TOWARD A COGNITIVE RADIO ARCHITECTURE: INTEGRATING KNOWLEDGE REPRESENTATION WITH SOFTWARE DEFINED RADIO TECHNOLOGIES

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ABSTRACT

The ultimate vision of cognitive radio technology encompasses many capabilities including autonomous execution of tasks that today require manual intervention. A conventional radio when operating in a particular communications mode always follows the same procedure and either succeeds or fails at a given task. A cognitive radio, by contrast, can have a knowledge-driven differential-response capability; that is, it can use knowledge of radio technology and policy, representations of the goals, and other contextual parameters to reason about a failed attempt to satisfy a goal and to identify alternative actions that would achieve the goal. We have built a prototype simulation framework for a cognitive radio that exhibits this capability in various scenarios. Based upon this experience, this paper proposes a general architecture that merges knowledge representation technologies (both ontologies and rules) with the processing structures of existing software defined radio technology to enable this capability as well as form a foundation for other cognitive abilities.

INTRODUCTION

The advent of software defined radio (SDR) [1] technology offers a more sophisticated form of processing resources than prior radio technology. Although the initial development of SDR technology was almost exclusively for military applications, as the field has matured its scope has broadened to include commercially-oriented perspectives (e.g., the SDR Forum [2]), and now both the standards for designing SDRs (e.g., the Software Communications Architecture [3]) and representative, open source implementations [4, 5] reflect industry-standard, object-oriented software practices. With this enhanced capability, however, comes the burden of developing the software and selecting configurations applicable for the various scenarios the SDR may encounter. One technology that promises to not only utilize this processing capability but to also provide an autonomous and flexible architecture that is applicable to a wide array of operational scenarios is the cognitive radio (CR) [6]. The ultimate vision of CR technology—denoted by Mitola as the "ideal cognitive radio (iCR)"—encompasses many facets of intelligent behavior such as context awareness, adaptation of action due to stimulus and prior information, reasoning including inferring information not explicitly stated, learning, natural language processing, and planning. A growing research community is investigating the means for taking advantage of the processing resources in SDR platforms to develop the iCR; to date, most researchers choose to focus on one or a few of these facets of intelligence. As a result, literature on the subject defines the term CR in a variety ways, usually in a narrow, application-specific manner.

As an example CR application, the Federal Communications Commission (FCC) is considering a case where vacant portions of the TV broadcast bands could be shared with unlicensed devices with sufficient intelligence to detect the licensed users and avoid causing harmful interference to those users [7]; a related effort by the IEEE 802.22 standards committee seeks to create a technical standard for a network of these devices [8]. While this definition of CR does include a radio with some awareness of the spectrum and some ability to adapt operating behavior based upon that information, this definition otherwise duplicates conventional radio technology with procedural-style specification of the radio's behavior.

The DARPA XG program [9] aims to demonstrate opportunistic spectrum access of otherwise idle spectrum under a range of conditions. An important component of that application is a policy checking entity that determines whether or not the dynamic spectrum access adheres to a policy. Their current approach employs a Prolog-based policy reasoner to evaluate such queries [10]. Other researchers such as Berlmann et al. [11] proposed policy-based reasoning to check a broader range of CR behaviors.

Work by Neel et al. [12] applied game theory principles to design distributed algorithms for adaptive behaviors. Rondeau et al. [13] proposed genetic algorithms for optimizing the settings of the many control parameters available to CRs. Both [12] and [13] addressed the problem of adaptation in CRs, and [13] could also be viewed as addressing a learning component.

The research group of Kokar investigated how to create CRs with self awareness of their own capabilities via an ontology framework [14] and how to replace procedural-style radio control constructs with machine reasoning techniques. The use of an ontology as a knowledge representation mechanism is central to this paper's approach too; references [15, 16] provide tutorial information on the topic of ontologies. On a related note, some of the authors of this paper took an ontology-based approach in providing CRs with context awareness; for example, the term *radio channel* has many possible meanings, and in order to reason about the availability of a radio channel the CR must know what definition applies in a given context [17].

Recognizing the possible applications and approaches for introducing machine reasoning to radio systems as discussed in this section, this paper explores a CR incorporating a *differential-response* capability by augmenting the existing SDR processing paradigm using knowledge representation concepts such as ontologies and rules. Sections that follow note the importance of a *knowledge-driven differential-response* capability not found in prior work and describe components necessary to instantiate it. Finally, the paper closes by describing a simulated prototype CR with this capability and how it can achieve goals despite facing conflicts that would have thwarted conventional radios.

