Collaborative Context Based Reasoning

Gilbert Barrett and Avelino Gonzalez

University of Central Florida - Intelligent Systems Laboratory
12424 Research Pkwy., Research Pavilion Suite #465A
Orlando, FL 32750
gilbarrett@isl.ucf.edu
Gonzalez@mail.ucf.edu

Abstract

A perspective towards modeling teamwork is presented. This perspective extends the Context Based Reasoning (CxBR) paradigm. The new paradigm is coined Collaborative Context Based Reasoning (CCxBR). CxBR corollaries are specified. Joint Intention Theory and Belief-Desire-Intention models are reviewed. CCxBR utilizes Joint Intention Theory as the justification for the theorems that are presented in this paper.

Introduction

In order to effectively model collaborative agents utilizing Context Based Reasoning (CxBR), it is first necessary to formalize modeling collaborative behaviors for the paradigm. The formalization discussed in this paper relates CxBR to the more popular Belief-Desire-Intention (BDI) [Georgeff *et. al.* 1999] models. This relation serves two purposes. First, developers unfamiliar with CxBR are provided a familiar basis of reference. Moreover, the more significant reason is that the current theories on collaboration [Cohen and Levesque, 1991], [Grosz and Kraus, 1999], [Tambe, 1997], and [Jennings, 1995] are primarily concerned with reasoning as accepted from a BDI perspective. The formalization of collaborative behaviors within CxBR discussed in this paper is founded on the most widely accepted of these collaborative theories, Joint Intentions Theory (JIT) [Cohen and Levesque, 1991], [Tambe, 1997], and [Jennings, 1995].

This paper is organized as follows: the next section provides a background of CxBR, BDI, and JIT. The subsequent section formalizes the relationship between CxBR and BDI and formalizes the relationship between CxBR and JIT thus defining teamwork within CxBR. Finally, a summary is provided.

Background

The formalization of modeling teamwork in Context Based Reasoning (CxBR) is founded on the Joint Intentions Theory (JIT) of Cohen and Levesque [1991]. Much of the definitions and theorems involved with JIT deal with terms and definitions common to Belief Desire Intention (BDI) models. To better understand the formalizations discussed in Sections 3 and 4 of this paper, an overview of JIT, BDI, and CxBR is provided in this section.

Belief Desire Intention Model

Perhaps the most common paradigm for modeling intelligent agents is the belief-desire-intention model [Georgeff *et. al.* 1999]. Georgeff loosely defines BDI in AI terms as follows:

- Beliefs - represent knowledge the agent possesses of the world.
- Desires - correspond to goals of the agent.
- Intentions - are plans to which an agent is committed.

These definitions are critical in defining terms related to collaboration and teamwork.

Joint Intentions Theory

The following definitions provide the foundation upon which Joint Intentions Theory [Cohen and Levesque, 1991] is built. The numbering is added to facilitate later discussions in this paper.

Definition 1 An <u>agent</u> has a **persistent goal** relative to q to achieve p iff:

1. The agent believes that p is currently false
2. The agent wants p to be true eventually
3. It is true (and the agent knows it) that (2) will continue to hold until the agent comes to believe either that p is true, or that it will never be true, or that q is false.

Definition 2 An <u>agent</u> **intends** relative to some condition to do an action just in case the agent has a persistent goal (relative to that condition) of having done the action and, moreover, having done it, believing throughout that the agent is doing it.

Definition 3 An <u>agent</u> has a **weak achievement goal** relative to q and with respect to a team to bring about p if either of these conditions holds:

- The agent has a normal achievement goal to bring about p, that is, the agent does not yet believe that p is true and has p eventually being true as a goal.
- The agent believes that p is true, will never be true, or is irrelevant (thus q is false), but has a goal that the status of p be mutually believed by all the team members.

Definition 4 <u>A team of agents</u> have a **joint persistent goal** relative to q to achieve p just in case

- They mutually believe that p is currently false
- They mutually know they all want p to eventually be true
- It is true (and mutually known) that until they come to mutually believe either that p is true, that p will never be true, or that q is false, they will continue to mutually believe that they each have p as a weak achievement goal relative to q and with respect to the team.

Definition 5 A <u>team of agents</u> **jointly intends**, relative to some escape condition, to do an action iff the members have a joint persistent goal relative to that condition of their having done the action and, moreover, having done it, mutually believing throughout that they were doing it.

