950s [Widrow and Lehr, 1990]. The concepts of robotics [Brooks, 1970] and expert systems [Giarrantans and Riley, 1989] were developed in the 1970s and 1980s, respectively. In 1992, the notion of genetic algorithms was proposed by J.H. Holland [Holland, 1992]. Then, distributed artificial intelligence and intelligent system technologies emerged since late 1980s [Bond and Gasser, 1988; Kurzweil, 1990; Chaib-Draa et al., 1992; Meystel and Albus, 2002, Meystel and Albus, 2002].

The origin of the term autonomous agent is based on Carl Hewitt and his colleagues’ artificial intelligence actor models proposed in 1973 [Hewitt et al., 1973, 1991]. Then, as a novel approach of artificial intelligence, agent technologies have been proliferated since the early 1990s [Foner, 1993; Genesereth and Ketchpel, 1994; Hayes-Roth, 1995; Axelrod, 1997; Huhns and Singh, 1997; Wooldridge and Jenings, 1995; Wooldridge, 2002, Wang, 2003b]. Pattie Maes perceived that a software agent is a process that lives in the world of computers and networks and that can operate autonomously to fulfill a set of tasks [Maes, 1991]. Dimitris N. Chorafas described a software agent as a new software paradigm of things that think [Chorafas, 1998]. Software agents are characterized by knowledge, learning, reasoning, and adaptation, which are rational to the extent that their behaviors are predictable by given goals and the solution environment [Russell and Norvig 1995; Poole, Mackworth, and Goebel 1997; Nilsson 1998].

Multi-agent systems are proposed in [Wittig, 1992; Wellman, 1999] as distributed intelligent systems [Bond and Gasser, 1988] in which each node is an autonomous software agent. The key technology of autonomous agent systems is how a variety of heterogeneous agents allocate their roles, coordinate their behaviors, share their resources, and communicate their information, beliefs, and needs [Maes, 1991]. The interaction mechanisms of multi-agent systems, such as cooperation, negotiation, belief reconciliation, information sharing, and distributed decision making, are identified as important issues in the design and implementation of multi-agent systems.

Autonomic computing is one of the fundamental technologies of software agents, which is a mimicry and simulation of the natural intelligence possessed by the brain using general computers. Autonomic computing was first proposed by IBM in 2001, where it is perceived that “Autonomic computing is an approach to self-managed computing systems with a minimum of human interference. The term derives from the body’s autonomous nervous system, which controls key functions without conscious awareness or involvement [IBM, 2006].” Various studies on autonomic computing have been reported following the IBM initiative [Kephart and Chess, 2003; Murch, 2004; Wang, 2004].

According to Wang’s abstract intelligence theory [Wang, 2008a, 2009], software agents are a paradigm of abstract and computational intelligence, which is a subset of or an application-specific virtual brain. Behaviors of a software agent are mirrored human behaviors. Therefore, a software agent may be more accurately named as an intelligent-ware, shortly, an intelware, parallel to hardware and software in computing, information science, and artificial intelligence. In this notion, intelware will be treated as a synonym of an autonomous agent system.

This paper presents a coherent theoretical framework of autonomous agent systems (AAS’s) or intelware from the facets of cognitive informatics, computational intelligence, and denotational mathematics. The nature of software agents and intelware is elaborated. A reference model of AAS with intelligent behaviors at three layers known as those of imperative, autonomic, and autonomous is developed from the bottom up. The theoretical
framework of AAS’s/intelware is presented on the basis of cognitive informatics and computational intelligence theories. A set of denotational mathematics is introduced in order to provide a fundamental mathematical means for formally and rigorously dealing with the highly complicated architectures and intricate behaviors of AAS’s and intelware.

THE NATURE OF SOFTWARE AGENTS AND INTELWARE

**Definition 1.** A software agent, or more actually an intelware, is an intelligent software system that autonomously carries out robotistic and interactive applications based on goal-driven cognitive mechanisms.

