Architectural Foundations for Real-Time Performance in Intelligent Agents

BARBARA HAYES-ROTH
Knowledge Systems Laboratory, Computer Science Department, Stanford University, Palo Alto, CA 94304

Abstract. Intelligent agents perform multiple concurrent tasks requiring both knowledge-based reasoning and interaction with dynamic entities in the environment, under real-time constraints. Because an agent's opportunities to perceive, reason about, and act upon the environment typically exceed its computational resources, it must determine which operations to perform and when to perform them so as to achieve its most important objectives in a timely manner. Accordingly, we view the problem of real-time performance as a problem in intelligent real-time control. We propose and define several important control requirements and present an agent architecture that is designed to address those requirements. The proposed architecture is a blackboard architecture, whose key features include: distribution of perception, action, and cognition among parallel processes, limited-capacity I/O buffers with best-first retrieval and worst-first overflow, dynamic control planning, dynamic focus of attention, and a satisficing execution cycle. Together, these features allow an intelligent agent to trade quality for speed of response under dynamic goals, resource limitations, and performance constraints. We illustrate application of the proposed architecture in the Guardian system for surgical intensive care monitoring and contrast it with alternative agent architectures.

1. Real-Time Performance in Intelligent Agents

Imagine an errand robot driving an automobile on its way to some destination. Noticing a yellow traffic light at the next intersection in its path, the robot infers from its current speed, distance to the light, and conservative traffic-light policy that it should stop. The robot immediately releases the accelerator and, after a few seconds, applies the brake to bring its vehicle to a gradual stop just before entering the intersection. The robot's behavior is satisfactory not simply because it produces the correct result, but because it does so at the right time. If the robot stopped very much before or after reaching the intersection, its behavior would be unsatisfactory and potentially catastrophic.

The errand robot illustrates a class of computer systems, which we call intelligent agents, whose tasks require both knowledge-based reasoning and interaction with dynamic entities in the environment, such as human beings, physical processes, other computer systems, or complex configurations of such entities. Tasks requiring an intelligent agent occur in
diverse domains, such as power plant monitoring (Touchton, 1988), process control (d'Ambrosio et al. 1987; Pardee, Shaff and Hayes-Roth 1989), experiment monitoring (O'Neill and Mullarkey 1989), student tutoring (Murray 1989), aircraft pilot advising (Smith and Broadwell 1988), and intensive care patient monitoring (Fagan 1980; Hayes-Roth et al. 1989).

To perform such tasks, an agent must possess capabilities for: perception—acquiring and interpreting sensed data to obtain knowledge of external entities; cognition—knowledge-based reasoning to assess situations, solve problems, and determine actions; and action—actuating effectors to execute intended actions and influence external entities. For example, the errand robot perceives signals from which it infers that the traffic light is yellow. It reasons with this perception, its traffic light policies, and other perceptions and knowledge to determine that gradually coming to a stop at the intersection is the desired result and that releasing the accelerator and applying the brake are the appropriate actions. It performs those actions in the appropriate temporal organization, thereby achieving the intended result.

Because external entities have their own temporal dynamics, interacting with them imposes aperiodic hard and soft real-time constraints on the agent's behavior. Following (Baker and Shaw 1989) we use the term aperiodic to describe tasks having irregular arrival times. Following (Faulk and Parnas 1988; Stankovic and Zhao 1988) we use the terms hard and soft to distinguish between constraints whose violation precludes a successful result versus those whose violation merely degrades the utility of the result. For example, a vehicle that happens to stop in front of the errand robot is an aperiodic event with a hard deadline. The robot must stop in time to avoid colliding with the other vehicle. When that is not possible, the robot should consider alternative actions, such as maneuvering around the stopped vehicle.

In a complex environment, an agent's opportunities for perception, action, and cognition typically exceed its computational resources. For example, in the scenario above, the errand robot has opportunities to perceive the physical features and occupants of other automobiles on the road and the buildings and landscape along the sides of the road. It might reason about any of these perceptions or other facts in its knowledge-base. It might perform a variety of actions more or less related to driving its automobile. Fortunately, the robot largely ignores most of these opportunities to focus on matters related to the traffic light. Otherwise, it might fail to perform the necessary perception, reasoning, and actions in time to stop its automobile at the right time. On the other hand, the errand robot cannot totally ignore incidental information without risking the consequences of rare catastrophic events. For example, the robot should notice a child running into its path. In some cases, the robot might benefit from noticing information that is not immediately useful. For example, it might notice a sign posting business hours on a shop window and use that information when planning a subsequent day's errands.

Because an intelligent agent is almost always in a state of perceptual, cognitive, and action overload, it generally cannot perform all potential operations in a timely fashion. While faster hardware or software optimization may solve this problem for selected application systems, they will not solve the general problem of limited resources or obviate its concomitant resource-allocation task (Stankovic 1988). For an agent of any speed, we can define tasks whose computational requirements exceed its resources. Moreover, we seek more from an intelligent agent than satisfactory performance of a predetermined task for which it has been optimized. Rather, we seek satisfactory performance of a range of tasks varying