Reactive Robotic Systems

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RUNNING HEAD: Reactive Robotic Systems

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1. INTRODUCTION

Reactive systems are a relatively recent development in robotics that has redirected artificial intelligence research. This new approach grew out of a dissatisfaction with existing methods for producing intelligent robotic response and a growing awareness of the importance of looking at biological systems as a basis for constructing intelligent behavior. Reactive robots are also referred to as behavior-based robots - they are instructed to perform through the activation of a collection of low-level primitive behaviors. Complex physical behavior emerges through the interaction of the behavioral set and the complexities of the environment in which the robot finds itself. This methodology provides more rapid and flexible response than is attainable through traditional methods of robotic control.

Some of the hallmark characteristics of purely reactive robotic systems include:

1. Behaviors are basic building blocks.

   A behavior in these systems is usually a simple sensorimotor pair, where sensory activity consists of providing necessary information to support low-level reactive motor response, such as avoiding obstacles, escaping from predators, being attracted to goals, etc.

2. Abstract representational knowledge is avoided.

   Creating and maintaining accurate representations of the world is a time-consuming error-prone process. Purely reactive systems do not maintain world models, instead reacting directly to the stimuli the world presents. This is particularly useful in highly dynamic and hazardous worlds, where the environment is unpredictable and potentially hostile.

3. Animal models of behavior are often used as a basis for these systems.

   Models from neuroscience, cognitive psychology, and ethology are used to capture the nature of the behaviors that are necessary for a robot's safe interaction with a hostile world.

4. Demonstrable robotic results have been achieved.

   These techniques have been applied to a wide range of robots including six-legged walking robots, pipe-crawling robots, robots for indoor/outdoor activities, mobile manipulators, dextrous hands, and entire herds of mobile robots. As these systems are highly modular, they can be constructed incrementally from the bottom up by adding new behaviors to an existing repertoire. From an engineering perspective this is quite desirable as it facilitates the growth and application of existing software and hardware systems to new domains.

Even more recently, hybrid reactive/deliberative robotic architectures have emerged which combine aspects of more traditional AI symbolic methods and use of abstract representational knowledge with the responsiveness, robustness and flexibility of purely reactive systems. Both purely reactive and hybrid architectures are discussed within this article.

2. BIOLOGICAL BASIS FOR REACTIVE ROBOTIC SYSTEMS

Many of the designers of reactive systems look to biology as a source of models for use in robots. Although the diversity of these efforts is significant, ranging from traditionally engineered systems to those that dedicate themselves to faithfully replicating biological behavior, this article reports on a few exemplars that have affected reactive and hybrid system design.

- Action-oriented perception

  Neuroscientists and psychologists (especially the cognitive and ecological communities) have provided models for the relationships between perceptual activities and behaviors required for a particular task. One excellent example is presented in (Arbib, 1972). His model of action-oriented perception shows that what an agent needs to perceive is based upon its needs to act. This is a primary guiding principle in the design of reactive robots. The traditional computer vision community often views perception as a disembodied perceiver that interprets images without consideration of what the knowing agent needs to do. In contrast, the strong coupling between action and perception is one of the hallmarks of purely reactive robotic systems. Neisser has further developed these ideas in the context of cognitive psychology (see (Arkin, 1990a) for a review of those aspects relevant to robotic systems).

- Ethological studies

  A pressing question for reactive robotic system designers is just what behaviors are necessary or sufficient for a particular task and environment. Many of these researchers have turned to ethological studies as a source for behaviors that are relevant in certain circumstances. Specific models used in reactive robotic systems have been quite varied including bird flocking, ant foraging, fish schooling, and cockroach escape, among others. One example involving toad detour behavior (Arbib and House, 1987) provided motivation and justification for the use of vector fields in reactive schema-based robot navigation (Arkin, 1990a).

- Co-existence of parallel planning and execution systems (hybrid systems)

  Norman and Shallice (Norman and Shallice, 1986) have modeled the co-existence of two distinct systems concerned with controlling human behavior. One system models "automatic" behavior and is closely aligned with reactive systems. This system handles automatic action execution without awareness, starts without attention, and consists of independent parallel activity threads (schemas). The second system controls "willed" behavior and expresses an interface between deliberate conscious control and the automatic system.