On the basis of Definition 1, an autonomous agent is a software agent that possesses high-level autonomous ability and behaviors beyond conventional imperative computing technologies.

**Definition 2.** An Autonomous Agent System (AAS) is a composition of distributed agents that possesses autonomous computing and decision making abilities as well as interactive communication capability to peers and the environment.

The classification of agent/intelware technologies can be described in Table 1, where $I$ and $O$ denote the inputs/outputs of a given AAS. When both input event ($I$) and output behavior ($O$) are constant, it denotes a routine intelware; while when both $I/O$ are variable, it represents the most complicated autonomous intelware. Otherwise, the combinations of variable event/constant behavior and constant event/variable behaviors indicate an algorithmic or autonomic intelware, respectively.

In Table 1, the routine and algorithmic AAS’s may be implemented by computational imperative behaviors. However, the autonomic AAS’s should be implemented by autonomic computing, as that of the autonomous AAS’s by autonomous mechanisms and behaviors.

THE REFERENCE MODEL OF INTELWARE/AUTONOMOUS AGENT SYSTEMS

The reference model of intelware/AAS’s is a hierarchical model with three layers known as those of imperative, autonomic, and autonomous behaviors. This section elaborates the mathematical models of the imperative and intelligent behaviors of intelware/AAS’s in the layered reference model of agent intelligence.

The Hierarchical Behavioral Model of Intelware/AAS’s

Behaviorism is a doctrine of psychology and cognitive informatics that describes the association between a given stimulus and an observed response of human brains and AAS’s. Cognitive informatics reveals that human and AAS behaviors may be classified into four categories known as the perceptive, cognitive, instructive, and reflective behaviors [Wang, 2007b].

<table>
<thead>
<tr>
<th>Event ($I$)</th>
<th>Behavior ($O$)</th>
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<tbody>
<tr>
<td>Constant</td>
<td>Routine</td>
<td>Autonomic</td>
</tr>
<tr>
<td>Variable</td>
<td>Algorithmic</td>
<td>Autonomous</td>
</tr>
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</table>
The reference model of AAS’s (RMAAS) is a hierarchical behavioral model of agent intelligence as illustrated in Fig. 1. In the RMAAS model, the hierarchy of agent behaviors can be divided into the imperative, autonomic, and autonomous layers. Conventional computing machines are implemented only by imperative behaviors. However, the autonomic computing systems and AAS’s are implemented by advanced cognitive behaviors. Imperative computing is an enclosure of instructive and passive behaviors. The autonomic computing is an enclosure of internally motivated behaviors beyond those of the imperative space. The autonomous computing is an enclosure of perceptive- and inference-driven behaviors beyond those of both imperative and autonomic computing. More formal descriptions of the three types of behaviors of AAS’s will be presented in the following subsections.

The Imperative Behavioral Layer of Intelware/AAS’s

According to the RMAAS model as illustrated in Fig. 1, the imperative behavioral intelligence of intelware and AAS’s can be formally modeled and elaborated in this subsection.

Definition 3. The imperative behavioral layer of AAS’s, $B_I$, is a set of instruction-based behaviors such as the event-driven behaviors ($B_e$), time-driven behaviors ($B_t$), and interrupt-driven behaviors ($B_{int}$), i.e.:

$$B_I = \{B_e, B_t, B_{int}\}$$

An imperative system implemented with $B_I$ may do nothing unless a specific program is loaded, in which the stored program transfers a general-purpose computer to a specific intelligent application. The imperative system is a passive system that implements deterministic, context-free, and stored-program controlled behaviors.

Definition 4. An event is an abstract variable that represents an external stimulus to a system or the occurring of an internal change of status, such as an action of users, an updating of the environment, and a change of the value of a control variable.

The types of events that may trigger a behavior can be classified into operational (@eS), time (@tTM), and interrupt (@int⊙) events, where @ is the event prefix, and S, TM, and ⊙ the type suffixes, respectively. The interrupt event is a kind of special event that models the interruption of an executing process, the temporal handover of controls to an Interrupt Service Routine (ISR), and the return of control after its completion.

