Reasoning Principles for Negotiating Agent

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Abstract—**Automated negotiation is an important applying field of agent theory and technology. For the current agent theoretical models have some troubles in explaining the agent's negotiation behaviors, this paper defines utility as costs and incomes coming from the transformation of the possible negotiation states. This lead to a semantic model fitting the agent's automated negotiation. Then, on the basis of the classical Belief-Desire-Intention model, a logic named BDI-U is completely proposed, which can explain the principles of the negotiating agent's reasoning process. Therefore, the model can support further design and development of negotiating agent. The work performs five steps: designing formal language, designing semantic model, explaining semantics, proposing and explaining system axioms, and the axioms' validity proof.**

***Index Terms*—agent, negotiating agent, automated negotiation, belief-desire-intention model**

I. INTRODUCTION

With rapid and deep development of E-Commerce, EC oriented automated negotiation has become an important applying field of the agent theory and technology [1] [2]. So far, research on automated negotiation is mainly focused on negotiation strategy and protocol [3] [4], but paid less attention to the study of negotiating agent, which is the main entity in the process of negotiation. Most research, such as literature [5] [6], first assume the agent participating in the negotiation process already has certain ability to make negotiation reasoning, and then propose some negotiation strategy algorithms. But some pivotal theoretical problem for constructing negotiating agent is not very clear. For example, how does the agent, as a rational entity, integrate negotiation problem with its mental states (belief, desire and intention) to perform reasoning? What is the rule the agent use to perform reasoning? In order to answer these questions, we must propose a novel theoretical model for the negotiating agent.

So far, there are two directions in the research method on building agent's theoretical model, one is based on logic, and another is based on utility theory. The logical method means a reasonable behavior can be deducted by existing information. The utility theory, however, means a reasonable behavior must be an action which can maximize the expecting utility [7]. The logical method is the most primary way to develop an agent's theoretical model, and the representative model is the BDI model and others derived from it [8] [9] [10]. But negotiation, as an important part of agent's cooperation, has its particularity different behavior attributes. BDI and its subsequent theory model, however, have not given negotiation enough regard, so the current model can not satisfy the development of automated negotiation.

In the process of automated negotiation, rational agent must make decision continuously, and utility plays a very important role in this process [12]. In the negotiation research field, the classical negotiation models are mainly based on utility theory. In Nash negotiation model, for example, the current negotiation state point, the feasible solution region, and the negotiation result (that is agreement point) are all expressed by utility value [11]. As a result, we cannot ignore the existence of utility when a theoretical model is to be built, which can support agent's negotiation reasoning. There have been some works discussing the relation between agent's mental states and utility, but not dealing with negotiation application. Literature [12] and [13], for example, proposed a kind of mental state model combined with utility, which can do some help for the work in this paper. However, since it only gave a description of the model, but be lack of the validity proof for the axiom derived from the model, so the model is not a complete logic system, and needs further work to perfect it.

We consider that one pivotal thing in the study of agent's negotiation reasoning mechanism is how to combine the agent's mental states with the utility. For in this way, we can integrate the agent's belief, desire and intention with negotiation model in decision theory. Concretely, we consider this kind of combination as follows: the negotiating agent produces negotiation desire on the basis of belief, and then produces negotiation intention on the basis of desire; on one hand, this process is based on logic, that means negotiating agent believe the negotiation desire can be realized, and has plan to do it; on the other hand, this process is based on utility too, that is to say, the produced negotiation intention is a desire which has the maximum utility in the all negotiation desires.

In order to validate this idea, this paper will completely propose a logic system BDI-U, which integrates logic with utility, and is fit for studying negotiation reasoning. This logic system can be regarded as a mathematical tool for supporting theoretical research in agent's negotiation reasoning. On the basis of the logic system, we explain the agent's reasoning principles in the process of negotiation, and design the reasoning rule according to the principle. The research result can also be used as a high level constraint language for describing and validating negotiating agent in the process of design and development of negotiating agent.

