Workshop Abstract

Point of View: Cognitive Dynamic Systems[1]

I see the emergence of a new discipline, called Cognitive Dynamic Systems[2], which builds on ideas in statistical signal processing, stochastic control, and information theory, and weaves those well-developed ideas into new ones drawn from neuroscience, statistical learning theory, and game theory. The discipline will provide principled tools for the design and development of a new generation of wireless dynamic systems exemplified by cognitive radio and cognitive radar with efficiency, effectiveness, and robustness as the hallmarks of performance.

Celebrated Tools and Their Neurobiological Implications

To elaborate, Kalman filtering and Bellman's dynamic programming feature prominently in classical dynamic systems; they both serve as major foci in the study of signal processing, communications, and control. Indeed, Kalman filter theory and the theory of dynamic programming are widely recognized in the literature for their mathematical elegance and applications. Nevertheless, they both have serious practical limitations of their own.

Kalman filter theory is formulated on the assumptions of system linearity and Gaussian distributions; unfortunately, these assumptions are often violated in one way or another by observable data encountered in practice. In recent years, particle filters rooted in Bayesian estimation and Monte Carlo simulation have emerged as new tools for overcoming the limitations of Kalman filters.

Dynamic programming suffers from the curse of dimensionality; this emotive term refers to the fact that as the input-space dimensionality is increased linearly, the demands on computation resources and size of observable data grow exponentially, eventually becoming prohibitive. To alleviate this difficulty, approximate dynamic programming procedures using neural networks and linear programming have been proposed.

There is neurobiological evidence that "Kalman-like filtering" is performed in the visual cortex and motor cortex. The author of this article is equally convinced that Kalman-like filtering is also performed in the auditory cortex.

Animals perform reinforcement learning, which is a minimally supervised form of learning that results from interactions with the environment for a certain goal in mind. The animals are not told what actions to perform; rather, they work out the actions themselves on the basis of reinforcement received from the environment. A special form of reinforcement learning known as temporal-difference (TD) learning is viewed as a combination of Monte-Carlo methods and ideas rooted in dynamic programming.

The brain of animals, central to the tasks of Kalman-like filtering and approximate dynamic programming, performs these difficult dynamic tasks effectively, efficiently, and in a robust manner.

Cognitive Dynamic Systems Defined

As a working definition, I say:

> **Cognitive dynamic systems build up rules of behavior over time through learning from continuous experiential interactions with the environment, and thereby deal with environmental uncertainties.**

In traditional radio systems, for example, only 10% of the electromagnetic radio spectrum assigned to a primary (legacy) user is typically employed at any given time, a waste of a highly valued natural resource. A cognitive radio

1. This article is reproduced from Proc. IEEE, Nov. 2006
2. S. Haykin, Cognitive Dynamic Systems, book under preparation.

system, on the other hand, would be able to identify sub-bands of the radio spectrum that are currently unemployed and assign them to unserviced secondary users.

For the example on radar, consider the performance of a surveillance system. The moment the radar is switched on, it becomes electromagnetically linked to its surrounding environment, thereby registering any changes perceived within the scope of its coverage. However, the environmental data accumulated by the standard surveillance radar last no longer than a few scans of the transmitting antenna. Valuable historical data, built up over time, are thus lost. This loss can be particularly serious when the environment is nonstationary, as is often the case. Cognitive radar, with its built-in capability to preserve environmental information for comparative evaluations, provides a novel method, not just for discerning environmental changes, but also for anticipating them by recognizing identifiable patterns.

A perfect example of cognitive radar is found in the echolocation system of the bat. In a classic demonstration of experimential learning, the bat stores environmental information concerning its habitat, which it has accumulated through a lifetime of experience. With this information, the bat is equipped to locate its prey with an accuracy and resolution that would be the envy of radar and sonar engineers.

Although the intended applications of cognitive radio and cognitive radar are indeed different, they do share two common features: The one feature is *scene analysis*, which enables the radio/radar receiver to "sniff" its surrounding environment on a continuous basis and thereby learn from it. The other one is the use of a *feedback channel*, which connects the receiver to the transmitter and thereby makes it possible for the transmitter to adapt itself to the environment in light of the information passed on to it by the receiver. Both cognitive radio and cognitive radar are therefore examples of closed-loop feedback control wireless systems. This feature illustrates two important points: First, feedback is the facilitator of intelligence. Second, care must be exercised in designing a cognitive dynamic system to maintain the stability needed to realize the full benefits of cognitive processing.

Cognitive dynamic systems will provide the tools for building a new generation of devices with dynamic applications, which include two important wireless systems: cognitive radio for communication, and cognitive radar for remote sensing.

Simon Haykin
McMaster University
Hamilton, Ontario, Canada