REQUIREMENTS FOR KNOWLEDGE-DRIVEN DIFFERENTIAL-RESPONSE

As a motivating example, this paper considers the problem of a CR attempting to gain access to a portion of the radio band governed by radio beacons at one or more locations. A number of beacon-based protocols are possible to facilitate dynamic spectrum access; this example assumes a policy regime in which both positive and negative control beacons are employed [18]. In order for the CR to be able to access a radio channel C, two conditions must be fulfilled: 1) the CR must be within radio range of a positive beacon station from which it receives a coded beacon message *authorizing* access to channel C, and 2) the CR must not simultaneously be in range of a negative beacon station from which it receives a coded beacon message *denying* access to C. Although there are a number of security, protocol, and radio engineering issues that must be addressed in the design and implementation of such beacons, it is not necessary to describe those aspects of the beacon in order to appreciate the value of differential-response capability. For both conventional radios and the CRs described in the previous section, if the radio's location is such that conditions (1) and (2) are not satisfied, it cannot access the channel, and—more fundamentally—it cannot reason about why the goal of channel access has failed or what alternative conditions would permit overcoming the failure. Note that there are essentially two ways in which the goal of using channel C can be thwarted: a) no positive beacon signal for access to C is received, and b) both positive and negative beacon signals for access to C are received. The cases in which no beacon signals are detected at all, or in which only negative beacon signals are received can be viewed as being subsumed under the other cases. For example, in the case where only negative signals are received, the radio needs to somehow get a positive signal, which is case (a). If it manages to solve that problem and it still is receiving one or more negative signals, then it is now in case (b) (otherwise it has solved the problem of gaining access).

The situations covered by cases (a) and (b) can be used to elaborate upon the notion of knowledge-driven differential-response. In both cases a radio will fail in its goal of getting access to channel C. Depending upon its functionality, a conventional radio might be able to distinguish between the two cases of failure, in the sense that it *goes* into a different internal state depending upon the circumstances. Through a user-interface it may be able to give an indication of its current state. However, even if the concrete indicators conveyed by the radio are different in the two cases, this is still not a knowledge-driven differential-response. First of all, one can say, with some justice, that in both cases the radio is really doing exactly the same thing: upon failure to access a channel convey the current internal state to the user. That is an accurate description of the radio's actions, because that is exactly how the radio is programmed to behave. Secondly, even if, for the sake of argument, the responses are deemed to be different, they do not illustrate *knowledge-driven* differential-response. The reason is that the radio being in a distinct internal state is an irreducible and non-analyzable *cause* of its taking whatever action it takes. From a formal point of view, we may say that the radio behaves as a finite-state machine. The particulars of the internal state and the way in which those particulars relate to aspects of the external world do not enter into an explanation of the radio's behavior. The latter is at least part of what is required in order for any agent to be capable of cognition, and this is what we mean by knowledge-driven differential-response.

So, returning to the example scenario, what could a CR do in case (b) as opposed to case (a)? A CR would have representations of policy conditions (1) and (2) and it could also have a representation of a *beacon signal conflict*, that is, a situation in which two or more conflicting beacon signals are received. It would also have the knowledge, expressed in a *rule*, that when a goal cannot be achieved due to such a conflict one can request a move to a location where only the desired beacon is in range. Depending on the radio's mobility capabilities, it could then act in a number of ways depending on the circumstances. For example, using its inherent signal strength detection capability it could guide its user to a region where only the desired beacon signal is received.

Furthermore, a general set of requirements can be extrapolated from this example:

1. Knowledge and Reasoning Requirements

Knowledge requirements for CR are of two sorts: *conceptual* and *rule-based*. Conceptual knowledge includes knowing the meanings of fundamental notions in a domain of interest as well as fundamental principles relating those concepts. In current practice, this kind of knowledge is said to be *ontological* and is formally encoded in knowledge representation frameworks known as *ontology* languages. *An ontology* is a formal representation of the key concepts and principles of a domain of interest. Rule-based knowledge, which is typically represented using some formal rule language, can be thought of as the bridge that relates conceptual knowledge to the problem-solving needs of a particular application.