Context Based Reasoning

Stensrud *et. al.* [2004] succinctly summarizes CxBR as follows: CxBR is a reasoning paradigm by which an autonomous agent can be modeled to execute a specifically defined task in either a simulated or real-world environment. The task assigned to the agent is encapsulated within a CxBR *mission*. This mission provides for the agent both a set of goals, which represent the criterion for completing the task, and a set of constraints specific to that task. Also present within a mission is a list of *contexts* that serve to partition the agent's task-related knowledge by the situations under which it applies.

A *context* represents a situation, based on environmental conditions and agent stimuli, which induces a certain agent behavior specific to that mission. When an agent is executing a mission within CxBR, its behavior is primarily controlled by the current applicable context, (known as the *active* context) a determination made by *context-transition logic*. At each time step, this transition logic examines the current stimuli on the agent and makes a determination of the active context for the subsequent time step. This logic is often in the form of *sentinel rules* that contain the conditions for a specific context-to-context transition; however the transition logic is not required to be rule-based.

The assignment of a certain CxBR behavior onto an autonomous agent (Autonomous Intelligent Platform, AIP) is done through the creation of a CxBR model. Encoded within a CxBR model is the mission assigned to the agent, a set of contexts applicable to that mission, and transition logic that defines the conditions under which each context is pertinent. Also present within the model is an interface connecting it to the physical or simulated agent responsible for executing the behavior. Because of this, the interface used by the CxBR model is representative of the agent it connects to. Low-level functions (such as moving, scanning, etc) are all encoded within this interface, as is the data representing the agent's current state (position, velocity, eye angle, etc). When the model determines a course of action, therefore, it does so in terms of the functions and representations within this interface.

A model is executed by assigning a mission to the agent interface. The first context listed by the mission is denoted as the *default context*, and serves as both the initial context and the context used if no situational determination can be made by the transition logic of the model. When executed, the initial context is either selected by the transition logic or assigned by the mission, and the behavior defined by the model begins. The model executes the logic encapsulated within the current active context, consults the transition logic for the appropriate next context (whether or not a transition is necessary), and repeats until the goal criteria are reached. [Stensrud *et. al.* 2004]

BDI and CxBR Formalisms

In this section, a preliminary attempt at formalizing aspects of CxBR is presented in the form of corollaries. A complete formalization for CxBR does not yet exist and is not provide here. Rather, the aspects focused on are, of course, those most pertinent to building a foundation for modeling collaborative behaviors in CxBR. For the purpose of discussing collaborative behaviors and teamwork the most noteworthy aspect relating CxBR to BDI is that CxBR fully encompasses the BDI structure in the following way.

Beliefs represent an agent's knowledge about its environment. CxBR provides a paradigm for representing an agent's knowledge through Missions, Major Contexts, and Sub-Contexts. However, an agent's environmental knowledge is largely independent of the CxBR structure.

Environmental knowledge could be stored in any suitable data structure. It is also important to note that although CxBR provides an organization for representing tactical knowledge in terms of Missions, Major Contexts, and Sub-Contexts – the exact AI utilization of this knowledge is not restricted by CxBR. For example, the knowledge required for transitioning to any given Context could be captured in a rule based system or could be contained in a neural network. Both rules [Gonzalez an Ahler 1998, Norlander 1999, Barrett *et. al.* 2003, Stensrud *et. al.* 2004] and neural networks [Stensrud 2004] have been successfully implemented as means to determine Context transitions. CxBR is only concerned with the organization of the knowledge not the specific AI implementation used to reason about the knowledge.

Desires correspond to goals of the agent. A CxBR Mission includes the highest level goal for an agent. Sub-goals, primarily concerned with accomplishing the Mission's goal, are either implicitly or explicitly contained within Contexts and Sub-Contexts.

Consider an oversimplified example of a driving scenario: *return home from work*. An obvious CxBR Mission *returnHomeFromWorkMission* would include the overall goal of *drive home from work*, which implicitly includes sub-goals of *avoid accidents with vehicles* and *avoid accidents with pedestrians*. A few of the likely Contexts contained in this Mission might be: *highwayDrivingContext*, *cityDrivingContext*, and *vehicleFailureContext*. Regardless of which Context is Active, the highest-level goal remains *drive home from work*. However, each Context is likely concerned with a set of sub-goals, which are likely necessary to accomplish the highest-level Mission goal. For instance, during *cityDrivingContext* the sub-goal of *obey traffic control devices* is certainly pertinent. This sub-goal *obey traffic control devices* allows for the fulfillment of other goals which may not be explicitly stated such as: *avoid citations* and *avoid collisions*.