  While purely reactive robotic systems are compatible with the modeled automatic system (e.g., (Brooks, 1986)), most hybrid robotic systems (e.g., (Arkin, 1990b; Gat, 1992)) incorporate both willed (deliberative) and automatic (reactive) components in a manner somewhat consistent with above model.

One problem confronting the reactive robotic systems designer is that much of the data reported by biological scientists is often presented statistically. While this may be useful within the context of their home disciplines, it is important for process models to be constructed whenever possible to facilitate the adoption of this work into intelligent robotic systems (see NEUROETHOLOGY, COMPUTATIONAL).

3. PURELY REACTIVE ROBOTIC SYSTEMS

Reactive robotic systems originate in the cybernetic movement of the 1940s. Grey Walter (1953) developed an electronic "tortoise" capable of moving about the world, avoiding perceived threats and attracted to certain goals. Of special interest was the inclusion of changing goals regarding the robot's recharging station. When power was low, the tortoise was attracted to and docked with the recharger. When sufficient energy was acquired, it lost its "appetite" (charger attraction) and was repelled by it. There was no use of abstract representational constructs as found in traditional AI; perception directly controlled motor action. Simple behaviors were created: head towards weak light, back away from strong light, and turn-and-push to avoid obstacles.

Braitenberg (1984) revived interest in this class of creatures. He demonstrated using simple analog circuitry that "creatures" could be built that manifested behaviors comparable to those found in animals, e.g., cowardice, aggression, love, exploration, and logic. These thought experiments in "synthetic psychology" showed that seemingly complex behavior could result from a collection of simple sensorimotor transformations.

Brooks (1986) was an early leader of the purely reactive robotic paradigm. His group pushed this approach with the development of the subsumption architecture. He articulated the departure from classical AI and broke away from the *sense-plan-act* paradigm that dominated AI in the 1970-80s as typified by robots like Shakey that used resolution theorem proving as its primary reasoning mechanism. This new position brought into question the role of representational knowledge in AI altogether. The subsumption architecture was biologically motivated only in the behaviorist sense as it produced overt results that resembled certain insect systems but was unconcerned for the underlying biological mechanisms that produced them.

At about the same time the subsumption architecture appeared, other researchers were interested in pursuing parallels in biological and mechanical systems. A sort of cybernetics revival occurred. Studies produced by ethologists, neuroscientists, and others provided models that were used within reactive robotic systems. These researchers' goals varied. For example, Arkin (1990a) exploited these models with the purpose of constructing intelligent robotic systems, using interacting schemas as a basis for reactive robotic control systems design (see SCHEMA THEORY). Beer, alternatively, used robotic systems to demonstrate the fidelity of neuroscientific models (see LOCOMOTION, INVERTEBRATE). Significant conferences now exist (e.g., Simulation of Adaptive Behavior: From Animals to Animats, 1994, (Cliff et al, Eds.) Cambridge:MIT Press) dedicated to animal and computational systems relationships.

Figure 1 presents a simple reactive control system example. A robot controlled by this system wanders around avoiding collisions until it finds a path, which it then follows until it locates its goal. It consists of four behaviors: avoid-obstacle prevents the robot from colliding with anything; wander ensures movement in the absence of goal or path attraction; stay-on-path guides the robot down a hall or road to find the goal near the path's end; move-to-goal attracts the robot to the final goal. The perceptual strategies for each behavior are also depicted. The behavior coordination mechanism can be of several forms. Arbitration or action-selection mechanisms are typically found in subsumption-style architectures where only one behavior is active at any given time. This action-selection mechanism can be complex, involving extensive connections between behaviors for inhibition/suppression. The schematic representation of this mechanism is greatly simplified in this figure. Other coordinators may involve blending, as in schema-based reactive control systems, where all active behaviors contribute somewhat to the overall coordinated motion.