Knowledge and reasoning go hand-in-hand. A piece of knowledge that is not somehow related to other pieces of knowledge through inference (i.e., reasoning) is essentially useless. Since the knowledge and reasoning requirements, including rules, are fundamental to the CR, the topic is addressed in a separate section ("Role of Knowledge Representation") of the paper.

2. Perceptual Requirements

It is clear from the example scenario that a CR must be able to recognize sensory inputs, or patterns thereof, as *being* or *representing* something in its environment The concept of *self-perception* is in this category too; broadly speaking, a CR must be able to recognize certain internal states and processes as representing certain facts about *itself*. For example, a CR should be able to perceive its current rate of power consumption as a property belonging to itself just as a human perceives a bodily sensation such as pain as something that is internal.

3. Action Requirements

A CR needs to be able to initiate action based upon the conclusions it reaches. For example, if a CR decides that it should attempt to communicate with another trusted host on behalf of its user during some emergency, then it must not only have knowledge of the communication protocol but also have the ability to execute the protocol.

The knowledge satisfying the above requirements also forms the basis of a *world model* and a *self model*, both of which are created and maintained within each CR.

ARCHITECTURE

The discussion thus far can be encapsulated in a proposed architecture for a CR device, as shown in fig. 1. In the left side of the figure we see that the goal of augmenting SDR processing structures is accomplished in this architecture by means of the *Perception & Action Abstraction Layer* (PAAL). The Perception and Action Abstraction Layer (PAAL) is defined in terms of certain *standard* radio concepts and is used to characterize device observables and actions in a *platform-independent* knowledge representation.

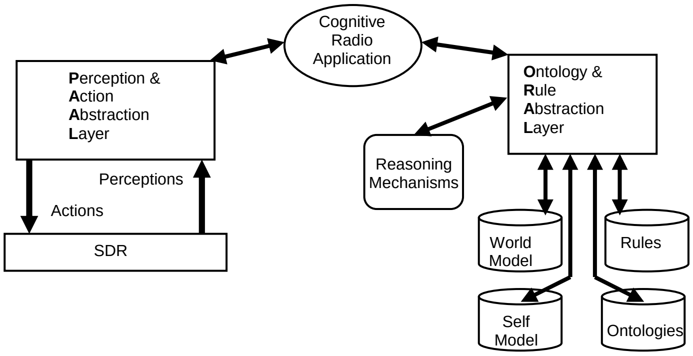

Figure 1. CR Architecture.

This is a key layer if one wants to allow for reuse of the cognitive portion of the architecture with different conventional radio implementations. That is, different radios could use different signal processing algorithms at a very low level that have no bearing on how a cognitive radio application perceives an instance of, for example, a certain kind of waveform. The PAAL makes it possible for a device to interpret its sensory input in perceptual terms that can be used to drive a CR's world and self models. Going in the other direction, it also makes it possible for a CR to *do* things by exporting SDR primitive actions in a platform independent format.

The right side of the figure shows the components involved in augmenting an SDR architecture to allow for cognitive capabilities including the previously mentioned World Model and Self Model components. The next section decribes the Rules, Ontologies, and Reasoning Mechanisms components. The remaining component is another abstraction layer, the Ontology & Rule Abstraction Layer. This layer serves a purpose that is symmetric to PAAL. It allows ontology and rule concepts to be represented in a *platform-independent standard.* This is important if one wants to allow the same radio implementation to be used with alternate ontology and rule reasoning platforms. Just as radio notions such as *signal* and *waveform* should have meaning independent of any particular radio implementation, so too notions such as *concept*, and *rule* should have meaning independent of any particular implementations.

As an overview of how the proposed architecture works to augment existing SDR implementations, one can consider the case where the radio senses some waveform. We assume that the radio's SDR interface can be used to program a *wrapper* around its existing methods so that such an event triggers a method defined in terms of PAAL that allows an appropriate instance of a *signal* object (as defined in the ontology) to be constructed and deposited into the world model. Conversely, suppose the reasoner concludes that a certain action, such as evacuating a channel, should be taken. From its self model it knows that it is capable of taking such an action. Then, by virtue of the PAAL layer, the ontological element that represents that action will be linked to a method that can invoke the radio's native interface with a call to perform that action (or perform some procedure).

ROLE OF KNOWLEDGE REPRESENTATION

This section elaborates on the types and forms of knowledge that a CR must have in order to exhibit a knowledge-driven differential-response.