The example above shows that an agent's desires are present, both explicitly and implicitly, throughout the context hierarchy.

Intentions are commitments toward a plan. A CxBR plan consists of a sequence of Major Contexts. During a scenario the plan is composed of the series of sequential Active Contexts. An agent's current Active Context determines the agent's current plan. Therefore, an agent's intentions are determined by the agent's Active Context.

<u>Corollary 1:</u> High level desires and goals are captured in CxBR Missions. Lower sub-goals and desires are captured in the Major Contexts and Sub-Contexts associated with the Mission.

To allow for more specific definitions and theorems of collaboration in CxBR, the formalism for transition logic must be expanded. "In order for a Context to be Active certain prerequisites must be met (with the exception of choosing a default Active Context). The prerequisites for choosing an Active Context are specified as the Transition Criteria and captured as part of the Transition Logic." [Stensrud *et. al.* 2004] Transition Logic should be considered as a set of criteria. It is possible that a criterion member from this set is sufficient for causing a Context transition, yet this criterion member may not be strictly necessary for the transition. In other words, the criterion will cause a Context transition, but its absence does not prohibit the transition. This criterion belongs to a disjunctive set of transition criteria. In contrast, there may be certain criteria that are necessary for Context transition. In other words, in order for the Context transition to occur certain criterion are absolutely required. These elements belong to a conjunctive set, which will be termed Transition Requirements. Hence, Context c with Transition Requirement q can be Active iff q is believed true.

<u>Corollary 2</u>: Given that fact q is a transition requirement of Context c, if c is the Active Context, then q is believed true.

<u>Corollary 3:</u> Given that Context c is part of the context set associated with Mission m, and m contains goal g, if c is the Active Context for an agent with Mission m, then the agent has Mission goal g and any other goals (Mission sub-goals) of c.

<u>Corollary 4:</u> The sequence of Active Contexts for a CxBR agent is the agent's plan.

These corollaries will be referred to later in this chapter during the explanation of implementing JIT in CxBR. Before that, however, an examination of Joint Intention Theory from a contextual reasoning perspective is presented in the following section.

Collaboration in CxBR

A major obstacle for agents seeking collaboration is in verifying the intentions and beliefs of prospective collaborators. It is expected that the complexity of this verification can be reduced through communicating in Contexts. For a correctly specified CxBR model, in order for a Context to be Active there are certain conditions that must be true and other conditions that are implied. Knowledge of these conditions provides insight as to an agent's beliefs, desires, and intentions. For simulated agents, each team member could be provided with knowledge of the other team members' Context and Mission specification. This knowledge includes transition requirements and goals of the Contexts and Mission. Therefore, once a prospective collaborating agent's Active Context is recognized or communicated the recipient can infer the prospects beliefs, desires and intentions. This inference can then be used to help determine whether or not collaboration exists between the agents.

Theorem 1: A CxBR agent has a **persistent goal** (individual commitment) relative to *q* to achieve *p* iff: The Active Context *c* has transition requirement *q* and goal *p* or if the Active Context *c* has transition requirement *q* and the Mission *m* has goal *p*.

This is justified from the JIT Definition 1 of a persistent goal and CxBR corollaries 2 and 3.

Theorem 2: A CxBR agent **intends** relative to some condition, consisting at a minimum of some transition criterion, to do an action determined by the agent's Active Context for the sake of a persistent goal.

This theorem is adapted from the JIT Definition 2 for intentions and the fact that actions in CxBR are determined by the agent's Active Context.

Theorem 3: A CxBR agent has a **weak achievement goal** relative to *q* and with respect to a team to bring about *p* if: The agent's Active Context is part of Mission *m*'s related Contexts intended to accomplish *p*, or the agent has a goal that the status of *p* be mutually believed by all other teammates, regardless of the current state of *p* (true, false, or irrelevant).

This is justified by the JIT definition for weak achievement goal and the fact that the sequence of Contexts forms a plan that allows the accomplishment of the Mission goal.

Theorem 4: A team of CxBR agents has a **joint persistent goal** relative to *q* to achieve *p* if each agent shares the same team Mission with goal *p*.

This is justified by the JIT Definition 4 for joint persistent goal and Corollary 1.

Theorem 5: A team of CxBR agents **jointly intends** to do some action iff they share the same team Mission and believe they are accomplishing their Mission by following a plan of Mission related Contexts.

Theorem 6: Theorem 4 and theorem 5 could both be extended to include Context rather than Mission as a matter of scale.