II. BDI-U LOGIC

A. Syntax

The semantics of BDI-U are based upon techniques that are by now standard in the modal and temporal logic communities. BDI-U contains the belief, desire, and intention modalities, and the usual apparatus of first-order logic.

BDI-U is essentially an expansion of first-order logic. We define its formal language by writing "L_{NA}".

(1)The alphabet of BDI-U thus contains the following symbols:

The classical connectives: "$\neg$" (means "not"), "$\rightarrow$" (means "if… then…").

The universal quantifier: "$\forall$".

The group membership operator: "$\in$".

The punctuation symbols: "(", ")", and ".".

The symbols for formulae: $\alpha, \beta, \gamma, \varphi, \psi\ldots$

The modal connectives: "*Bel*"- the belief modality, "*Des*"- the desire modality, "*Int*"- the intention modality;

The symbols for Agents: $i, j, k, i_1, j_1, k_1\ldots$

The symbols for Utility: $u, u_1, u_2\ldots$

The symbols for Speech-Acts: $\delta_1, \delta_2, \delta_3\ldots$

We assume that the remaining connectives of classical logic (i.e., "$\wedge$" means "and", "$\vee$" means "or") have been defined as normal, in terms of "$\neg$" and "$\rightarrow$".

$$\alpha \wedge \beta =_{def} \neg(\alpha \rightarrow \neg\beta)$$

$$\alpha \vee \beta =_{def} \neg\alpha \rightarrow \beta$$

Similarly, we assume that the existential quantifier, "$\exists$", has been defined as the dual of "$\forall$".

$$\exists x \cdot \alpha =_{def} \neg\forall x \cdot \neg\alpha$$

(2) The rules forming formulae in language L_{NA} is:

Arbitrary proposition variable p is a formula;

If α is a formula, then $\neg\alpha$ is a formula too;

If α, β is a formula, then $(\alpha \rightarrow \beta)$, $Bel(i,\alpha)$, $Des(i,\alpha)$, $Int(i,\alpha)$, $Bel(i,\alpha,u)$, $Des(i,\alpha,u)$, $Int(i,\alpha,u)$, are either formulae; where:

$Bel(i,\alpha,u)$ means negotiating agent i believes proposition α is true with the utility u for making this decision;

$Des(i,\alpha,u)$ means negotiating agent i has a desire α with the utility u for making this decision;

$Int(i,\alpha,u)$ means negotiating agent i has an intention α with the utility u for making this decision.

Notice the use of parentheses in operators such as *Bel*, in order to make explicit the binding between a modality and its arguments. To make the intended interpretation of a formula clear, we also use parentheses and other brackets where necessary.

Definition 1 L_{NA}*-Formula*: α is a L_{NA}*-Formula*, if and only if, α is a L_{NA} non-null symbol string, by using rules forming formulae finitely. Here prescribe the PRI of *Bel*, *Des*, *Int* is same to $\neg$, and then $\rightarrow$, the brackets outside the formula can be omitted.

Definition 2 *Form(*L_{NA}*)* is a formulae set made up of the all L_{NA}*-Formula*.

B. Semantics model

The semantics model for BDI-U logic in this paper is based on a set of possible negotiation states. Here, we let W be the set. The concept of possible negotiation states is coming from the concept of possible world in Kripke semantics. The possible negotiation state represents and describes the observed negotiation states when a negotiation is going on. In this semantic model, the process of negotiation evolves continuously, transforms from one negotiation state to another. Diverse speech acts performed by the negotiating agent's and different negotiation environment affairs will make the process of negotiation evolves in different ways. Therefore, the process of negotiation probably has numbers of evolving directions from an arbitrary negotiation state.

In order to represent such a model, we use a branching structure, which is showed in figure 1. It indicates the model of possible negotiation states is: Discrete; Bounded in the past (there is a "start of negotiation state"); Unbounded in the future (there is no "end of negotiation state"); Linear in the past (there is only one past history); Branching in the future (the course of future negotiation states is yet to be determined).