Conceptual knowledge is the kind of knowledge that ontologies are intended to represent. Conceptual knowledge is typically either *analytic* or *axiomatic* in nature. These types of knowledge are both thought of as representing necessary truths, but for different reasons. A piece of knowledge is analytic if it expresses or follows from the *meaning* of concepts. For example, it is useful to talk about radios that can be moved from place to place (without impairing their operational capabilities). The concept of a *mobile radio* would therefore be defined as a radio that has this property. Representing this definition in an ontology would make it possible for it to be applied in a formal reasoning system.

Axiomatic conceptual knowledge, on the other hand, expresses fundamental conceptual relationships that are not based on meaning alone. For example, the fundamental principles that radio waves are a form of electromagnetic energy and that they travel at the speed of light might be considered axioms within an ontology of radio knowledge. What might be considered an axiom from the point of view of one ontological domain, however, might be considered a derived piece of knowledge (e.g., a theorem) from the point of view of a more fundamental domain. This relativity of what is an axiom has been demonstrated many times in the history of science. Kepler's laws of planetary motion, for example, had the status of independent axioms when initially formulated, but were later shown to be consequences of Newton's general laws of motion.

Rules are also important; they may be thought of as theorems that are worth committing to memory, so to speak, because, 1) they are useful in an application of interest and, 2) the computational cost of deriving them from axioms on demand is prohibitive. For example, it is known that certain frequencies of radio signals are likely to degrade because of atmospheric conditions, and mathematical laws governing this phenomenon can be derived from first principles. However, for any application in which this kind of knowledge is critical, it is highly likely that even a human expert would depend upon known rules for calculating such attenuation rather than performing an analysis based on the fundamental laws of electromagnetism and meteorology. Numerous rule languages or rule-based systems have been developed and deployed in various applications. These tools allow rules to be represented and typically provide an *inference* mechanism whereby rules are automatically invoked and applied in an application environment.

As seen in the review of related research and in the discussion of the beacon CR scenario, there is a need to represent *policies* in a way that a CR can both be guided by them and reason about them. A policy itself is a convention or a norm that ought to be followed and is not something that is, strictly speaking, true or false. However, *that* a particular policy is in force in some region at some time is something that is true or false. Knowing what behavior is required in order to be in compliance with a policy is also factual information, but may sometimes require a complex reasoning process to derive. Therefore, statements that relate the existence of a policy in a region to actions that need to be taken (or avoided) in order to be in compliance with that policy might often be worth committing to memory in the form of rules.

Ontologies also enable reasoning. From a theoretical point of view the kind of reasoning afforded by ontologies differs from rule-based reasoning. *Subsumption* reasoning is one example. Thus, as discussed above, from the fact that R is a radio and has the property of being mobile, and the definition of *mobile radio*, one can infer that R is a mobile radio. In practice, subsumption reasoning can be implemented using an underlying rule-based approach, but that is not necessary.

SCENARIO USING PROTOTYPE SIMULATION

We have implemented a prototype simulation environment capable of handling the beacon signal conflict scenario we outlined above. The ontological knowledge is expressed in OWL [20]. We use Jena [19] as our ontology API and we also use the rule language provided with Jena for representing rules. The inference mechanisms are also Jena-based. The PAAL is implemented by linking the ontology API with our own interface to a simple software defined radio emulation in Java.

The simulation enables one or more CRs and one or more beacons to be represented in a two dimensional space. The CRs can be mobile. Currently this means that they are associated with a user who can move around in the simulation environment. As a radio is moved and as the various components of the environment change, an environment handler and a simulation manager ensure that the necessary events are propagated to the various elements of the simulation. Fig. 2 shows an example of the current system display and CR user interface.