Definition 5. An interrupt, denoted by $\downarrow$, is a parallel process relation in which a running process $P$ is temporarily held by another higher priority process $Q$ via an interrupt event @int⊙ at the interrupt point ⊙, and the interrupted process will be resumed when the high priority process has been completed, i.e.:

$$P \downarrow Q \triangleq P \parallel (@int⊙ \downarrow Q \uparrow ⊙)$$

where $\downarrow$ and $\uparrow$ denote an interrupt service and an interrupt return, respectively.

In general, all types of events, including the operational events, timing events, and interrupt events, are captured by the system in order to dispatch a designated behavior.

Definition 6. An event-driven behavior $B_e$ denoted by $\leftarrow e_i$ is an imperative process in which the $i$th behavior in term of a designated process $P_i$ is triggered by a predefined event @e_iS, i.e.:

$$B_e \triangleq \bigcup_{i=1}^{n} (@e_iS \leftarrow e_i P_i)$$

where the big-R notation is a mathematical calculus that denotes a sequence of repetitive/iterative behaviors or a set of recurring structures [Wang, 2007a].
Definition 7. A time-driven behavior \( B_t \), denoted by \( \lhd_{TM} \), is an imperative process in which the \( i \)th behavior in term of process \( P_i \) is triggered by a predefined point of time \( @t_i \), i.e.:

\[
B_t \triangleq \bigcup_{i=1}^{n} (@t_i \lhd_{TM} P_i)
\]  

where \( @t_i \) may be a system timing or external timing event.

Definition 8. An interrupt-driven behavior \( B_{int} \), denoted by \( \lhd_{int} \), is an imperative process in which the \( i \)th behavior in term of process \( P_i \) is triggered by a predefined system interrupt \( @int_i \), i.e.:

\[
B_{int} \triangleq \bigcup_{i=1}^{n} (@int_i \lhd_{int} P_i)
\]

As a summary, an imperative computing system can be described as follows.

Definition 9. An Imperative Computing (IC) system is a passive system that implements deterministic, context-free, and stored-program controlled behaviors.

The Autonomic Behavioral Layer of Intelware/AAS’s

According to the RMAAS model as illustrated in Fig. 1, the autonomic behavioral intelligence of intelware and AAS’s can be formally modeled and elaborated in this subsection.

Definition 10. The autonomic behavioral layer of AAS’s \( B_A \), is a set of internally motivated and self-generated behaviors such as the goal-driven behaviors \( B_g \) and decision-driven behaviors \( B_d \) on the basis of the imperative layer \( B_I \), i.e.:

\[
B_A \triangleq \{ B_g, B_d \} \cup B_I
\]

Definition 11. A goal-driven behavior \( B_g \), denoted by \( \lhd_{g} \), is an autonomic process in which
the \( i \)th behavior in term of process \( P \) is generated by the system itself, rather than be given, corresponding to the goal \( g_{\text{ST}} \), i.e.:

\[
B_g \triangleq \bigcup_{i=1}^{n} (@g_{\text{ST}} \xrightarrow{L_{g}} P_i)
\]

(7)

where the goal, denoted by \( g_{\text{ST}} \), is a triple, i.e.:

\[
g_{\text{ST}} = (P, \Omega, \Theta)
\]

(8)

in which that \( P = \{p_1, p_2, \ldots, p_n\} \) is a finite nonempty set of purposes or motivations, \( \Omega \) is a finite set of constraints for the goal, and \( \Theta \) is the environment of the goal.