For example, in figure 1, from the original negotiation state w_0, the process of negotiation will probably evolve in w_1 of w_2. The condition for the process evolves in w_1 is that event e_1 occurs or a speech act δ_1 is performed by the negotiating agent. When the negotiation process is at state w_1, it will evolve in state w_3 or w_4. If negotiation process evolves in state w' from w, then we refer to w' as accessible negotiation state of w. For example, in figure 1, w_1 and w_2 is w_0's accessible negotiation state.

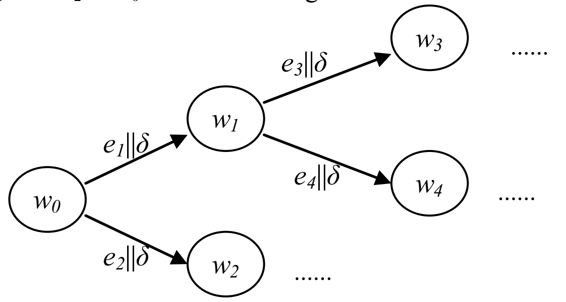

Figure1. Negotiation's branching structure of possible negotiation states

The state of an agent is defined by its beliefs, desires, and intentions. The semantics of beliefs, desires, and intentions are given using possible negotiation states.

Thus an agent's beliefs in any given negotiation state are characterized by a set of states, those that are consistent with the agent's beliefs. An agent is then said to believe φ if φ is true in all these possible negotiation states. We refer to this set of "belief alternatives" as belief-accessible negotiation states. Similarly, an agent's desires in any given situation are characterized as a set of negotiation states, those that are compatible with the agent's desires. As might be expected, we refer to these as desire-accessible negotiation states. Finally, an agent's intentions in a given situation are characterized by a set of intention-accessible negotiation states, each of which represents a state of affairs compatible with the agent's intentions.

The semantics model of BDI-U logic can be formally defined as follows:

Definition 3 $F=<W,Ag,B,D,I,U,\Theta,SA,\tau>$ is a frame, where:

(1) W is a set of possible negotiation states;

(2) $Ag=\{i,j,k,i_1,j_1,k_1,\cdots\}$ is the set of all negotiating agent's symbol;

(3) $B:Ag\to W\times W$ is a belief accessibility relation, which represents that negotiating agent *i* has belief accessible negotiation state *w'* at possible negotiation state *w*. In order to characterize the beliefs of each agent, we use a function *B*, which assigns to every agent a belief-accessible relation over possible negotiation states. Here refers to functions *B* as belief accessibility relations, even though, strictly speaking, this function assigns belief accessibility relations to agent.

(4) $D:Ag\to W\times W$ is a desire accessibility relation, which represents that negotiating agent *i* has desire accessible negotiation state *w'* at possible negotiation state *w*. This function assigns belief accessibility relations to agent and characterizes the desires of each negotiating agent.

(5) $I:Ag\to W\times W$ is an intention accessibility relation, which represents that negotiating agent *i* has intention accessible negotiation state *w'* at possible negotiation state *w*. This function assigns intention accessibility relations to agent and characterizes the intentions of each negotiating agent.

(6) $U:W\times W\to R$ is utility function, is a mapping from a Cartesian product of possible negotiation states set W to real number set. It is used for measuring the accessible utility between two possible negotiation states. It is reasonable. When the negotiation state transforms from one to another, the negotiating agent must perform corresponding decisions and speech acts, and will consume some resource for that. On the other hand it will receive some income from doing that. As a result, the utility function describes correctly the utility mental of negotiating agent, and makes the agent's outcome and income measurable during the evolving process of negotiation states.

(7) Θ is utility threshold, which is the minimum utility for negotiating agent making a decision. Normally, different agent has different Θ, and one agent has different Θ in different circumstances.