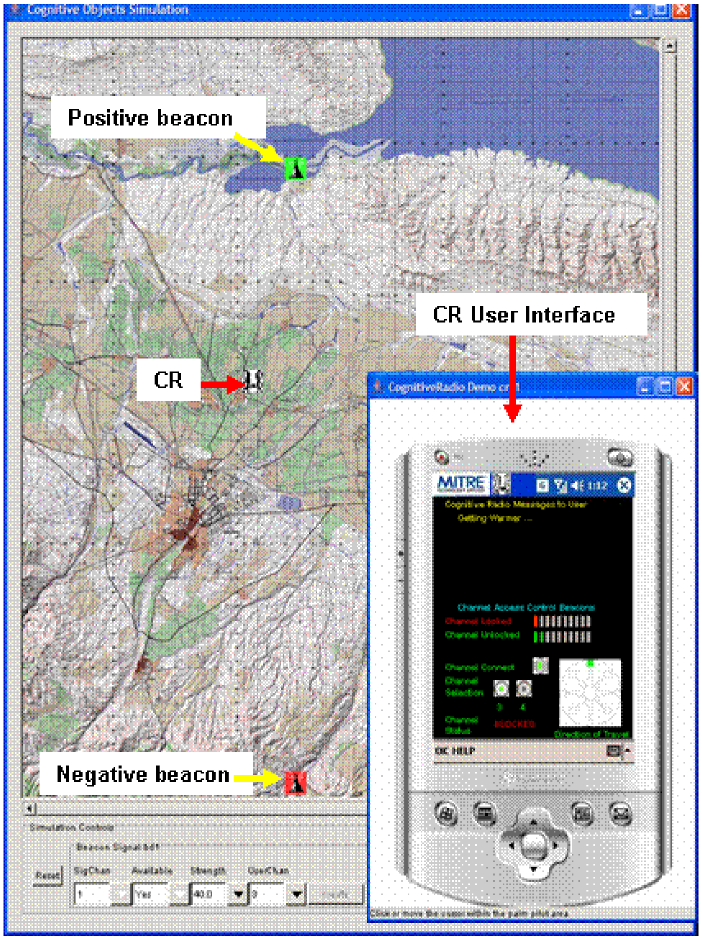

Figure 2. Screen Capture of Prototype.

A beacon signal conflict situation occurs when two beacons with opposing policies for the same channel overlap in some region. In fig. 2 the CR is positioned more or less equidistant from two such beacons. Such a conflict will matter to a CR only if it causes a problem with respect to a one of its goals. Suppose that the CR user has indicated a desire to use channel C and that a beacon signal conflict exists for C. The CR knows that its user wants to use channel C directly from user input. In terms of our architecture this knowledge is encoded in the self model of the CR. How does the CR know that a beacon signal conflict with respect to channel C exists? It knows this due to a series of inferences which are enabled by its ontological knowledge. In terms of the architecture in fig. 1, the sequence of events tracks the following pattern. The basic SDR component processes the two incoming signals. Thanks to the PAAL, two distinct instances of type signal are added to the world model of the CR. Each signal is known to be associated with a certain logical channel, and certain logical channels are known to be reserved for beacons. Therefore, using its ontological knowledge, the CR concludes that the two signals it is receiving are two distinct beacon signals. Once a signal is known to be from a beacon the CR is able to interpret the content of the signal based on properties of the signal. So the CR is at that point in a position to know it is receiving a signal saying the CR is allowed to use channel C and a signal that saying the CR is not allowed to use channel C. The CR also knows the strength of each of these signals.

Formally, the kind of ontological reasoning just described relies upon the use of well-defined frameworks, such as OWL [20], in which definitions such as the following (schematic) definition can be encoded:

```
Beacon-Signal-Conflict-For-Channel-Use
 subclass-of Radio-Policy-Conflict
GIVEN:
  Logical-Channel c;
  Beacon-Signal b1;
  Beacon-Signal b2;
SUCH THAT:
  b1 NOT-EQUAL b2;
  b1 signal-content IS “c is available”;
  b2 signal-content IS “c is unavailable”;
```

This definition provides a sufficient condition for determining when a beacon signal conflict exists. In our scenario, the world model of the CR contains two beacon signals that satisfy the conditions of this definition. This will automatically cause an instance of a Beacon-Signal-Conflict-For-Channel-Use conceptual object to also be inserted in the CR’s world model. This instance is parameterized with the references to other objects, such as logical channel C, that caused it to be inserted in the world model.

From the description thus far one can see that ontologies are the key logical device for providing understanding or interpretation of the lower level factual inputs deposited into the world and self models of a CR through the PAAL. This is in keeping with the characterization of ontologies as providing knowledge concerning the analytic and axiomatic foundations of a domain. Rules, by contrast, come into play as a more targeted form of knowledge relative to the application environment and typically encode knowledge about actions necessary to achieve goals, including cases where the normal course of action is not available.