**Definition 12.** A decision-driven behavior \( B_d \), denoted by \( \xrightarrow{d_{\text{ST}}} \), is an autonomic process in which the \( i \)th behavior in term of process \( P_i \) is generated by a given decision \( @d_{\text{ST}} \), i.e.:

\[
B_d \triangleq \bigcup_{i=1}^{n} (@d_{\text{ST}} \xrightarrow{L_{d}} P_i)
\]

(9)

where the decision, denoted by \( d_{\text{ST}} \), is a selected alternative \( a \in A \) from a nonempty set of alternatives \( A \), based on a given set of criteria \( C \), i.e.:

\[
d = f(A, C)
\]

\[
f : A \times C \rightarrow A, \ A \neq \emptyset
\]

(10)

**Definition 13.** An Autonomic Computing (AC) system is an intelligent system that implements nondeterministic, context-dependent, and adaptive behaviors based on goal- and decision-driven mechanisms.

The autonomic systems do not rely on instructive and procedural information, but are dependent on internal status and willingness that formed by long-term historical events and current rational or emotional goals [Wang, 2007d].

### The Autonomous Behavioral Layer of Intelware/AAS’s

According to the RMAAS model as illustrated in Fig. 1, the autonomous behavioral intelligence of intelware and AAS’s can be formally modeled and elaborated in this subsection.

**Definition 14.** The autonomous behavioral layer of AAS’s, \( B_A \), is a set of autonomously generated behaviors by internal cognitive processes such as the perception-driven behaviors \( (B_p) \) and inference-driven behaviors \( (B_{inf}) \) on the basis of the imperative space \( B_I \) and the autonomic space \( B_C \), i.e.:

\[
B_A \triangleq \{B_p, B_{inf}\} \cup B_I \cup B_C
\]

\[
= \{\text{obs}, \text{act}, \text{inf}, \text{inf}, \text{appr}, \text{inf}\}
\]

(11)

The new forms of behaviors covered in the autonomous layer can be elaborated as follows.

**Definition 15.** A perception-driven behavior \( B_p \), denoted by \( \xrightarrow{p_{\text{PC}}} \), is a cognitive process in which the \( i \)th behavior in term of process \( P_i \) is generated by the result of a perceptive process \( @p_{\text{PC}} \), i.e.:

\[
B_p \triangleq \bigcup_{i=1}^{n} (@p_{\text{PC}} \xrightarrow{L_{p}} P_i)
\]

(12)

where \( \text{PC} \) stands for a type of process, and the perception result \( p_{\text{PC}} \) is an outcome of the cognitive process of perception that an AAS may generate.

Inferences are cognitive processes that reason about a possible causality from given premises based on known causal relations between a pair of cause and effect proven true by empirical arguments, theoretical inferences, or statistical regulations.

**Definition 16.** An inference-driven behavior \( B_{inf} \), denoted by \( \xrightarrow{inf} \), is a cognitive process in which the \( i \)th behavior in term of process \( P_i \) is
generated by the result of an inference process @inf PC, i.e.:

\[ B_{inf} \triangleq \bigcap_{i=1}^{n} (\inf_{\bigvee} \longleftarrow \inf_{Pi}) \]  

(13)

where formal inferences can be classified into the deductive, inductive, abductive, and analogical categories, as well as modal, probabilistic, and belief theories [Wang, 2007e].

As shown in Definition 16 and Fig. 1, an AAS implemented on \( B_I \) extends the conventional behaviors \( B_I \) and \( B_C \) to more powerful and intelligent behaviors, which are generated by internal and autonomous processes such as the perception and inference processes. With the possession of all the seven forms of intelligent behaviors in \( B_A \), the AAS may advance closer to the intelligent power of human brains.

**Relationships between the Agent Behaviors of Intelware/AAS’s at the Three Layers of RMAAS**

Contrasting Definitions 3, 10, and 14, the following relationships among the three-layer agent intelligent behaviors can be established on the basis of the RMAAS model as illustrated in Fig. 1.