This is justified since Mission is essentially a special form of context. "The general idea of contexts is sub-divided hierarchically into three types: These are 1) the *Mission Context*, 2) the *Major-Contexts* and 3) the *Sub-contexts*." [Gonzalez and Ahler, 1998] When considering a Context hierarchy including multiple Missions, the Missions themselves become the Context-set of some higher Mission. "No more than one Mission will be active at any one time, and Missions are mutually exclusive. So, a new Mission would have to bump an existing Mission from active status." [Gonzalez and Ahler, 1998] It could be argued that the representation of multiple Missions is simply a matter of scale on which the simulated agent is expected to operate. An agent capable of multiple Missions is certainly more versatile than an agent capable of a single Mission. In real world applications, where agents represent humans or autonomous robots, agents only capable of a single Mission are quite handicapped in their usefulness. For the purpose of this research, the Context hierarchy is assumed to be scalable beyond one Mission.

Testing and Results

The corollaries and theorems explained in the previous section deal primarily with understanding intentions through the beliefs a CxBR agent has regarding another agent's Active Context. For example, agent1 can infer certain facts about agent2 based on agent2's Active Context, assuming agent1 possesses some understanding of agent2's Contexts. The theorems propose a methodology of ascertaining collaboration through this knowledge of prospective teammates Contexts and Mission(s).

As a way of testing this, three models are built. All three models represent a soccer team capable of playing on the RoboCup soccer server. The first of these teams is incapable of recognizing and reasoning about teammates' intentions no their Active Contexts. The second model provides a means for agents to infer intentions based on teammates observed actions. The third model will incorporate the theories set forth above resulting in a CCxBR prototype. Agents in this model will be able to recognize the Active Contexts of their teammates and infer their teammates intentions based on those Active Context.

Results are forthcoming and will be included in a journal submission later this year.

Summary

This paper presents a formalization of concepts regarding modeling collaborative behaviors in Context Based Reasoning (CxBR). First, to formalize teamwork in CxBR it is necessary to define collaboration in CxBR. This definition is based on the widely accepted Joint Intentions Theory (JIT). Formalisms are presented that explain how Belief-Desire-Intention (BDI) models are encompassed within the CxBR paradigm. From a base of corollaries on CxBR, theorems are then developed to justify CxBR model behaviors in terms of JIT definitions. These corollaries and theorems are used to justify the communication of agents' intent through Context recognition. It is shown that by knowing which of an agent's Contexts is the currently Active Context, and having some knowledge of that Context's specification, much can be inferred about the agent's intent. From this, agents are able to make decisions regarding collaboration of other agents.

References

Barrett, G., Stensrud, B., Gonzalez, A., & Lisetti. C., 2003, "Modeling Affect in Context-Based Reasoning" *Proceedings of Behavior Representation In Modeling and Simulation,* 2003

Cohen, P. R., Levesque, H. J., 1991 "Teamwork." *Nous,* 35 1991

Georgeff, M. Pell B., Pollack M., Tambe M., and Wooldridge M. The belief-desire-intention model of agency. In *Proceedings of Agents, Theories, Architectures and Languages (ATAL),* 1999.

Grosz, B. and Kraus, S. 1999. *The evolution of SharedPlans.* In Rao, A. and Woolridge, M., editors, Foundations and Theories of Rational Agency, pages 227--262. Kluwer.

Gonzalez, A. J. & Ahlers, R. Context-based representation of intelligent behavior in training simulations. *Transactions of the Society for Computer Simulation.* 15(4), 153-166. 1998.

Jennings, N. R., 1995, "Controlling Cooperative Problem Solving in Industrial Multi-Agent Systems using Joint Intentions." *Journal of Artificial Intelligence,* 74(2), 1995.

Norlander, L. *A Framework for Efficient Implementation of Context-Based Reasoning in Intelligent Simulation.* Master's Thesis, ECE Dept., University of Central Florida. 1999.

Stensrud, B. 2004 "FAMTILE: An Algorithm for Learning High-Level Tactical Behavior from Observation" Doctoral Dissertation, Department of Electrical and Computer Engineering, University of Central Florida, 2004

Stensrud, B., Barrett, G., Trinh, V., and Gonzalez, A., 2004 "Context Based Reasoning: A Revised Specification." In the proceedings of *Florida Artificial Intelligence Research Society* 2004.

Tambe, M., 1997, "Towards Flexible Teamwork." *Journal of Artificial Intelligence Research* 7, pp. 83-124.