4. HYBRID REACTIVE/DELIBERATIVE ROBOTIC SYSTEMS

Hybrid architectures permit reconfiguration of reactive control systems based on available world knowledge, adding considerable flexibility over purely reactive systems. Dynamically reconfiguring the control system based on deliberation (reasoning over world models) is an important addition to the overall competence of general-purpose robots.

It should be recognized that purely reactive robotic systems are not appropriate for every robotic application. In situations where the world can be accurately modeled, where there is restricted uncertainty, and there exists some guarantee of virtually no change in the world during execution (such as an engineered assembly workcell), deliberative methods are often preferred since a plan can, most likely, be effectively carried out. In the real world, in which biological agents function, these prerequisites for purely deliberative planners do not exist. If roboticists hope to have their machines functioning in the same environments that we do, methods like reactive control are required. Many feel that hybrid systems capable of incorporating both deliberative reasoning and reactive execution are needed to deliver the full potential of robotic systems.

Arkin was among the first to advocate the use of both deliberative (hierarchical) and reactive (schema-based) control systems within the Autonomous Robot Architecture. Incorporating a traditional planner that could reason over a flexible and modular reactive control system, specific robotic configurations could be constructed that integrated behavioral, perceptual and *a priori* environmental knowledge (Arkin, 1990b). This system was tested on a wide range of applications, both inside and outdoors.

Gat (1992) proposed a three level hybrid system (Atlantis) incorporating a Lisp-based deliberator, a sequencer that handled failures of the reactive system, and a reactive controller. This system was fielded and tested successfully on Mars rover prototypes.

5. PERCEPTION AND REACTIVITY

A fundamental guiding principle for purely reactive systems is that perceptual activities should always be viewed on the basis of motor needs (i.e., *a need-to-know basis*). A large body of mainstream computer vision research is concerned with the abstract task of image understanding which typically is independent of a particular agent's needs. Proponents of purely reactive control advocate that perception serves motor action, and image interpretation algorithms must take this into account. Sensing strategies should be constructed taking advantage of the knowledge of underlying behavioral requirements. This eliminates the need to construct global representations of the world, an activity avoided in purely reactive robotic systems. By creating perceptual algorithms that extract only relevant information and that exploit expectations of what is necessary and sufficient to be perceived, efficient sensor processing is a natural consequence.

Hybrid approaches, nonetheless, are more consistent with the views of neuroscientists (e.g., (Mishkin, Ungerleider, and Macko, 1983)) on "what" and "where" visual systems which account for the maintenance of spatial relationships in a more than purely reactive manner.

There are three ways in which reactive systems can utilize perceptual information: perceptual channelling (sensor fission), action-oriented sensor fusion, and perceptual sequencing. Perceptual channelling is straightforward: a motor behavior requires a particular stimulus for it to be invoked, so a single sensor system is created. A simple sensorimotor circuit results. There are numerous examples (e.g., (Brooks, 1991; Maes, 1990).

Action-oriented sensor fusion (Arkin, 1993) permits the construction of representations (percepts) which are local to individual behaviors. Restricting the representation to the requirements of a particular behavior allows the benefits of reactive control to remain while permitting more than one sensor to provide input, resulting in increased robustness.

Sometimes fixed action patterns require varying stimuli to support them over time and space. As a behavioral response unfolds, it may be modulated by different sensors or different views of the world. Perceptual sequencing provides for the coordination of multiple perceptual algorithms over time in support of a single behavioral activity. Perceptual algorithms are phased in and out based on the needs of the agent and the environmental context in which it is situated.

6. DISCUSSION

Space prevents an extensive survey of the wide range of reactive robotic systems - the reader is referred to (Maes, 1990; Efken and Shaw, 1993; Brooks, 1991; Lyons and Hendriks, 1992) for additional information. These methods have gained dramatically in popularity and utility since the mid-1980's and are being applied to robotic systems throughout the world.

Hybrid reactive/deliberative architectures have been created to address several of the potential shortcomings of purely reactive systems. They permit the incorporation of world knowledge and the construction of global representations, yet preserve the strength of reactive execution and responsiveness to environmental change.

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Figure 1: Example Reactive Control System