(8) $SA=\{\delta_1,\delta_2,\cdots,\delta_n\}$ is the set of speech acts which can be used by negotiating agent;

(9) $\tau:W\times SA\to W$ is a state transfer function, which is a mapping from a Cartesian product of possible negotiation states set W and speech act set SA to possible negotiation states set. This function represents the transferring process of possible negotiation states induced by a negotiating agent performing a certain speech act.

In order to simplify what follows, we write $B_w(i)$ to denote the set of possible negotiation states accessible to agent *i* from negotiation state *w*. Formally, $B_w(i)$ is defined as follows. As with belief accessibility relations, we write $D_w(i)$ and $I_w(i)$ to denote the desire and intention accessible negotiation states for agent *i* from negotiation state *w*.

Definition 4 for $\forall w\in W$, $B_w(i)$, $D_w(i)$ and $I_w(i)$ is respectively the set of Agent *i's* all belief accessible, desire accessible and intention accessible possible negotiation states from *w*. Formally, we have

$$B_w(i)=_{def}\{w'\mid w'\in W \text{ and} <w,w'>\in B(i)\}$$

$$D_w(i)=_{def}\{w'\mid w'\in W \text{ and} <w,w'>\in D(i)\}$$

$$I_w(i)=_{def}\{w'\mid w'\in W \text{ and} <w,w'>\in I(i)\}$$

In rigorous sense, the function *B*, *D*, *I* proposed in definition 3 assigns corresponding accessibility relation to negotiating agent. For convenience, here we let *B*, *D*, *I* denote respectively belief accessibility relation, desire accessibility relation, intention accessibility relation. These three accessibility relations are required to satisfy several properties in order to make the negotiating agent logic system to be consistent with the classical modal logic system, we therefore have following definitions.

Definition 5 assuming *W* is an arbitrary set of possible negotiation states. *B*, *D*, *I* is respectively belief accessibility relation, desire accessibility relation, intention accessibility relation over *W*. Where

B is serial, transitive, and Euclidean. In detail

(1)*B* is said to be serial, if $\forall w\in W$, $\exists w'\in W$ such that $w'\in B_w(i)$, which means that for all negotiation states *w*, there is some possible negotiation state *w'* such that $w'\in B_w(i)$;

(2)*B* is said to be transitive if $\forall w,w',w''\in W$, we have $w'\in B_w(i)$ and $w''\in B_{w'}(i)$ implies $w''\in B_w(i)$;

(3) *B* is said to be Euclidean if $\forall w,w',w''\in W$, we have $w'\in B_w(i)$ and $w''\in B_w(i)$ implies $w'\in B_{w''}(i)$;

These requirements ensure that the logic of belief corresponds to the well-known modal logic system KD45 [14].In a similar way, agent's desires are given by a function *D*, and agent's intentions are given by a function *I*.

Both *D* and *I* are assumed to assign agents serial relations. This ensures that the desire and intention modalities have logic of KD [14]; we also require that both *D* and *I* satisfy the following properties

(4)D is said to be serial if $\forall w \in W$, $\exists w'$ such that $w' \in D_w(i)$.

(5)I is said to be serial if $\forall w \in W$, $\exists w'$ such that $w' \in I_w(i)$.

In order to give a meaning to formulae of BDI-U, we need various functions that associate symbols of the language with objects in the domain.

Definition 6 $F = < W, Ag, B, D, I, U, \Theta, SA, \tau >$ is an arbitrary frame, V is a variable assignment of L_{NA}-*Formula* over frame F, if and only if $V : Form(L_{NA}) \times W \to \{0,1\}$, where 1 denote true, 0 denote false, and for arbitrary L_{NA}-*Formula* α and arbitrary $w \in W$, satisfies:

[V_{Bel}]:

$$V(Bel(i,\alpha,u),w) = \begin{cases} 1, & \text{for } \forall w' \in W, u = U(w,w') \\ & \text{if } w' \in B_w(i) \text{ then } V(\alpha,w') = 1, \text{ then } u \geq \Theta \\ 0, & \text{otherwise} \end{cases}$$

Intuitively, the meaning of definition [V_{Bel}] is: negotiating agent believes proposition α is true at possible negotiation state *w*, if and only if α is always true in all *w'*s belief accessible negotiation states. At the same time, the utility *u* is considered in the modal formula. Therefore, the model must guarantee *u* cannot be less than the threshold Θ . We can know the meaning of [V_{Des}] and [V_{Int}] in the same way.