**Theorem 1.** The relationships of the imperative behaviors \( B_I \), autonomic behaviors \( B_C \), and cognitive behaviors \( B_A \) of intelware or AAS’s are hierarchical and inclusive, i.e.:

\[ B_I \subseteq B_C \subseteq B_A \]  

(14)

Theorem 1 and Definition 14 indicate that any lower layer behavior of an intelware or AAS is a subset of those of a higher layer. In other words, any higher layer behavior is a natural extension of those of lower layers as shown in Fig. 1. Therefore, the necessary and sufficient conditions of AAS’s, \( C_{AAS} \), are the possession of all behaviors at the three layers.

**Corollary 1.** The behavioral model of intelware or AAS, \( \Pi_{AAS} \), can be logically modeled by a set of parallel processes that encompasses the imperative behaviors \( B_I \), autonomic behaviors \( B_C \), and autonomous behaviors \( B_A \) from the bottom-up, i.e.:

\[ \Pi_{AAS} \triangleq \{(B_I, B_C, B_A) \} / / B_I \]  

\[ / || (B_e, B_I, B_{int}, B_g, B_d) \} / / B_C \]  

\[ / || (B_e, B_I, B_{int}, B_g, B_d, B_p, B_{inf}) \} / / B_A \]  

(15)

where || denotes a parallel relation in RTPA.

**THEORETICAL FOUNDATIONS OF INTELWARE/AAS’S**

Recent research reveals that the foundations of agent technologies root in cognitive informatics, denotational mathematics, and computational intelligence [Wang, 2002a, 2003b, 2008a]. Along with the latest advances in cognitive informatics, non-imperative autonomous agent systems known as intelware and cognitive computers are emerging. This section explores the theoretical foundations of AAS’s and intelware. The latest development of fundamental theories and technologies underpinning AAS’s and intelware are highlighted.

**Denotational Mathematics for AAS’s**

Applied mathematics can be classified into two categories known as analytic and denotational mathematics [Wang, 2002b, 2007a, 2008a, 2008c]. The former are mathematical structures that deal with functions of variables as well as their operations and behaviors; while the latter are mathematical structures that formalize rigorous expressions and inferences of system architectures and behaviors with abstract concepts, complex relations, and dynamic processes. The denotational and expressive needs in cognitive informatics, com-
Computational intelligence, software engineering, and knowledge engineering have led to new forms of mathematics collectively known as denotational mathematics.

**Definition 17.** Denotational mathematics is a category of expressive mathematical structures that deals with high-level mathematical entities beyond numbers and simple sets, such as abstract objects, complex relations, behavioral information, concepts, knowledge, processes, intelligence, and systems.

The term denotational mathematics is first introduced by Yingxu Wang in the emerging discipline of cognitive informatics [Wang, 2002a, 2007a, 2008c]. Typical paradigms of denotational mathematics are comparatively presented in Table 1, where their structures, mathematical entities, algebraic operations, and usages are contrasted. The paradigms of denotational mathematics as shown in Table 1 are concept algebra [Wang, 2008d], system algebra [Wang, 2008e], and Real-Time Process Algebra (RTPA) [Wang, 2002b, 2008f].

The emergence of denotational mathematics is driven by the practical needs in cognitive informatics, computational intelligence, computing science, software science, and knowledge engineering, because all these modern disciplines study complex human and machine behaviors and their rigorous treatments. Among the new forms of denotational mathematics, concept algebra is designed to deal with the abstract mathematical structure of concepts and their representation and manipulation in knowledge engineering. System algebra is created to the rigorous treatment of abstract systems and their algebraic relations and operations. RTPA is developed to deal with series of behavioral processes and architectures of human and systems.

Denotational mathematics provides a powerful mathematical means for modeling and formalizing AAS’s. Not only the architectures of AAS’s, but also their dynamic behaviors can be rigorously and systematically manipulated by denotational mathematics. Applications of denotational mathematics in cognitive informatics and computational intelligence have been elaborated with a wide range of real-world case studies [Wang, 2008a, 2008c], which demonstrate that denotational mathematics is an ideal mathematical means for dealing with concepts, knowledge, behavioral processes, and human/machine intelligence in ASS’s and intelware.

