



Toward Theoretical Foundations of Autonomic Computing¹

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ABSTRACT

Autonomic computing (AC) is an intelligent computing approach that autonomously carries out robotic and interactive applications based on goal- and inference-driven mechanisms. This article attempts to explore the theoretical foundations and technical paradigms of AC. It reviews the historical development that leads to the transition from imperative computing to AC. It surveys transdisciplinary theoretical foundations for AC such as those of behaviorism, cognitive informatics, denotational mathematics, and intelligent science. On the basis of this work, a coherent framework toward AC may be established for both interdisciplinary theories and application paradigms, which will result in the development of new generation computing architectures and novel information processing systems.

Keywords: *autonomic computing; AI; behavioral models; cognitive informatics; cognitive models; imperative computing; intelligence models; knowledge science; mathematical models; natural intelligence; software engineering; software science*

INTRODUCTION

Autonomic computing (AC) is a mimicry and simulation of the natural intelligence possessed by the brain using generic computers. This indicates that the nature of software in AC is the simulation and embodiment of human behaviors, and the extension of human capability, reachability, persistency, memory, and information processing speed.

The history toward AC may be traced back to the work on automata by Norbert Wiener, John von Neumann, Alan Turing, and Claude E. Shannon as early as in the 1940s (Rabin & Scott, 1959; Shannon, 1956; Turing, 1950; von

Neumann, 1946, 1958, 1963, 1966; Wiener, 1948). In the same period, Warren McCulloch proposed the term of artificial intelligence (AI) (McCulloch, 1965, 1993; McCulloch & Pitts, 1943), and 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 & Lehr, 1990). The concepts of robotics (Brooks, 1970) and expert systems (Giarrantans & Riley, 1989) were developed in the 1970s and 1980s, respectively. Then, intelligent systems (Meystel & Albus, 2002) and software agents (Negreonte, 1995; Jennings, 2000) emerged in

the 1990s. These events and developments lead to the formation of the concept of AC.

AC was first proposed by IBM in 2001 where it is perceived that, "AC is an approach to self-managed computing systems with a minimum of human interference. The term derives from the body's autonomic nervous system, which controls key functions without conscious awareness or involvement" (IBM, 2001). Various studies on AC have been reported following the IBM initiative (Kephart & Chess, 2003; Murch, 2004; Pescovitz, 2002). The cognitive informatics foundations of AC have been revealed by Wang (2002a, 2003a, 2003b, 2004, 2006b, 2006f, 2007a, 2007c) and Wang and Kinsner (2006). A paradigm of AC in term of cognitive machine has been surveyed by Kinsner (2007) and investigated by Wang (2006a, 2007b).

Based on cognitive informatics theories (Wang, 2002a, 2003a, 2007b), AC is proposed as a new and advanced technology for computing built upon the routine, algorithmic, and adaptive systems as shown in Table 1.

The first three categories of computing techniques, such as routine, algorithmic, and adaptive computing, as shown in Table 1, are imperative. In contrary, the AC systems do not rely on imperative and procedural instructions, but are dependent on goal-, perception-, and inference-driven mechanisms.

- **Definition 1:** An *imperative computing (IC) system* is a passive system that implements deterministic, context-free, and stored-program controlled behaviors.

- **Definition 2:** An *autonomic computing system* is an intelligent system that implements non-deterministic, context-dependent, and adaptive behaviors based on goal- and inference-driven mechanisms.

This article attempts to explore the theoretical foundations and engineering paradigms of AC. It is extended from two invited keynote speeches of the author in the Third IEEE International Conference on Cognitive Informatics (ICCI'04) (Wang, 2004) and the First International Conference on Agent-Based Technologies and Systems (ATS'03) (Wang, 2003b). In the remainder of this article, the historical development that transfers IC to AC is reviewed. Then, a comprehensive set of theoretical foundations and paradigms for AC is explored, encompassing those of behaviorism, cognitive informatics, denotational mathematics, and intelligent science. On the basis of this work, a coherent framework toward AC may be established for the development of interdisciplinary theories and application paradigms.

FROM IMPERATIVE TO AUTONOMIC COMPUTING

The general-purpose computers may do anything unless a specific program is loaded, in which the stored program transfers a computer as a general behavioral implementing machine to specific intelligent applications. The approaches to computing, or ways for embodiment of intelligent behaviors, can be classified into two categories known as IC and AC as given in Definitions 1 and 2.

Table 1. Classification of computing methodologies and systems

| | | Behavior (O) | |
|-------------------------|----------|----------------------|-------------------------|
| | | Constant | Variable |
| Event (I) | Constant | Routine | Adaptive |
| | Variable | Algorithmic | Autonomic |
| <i>Type of behavior</i> | | <i>Deterministic</i> | <i>Nondeterministic</i> |

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