Rules are also useful for implementing constraints on action imposed by policy. The Reasoning Mechanisms component shown in fig. 1 is responsible for making sure that any rule that is applicable in the current world and self model states is evaluated.

There are a number of rules relevant to the beacon-signal-conflict scenario. The rules implementing policy constraints come into play because the CR has the goal of using channel C. The rules state that a channel can be accessed only if there is a beacon signaling that the channel is available and that there is no conflicting beacon signal in the world model. Since the current situation includes a beacon signal conflict, the later rule would not be satisfied. Rather, a complementary rule, disallowing the use of C due to the conflict would be satisfied. When evaluated, this rule has the effect of modifying the CR's self model to include the fact that the goal of using channel C is currently blocked due to the presence of a conflict. This change causes the Reasoning Mechanism to review the set of rules again. At that point a **Beacon-Signal-Conflict-Rule** which can be given the following English rendering would be satisfied:

If

the goal of using channel C is blocked by a
Beacon-Signal-Conflict-For-Channel-Use
and b1 is the beacon-signal allowing use of C
and b2 is the beacon-signal disallowing use of C

Then

Attempt to move to a region in which b1 is still received
but b2 is not received.

The "**Then**" part of the actual rule in our simulation attempts to invoke a procedure (defined in terms of basic actions included in the CR's self model), that would cause the CR to ask the user to move in a direction. The user picks a direction and moves. The CR in this example only has a single, omnidirectional antenna. When following the aforementioned procedure, it lets the user know whether he is getting "Warmer," "Colder," or there is "No Change" in his status. To be "Warmer" means that the signal strength of b1 is increased and the signal strength of b2 is decreased. This interactive procedure is repeated until signal b2 is no longer received. At that point, a rule allowing use of C would be satisfied and the CR would be able to take appropriate action to access the channel. The simulation also offers the option of emulating an enhanced, multiantenna CR with direction-finding capability and the ability to inform the user of the bearings of the negative and positive beacon signals. The overall interactive procedure, however, is essentially the same with the enhanced CR.

In addition to illustrating the notion of knowledge-driven differential-response, this scenario also serves to illustrate important benefits of hybrid ontology-rule knowledge representation. One of the long-standing problems of knowledge representation is known as the issue of *qualification* which is related to the impossibility of stating rules in such a way that satisfaction of their conditions guarantees that the actions they recommend will have the desired result [21]. For example, if a CR is not mobile, then the above rule cannot succeed because the radio cannot be moved. The "**If**" part of the **Beacon-Signal-Conflict-Rule** could be augmented with conditions stating that the CR must be mobile, and that it must actually have some means of locomotion, such as a user who is capable of self-locomotion. But this process degrades into an impossible situation if the goal is to state absolutely precise circumstances in which the rule can achieve the desired result. Thus, it need not be the case that the CR user is self-moving, rather it could also be the case that the CR user is merely mobile (not self-moving) but in control of another device that is self-moving. Or it could be the case that the latter device is also not self-moving but in control of another device and so on. In practical terms, the issue is how precise does one have to be in stating the conditions required for a rule to be applicable? Stated thusly, the problem is similar to any software validation problem: how does one know that a piece of code takes the correct action for all possible input cases?

The combination of ontologies with rules provides a mechanism for dealing with such problems in a modular fashion. Instead of worrying about qualifying a rule with absolute precision, the rule can be stated in a simpler general form and the qualifications can be embedded in the appropriate ontological concepts. Thus, for example, a CR that does not have a means of locomotion at its disposal would know that it does not have any way of attempting to move. It would know this because the analytic knowledge contained in its ontology together with the knowledge contained in its self-model implies that it cannot move. Therefore it will not attempt to apply the **Beacon-Signal-Conflict-Rule** even if the "**If**" part is satisfied by its current circumstances.

CLOSING REMARKS

The work presented in this paper is based on the premise that the path to CR is sure to be incremental. We have presented a high-level architecture that accommodates an incremental approach towards augmenting the SDR architecture with components required for CR. We have shown how the components we have discussed can work together to provide a system with a more robust form of goal-directed behavior, namely, knowledge-driven differential-response. We have built a simulation environment within which a scenario illustrating this cognitive capability has been successfully executed. Currently we are working to expand the simulation so that a wider range of scenarios can be accommodated.

ACKNOWLEDGEMENT

This work was supported under MITRE Sponsored Research project 07MSR215.

DISCLAIMER

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