**Cognitive Informatics Theories of AAS**

Cognitive informatics is the transdisciplinary enquiry of cognitive and information sciences that investigates into the internal information processing mechanisms and processes of the brain and natural intelligence, and their engineering applications via an interdisciplinary approach [Wang, 2002a, 2003a, 2003b, 2006, 2007a, 2007b, 2007c, 2007d]. According to the abstract intelligence theory [Wang, 2008a, 2009], because cognitive informatics investigates the internal information processing mechanisms and processes of the brain and natural intelligence, its research results underlie the engineering applications of AAS’s. Cognitive informatics reveals that artificial intelligence (AI) is a subset of natural intelligence (NI) [Wang, 2007a, 2007b]. Therefore, AAS’s may be referred to the natural intelligence and behavioral mechanisms of human beings.

A Layered Reference Model of the Brain (LRMB) is developed [Wang, et al., 2006] that reveals the logical model of NI and a coherent set of cognitive mechanisms. LRMB presents a systematical view toward the formal description and modeling of architectures and behaviors of AAS’s, which are created to extend human capability, reachability, and/or memory capacity. The LRMB model explains the functional mechanisms and cognitive processes of the natural intelligence with 39 cognitive processes at seven layers known as the sensation, memory, perception, action, meta-cognitive, meta-inference, and higher cognitive layers from the bottom up. LRMB elicits the core and highly repetitive recurrent cognitive processes from a
Table 2. Paradigms of Denotational Mathematics

| Paradigm | Structure | Algebraic operations | Mathematical entities | No. Para-
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</tr>
</thead>
<tbody>
<tr>
<td>Systemalgebra</td>
<td>${\Theta \cup \mathcal{V}, \mathcal{F}, \mathcal{R}, \mathcal{M} }$</td>
<td>$\Theta {\bullet, \ast}$</td>
<td>$\Theta {\bullet, \ast}$</td>
<td>3</td>
</tr>
<tr>
<td>Real-time processes (RTPA)</td>
<td>$\mathcal{S} \equiv \mathcal{F} \cup \mathcal{M} \cup \mathcal{R}$</td>
<td>$\Theta {\bullet, \ast}$</td>
<td>$\Theta {\bullet, \ast}$</td>
<td>2</td>
</tr>
<tr>
<td>Concepts of abstract systems</td>
<td>$\mathcal{C} \equiv \mathcal{F} \cup \mathcal{M} \cup \mathcal{R}$</td>
<td>$\Theta {\bullet, \ast}$</td>
<td>$\Theta {\bullet, \ast}$</td>
<td>1</td>
</tr>
</tbody>
</table>
huge variety of life functions, which may shed light on the study of the fundamental mechanisms and interactions of complicated mental processes as well as AAS’s, particularly the relationships and interactions between the inherited and the acquired life functions as well as those of the subconscious and conscious cognitive processes. The cognitive model of the brain can be used as a reference model for goal- and inference-driven technologies in AAS’s.

**Definition 18.** The cognitive model of the kernel of an AAS or intelware, $AAS_k$, can be described as a real-time intelligent system with an inherited Agent Operating System $AOS$ and a set of Agent Intelligent Behaviors $AIB$ in parallel, i.e.:  

$$ AAS_k \triangleq AOS \parallel AIB $$  \hspace{1cm} (16) 

**Definition 19.** The Cognitive Models of Memory (CMM) states that the architecture of human memory is parallel configured by the Sensory Buffer Memory (SBM), Short-Term Memory (STM), Long-Term Memory (LTM), Conscious Status Memory (CSM), and Action-Buffer Memory (ABM), i.e.:  

$$ CMM \triangleq ( \begin{array}{c} LTM \\ STM \\ CSM \\ SBM \\ ABM \end{array} ) $$  \hspace{1cm} (17) 

The CMM model provides a neural informatics foundation of natural intelligence. With the CMM model, the broad sense of an AAS, AAS’, can be described by mimicking the abstract architecture and mechanisms of the brain.

