Swarm Intelligence in Cellular Robotic Systems

Gerardo Beni and Jing Wang

College of Engineering
University of California, Riverside
Riverside, California 92521, USA

Abstract

Cellular Robotic Systems are capable of 'intelligent' behavior. The meaning of this intelligence is analyzed in the paper. We define robot intelligence and robot system intelligence in terms of unpredictability of improbable behavior. The concept of unpredictability is analyzed in relation to (1) statistical unpredictability, (2) inaccessibility, (3) undecidability, (4) intractability, and (5) non-representability. We argue that the latter two type of unpredictability, when exhibited by systems capable of producing order, can result in a non-trivial, different form of intelligent behavior (Swarm Intelligence). Engineering problems related to Swarm Intelligence are mentioned in relation to Cellular Robotic Systems which consist of collections of autonomous, non-synchronized, non-intelligent robots cooperating to achieve global tasks.

1. Introduction

1.1 The Concept of CRS

As a simplified model of general distributed robotic systems, the concept of Cellular Robotic Systems (CRS) has been introduced in [1]. A CRS consists of a large (finite) number of robots and operates on a finite n-dimensional cellular space under distributed control. No system wide centralized mechanism, synchronous clock or shared memory is assumed. Limited communication exists only between adjacent robots. On one hand, these robots have to operate autonomously; on the other hand, they have to cooperate to accomplish predefined global tasks. Detailed discussion on CRS has been presented in [2] and potential applications of CRS are shown in [3].

The advantages of cellular robotic systems are:

(1) As compared with centralized robotic systems designed for the same task, each robotic unit of a CRS is of much lower complexity. The robotic units can be modularized, mass produced, interchangeable and (maybe) disposable.

(2) Since CRSs are under distributed control, and since in general they are highly redundant, systems based on CRS are highly reliable. These systems can be designed to survive through various kinds of disturbances and to have the ability to dynamically adapt to their working environment. This is crucial in situations where very high reliability is required.

(3) Since a CRS is essentially a massively parallel processing system, its collective computational power makes it attractive to carry out robotic tasks that are impossible for any single robot.

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1.2 Closely Related Areas

One of the areas from which the CRS research arose is the theory of cellular automata [4]. The cellular model was introduced by Von Neumann in the context of machine reproduction [5]. Since then it has been used to model various physical and biological phenomena such as pattern growth [6], perception [7] and language recognition [8]. Hardware implementations range from the Connection Machine [9] to the MIT CAM board that can be used with an IBM PC [10].

As compared with systems based on the cellular automata model, which are essentially *homogeneous*, *static* and *synchronous*, a CRS employs intelligent machines (robots) capable of processing both *information* and *matter*. In the theory of cellular automata, no conceptual distinction has been made between the two entities. Matter, if any, has been embedded into the set of states of the system. Therefore, general models of cellular automata are (though capable) not the best to capture characteristics of the physical activities of actual robotic systems. Taking matter processing into account, the CRS model puts restrictions on cellular automata to reflect the material nature of the cell elements. Because of this essential difference, CRS based systems have to be *heterogeneous*, *kinetic* and *asynchronous*.

Another area that has great influence on CRS research is distributed computing[11]. It has been observed that there is a collection of common "sub" (low level) protocols upon which various "main" protocols operate. Moreover, these main-protocols are in general independent of, or at least may be isolated from, these supporting protocols. It is not surprising to realize that these supporting protocols are often directly related to many current research issues of distributed computing. A protocol that governs coordinated robot motion without collision exemplifies protocols in this category (This problem will be discussed in Section 4). Many classical problems in distributed computing, e.g., *mutual exclusion*, *leader finding*, *agreement* and *majority voting* can all find their "applications" in the CRS theory.

1.3 Paper Organization

The next section defines Swarm Intelligence. The definition requires a discussion of the concept of 'unpredictability' which is the main contribution of the paper. Implications and engineering issues in CRS are mentioned in the last two sections. The paper includes conjectures and tentative results and is not intended to be mathematically rigorous.

2. "Swarm" Intelligence

2.1 Robot Intelligence

CRS are capable of 'intelligent' behavior in the following sense.

First we specify the meaning of some basic terms as used in this paper. "Machine" is defined as an entity capable of mechanical behavior (i.e. transfer and/or processing matter/energy). "Automaton" is defined as an entity capable of informational behavior (i.e. transfer and/or processing information). "Robot" is defined as an entity capable of *both* mechanical and informational behavior (i.e. a robot is both an automaton and a machine). These definitions are somewhat different from the common usage, but they help avoiding confusion since they contain only the two well-defined concepts of "matter/energy" and "information". An additional specification is also necessary for the term 'environment'. In what follows environment is intended to include everything which is not the system itself.