**Definition 20.** The cognitive model of AAS’s, $AAS$, is represented by a real-time intelligent system that encompasses the intelware and the CMM as well as their interactions, i.e.:  

$$ AAS \triangleq \begin{array}{c} Intelware \\ || CMM \end{array} = ( \begin{array}{c} AOS \\ || AIB \end{array} ) $$

$$ || ( \begin{array}{c} LTM \\ STM \\ CSM \\ SBM \\ ABM \end{array} ) $$  \hspace{1cm} (18) 

Eq. 18 indicates that although intelware is considered the center of AAS’s, the memories are essential to enable it to properly function, and to keep temporary and permanent results physiologically retained and retrievable.

**Computational Intelligence Theories of AAS’s**

According to the abstract intelligence theory [Wang, 2008a, 2009], intelligence is perceived as the driving force or the ability to acquire and use knowledge and skills, or to reason in problem solving. It was conventionally perceived that only human beings possess higher-level intelligence. However, the development of computers, robots, intelligent systems, and AAS’s indicates that intelligence may also be created or implemented by machines and man-made systems.

**Definition 21.** Intelligence, in the narrow sense, is a human or a system ability that transforms information into behaviors; and in a broad sense, it is any human or system ability that autonomously transfers the forms of abstract information between data, information, knowledge, and behaviors in the brain.

**Definition 22.** The Generic Abstract Intelligence Model (GAIM), as shown in Fig. 2, represents abstract intelligence in four forms known as the perceptive, cognitive, instructive, and reflective intelligence, corresponding to the specific forms of cognitive information and their memories.
The GAIM indicates that different forms of intelligence are the driving force that transfers between a pair of abstract objects in the brain such as data ($D$), information ($I$), knowledge ($K$), and behavior ($B$). It is noteworthy that each abstract object is physiologically retained in a particular type of memories as given in the CMM model. This is the neural informatics foundation of natural intelligence, and the physiological evidences of why natural intelligence can be classified into four forms as shown in Fig. 2.

According to Definitions 21 and 22, computational intelligence is a paradigm of abstract intelligence. Computational intelligence models human intelligence by computational methodologies and cognitively inspired models.

**Definition 23.** The computational intelligence model of AAS’s and intelware, $\text{§AAS}^{\text{ST}}$, is a parallel structure represented by the Agent Operating System ($\text{AOS}^{\text{ST}}$) and a set of agent intelligence represented by the Agent Intelligent Behaviors ($\text{AIB}^{\text{ST}}$), as shown in Fig. 3.

The GAIM and $\text{§AAS}^{\text{ST}}$ model reveal that NI and AI share the same cognitive informatics foundations on the basis of abstract intelligence. The compatible intelligent capability states that NI, AI, AAS’s, and intelware are compatible by sharing the same mechanisms of intelligent capability and behaviors. In other words, at the logical level, NI of the brain shares the same mechanisms as those of AI and computational intelligence. The differences between NI and AI are only distinguishable by the means of implementation and the extent of intelligent ability. Therefore, the studies on NI and AI in general, and intelware and AAS’s in particular, may be unified into a coherent framework based on cognitive informatics and computational intelligence, which are formalized by denotational mathematics.

**CONCLUSION**

This paper has presented a coherent theoretical framework of Autonomous Agent Systems (AAS), known as intelware, from the facets of cognitive informatics, computational intelligence, and denotational mathematics. A reference model of AAS has been developed with three-layer intelligent behaviors known as the imperative, autonomic, and autonomous agent intelligence from the bottom up. It has been recognized that the characteristics of an AAS is its perception-driven and inference-driven behaviors beyond the imperative and autonomic ones as provided by conventional imperative and autonomic computing.

In order to formally and rigorously deal with the highly complicated architectures and intricate behaviors of intelware and AAS’s, a new mathematical means known as denotational mathematics has been developed. Typical paradigms of denotational mathematics have been
Fig. 3 The computational intelligence model of AAS

\[
\begin{align*}
\text{The Computational Intelligent Model of AAS} \\
\text{\#AASST} & \triangleq \text{AASST} \quad \text{// Agent operating system} \\
\text{\#AIBST} & \triangleq \text{AIBST} \quad \text{// Agent intelligent behaviors} \\
\text{\#Sensors[ptrPST]} & \triangleq \text{SENSEST} \\
\text{\#Memory[addrPST]} & \triangleq \text{MEM[addrPST]} \\
\text{\#STMST} & \triangleq \text{STM[addrPST]} \\
\text{\#CSTMST} & \triangleq \text{CSTMST} \\
\text{\#LTMST} & \triangleq \text{LTMST} \\
\text{\#ABMST} & \triangleq \text{ABMST} \\
\text{\#Process[HIST]} & \triangleq \text{PROC[HIST]} \\
\text{\#ObjectIdentificationST} & \triangleq \text{ObjectIdentificationST} \\
\text{\#AbstractionST} & \triangleq \text{AbstractionST} \\
\text{\#ConceptEstablishmentST} & \triangleq \text{ConceptEstablishmentST} \\
\text{\#SearchST} & \triangleq \text{SearchST} \\
\text{\#CategorizationST} & \triangleq \text{CategorizationST} \\
\text{\#ComparisonST} & \triangleq \text{ComparisonST} \\
\text{\#MemorizationST} & \triangleq \text{MemorizationST} \\
\text{\#QualificationST} & \triangleq \text{QualificationST} \\
\text{\#QuantificationST} & \triangleq \text{QuantificationST} \\
\text{\#SelectionST} & \triangleq \text{SelectionST} \\
\text{\#DeductionST} & \triangleq \text{DeductionST} \\
\text{\#InductionST} & \triangleq \text{InductionST} \\
\text{\#AbductionST} & \triangleq \text{AbductionST} \\
\text{\#AnalogyST} & \triangleq \text{AnalogyST} \\
\text{\#AnalysisST} & \triangleq \text{AnalysisST} \\
\text{\#SynthesisST} & \triangleq \text{SynthesisST} \\
\text{\#ComprehensionST} & \triangleq \text{ComprehensionST} \\
\text{\#LearningST} & \triangleq \text{LearningST} \\
\text{\#PlanningST} & \triangleq \text{PlanningST} \\
\text{\#ProblemSolvingST} & \triangleq \text{ProblemSolvingST} \\
\text{\#DecisionMakingST} & \triangleq \text{DecisionMakingST} \\
\text{\#CreationST} & \triangleq \text{CreationST} \\
\text{\#PatternRecognitionST} & \triangleq \text{PatternRecognitionST} \\

\text{\#Relative clock} & \triangleq \text{TMST} \\
\end{align*}
\]

\[
\begin{align*}
\text{\#AIBST} & \triangleq \text{AIBST} \\
\text{\#Event-driven behaviors (B_e)} & \triangleq \text{ErPST} \\
\text{\#Time-driven behaviors (B_t)} & \triangleq \text{LTPST} \\
\text{\#Interrupt-driven behaviors (B_{int})} & \triangleq \text{IpPST} \\
\text{\#Goal-driven behaviors (B_g)} & \triangleq \text{GPST} \\
\text{\#Decision-driven behaviors (B_d)} & \triangleq \text{DPST} \\
\text{\#Perception-driven behaviors (B_p)} & \triangleq \text{PPST} \\
\text{\#Inference-driven behaviors (B_{inf})} & \triangleq \text{IPST} \\
\end{align*}
\]
introduced such as concept algebra, system algebra, and RTPA. The findings of this work, particularly the necessary and sufficient conditions of imperative and autonomous computing, and the abstract intelligence model of natural and artificial intelligence, have formed a solid foundation for explaining and developing advanced autonomous computing systems and their engineering applications.

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