Definition 7 $M = < W, Ag, B, D, I, U, \Theta, SA, \tau, V >$ is a modal, if and only if $F = < W, Ag, B, D, I, U, \Theta, SA, \tau >$ is a frame, and *V* is a variable assignment over *F*. We can also say that *M* is a modal over *F.*

Definition 8 $M = < W, Ag, B, D, I, U, \Theta, SA, \tau, V >$ is an arbitrary model, α is an arbitrary L_{NA}-*Formula*,

(1) For $\forall w \in W$, if $V(\alpha, w) = 1$, then we say α is true over *w*, by writing $< M, V, w > \vDash \alpha$, if $V(\alpha, w) = 0$, we say α is false over *w* by writing $< M, V, w > \nvDash \alpha$.

(2) If $\exists w \in W$ brings $< M, V, w > \vDash \alpha$, then we say α can be satisfied over *M;*

(3) If for $\forall w \in W$ we have $< M, V, w > \vDash \alpha$, then we say α is effective over *M* by writing $M \vDash \alpha$.

Definition 9 $F = < W, Ag, B, D, I, U, \Theta, SA, \tau >$ is an arbitrary frame, α is an arbitrary L_{NA}-*Formula*

(1) If there is a model *M over F*, and $M \vDash \alpha$, then we say α can be satisfied over *F*,

(2) If for arbitrary model *M* over *F* we have $M \vDash \alpha$, then we say α is valid over *F* by writing $F \vDash \alpha$.

It is easy to validate that α is valid over *M* or *F*, if and only if $\neg\alpha$ can not be satisfied over *M* or *F*.

C. Semantics Definition

The semantics of formulae are given via the formula satisfaction relation, "$\vDash$", which holds between formulae interpretations and formulae. A formula interpretation is a structure *<M, V, w>*, where *M* is a model, *V* is a variable assignment, *w* is a negotiation state in *M*. the rules defining the formula satisfaction relation are given as follows. If $< M, V, w > \vDash \varphi$, then we say *<M, V, w>* satisfies φ , or equivalently, that φ is true in *<M, V, w>*.

Definition 10 the semantics of main modal formulae in the logic system is defined as follows:

(1) $< M, V, w > \vDash Bel(i, \alpha, u)$ iff for $\forall w' \in B_w(i)$, $u = U(w, w')$, then $< M, V, w' > \vDash \alpha$, and $u \geq \Theta$.

(2) $< M, V, w > \vDash Des(i, \alpha, u)$ iff for $\forall w' \in D_w(i)$, $u = U(w, w')$, then $< M, V, w' > \vDash \alpha$, and $u \geq \Theta$.

(3) $< M, V, w > \vDash Int(i, \alpha, u)$ iff for $\forall w' \in I_w(i)$, $u = U(w, w')$, then $< M, V, w' > \vDash \alpha$, and $u \geq \Theta$.

In the definition above, negotiating agent's belief in any given negotiation state heavily depends on $B_w(i)$, the set of belief accessible negotiation states. If the negotiating agent believe in a proposition α is true, if and only if the proposition is true in all belief accessible negotiation states. This is the meaning expressed by definition (1). Similarly, we can understand the semantics of desire formula and intention formula. At the same time, all definition involves utility *u*, and they all require that the *u* cannot be less than the corresponding threshold, which is the minimum utility standardization the agent can receive. Otherwise, the negotiating agent will not have the corresponding belief, desire and intention. More over, the *u* here are all defined by unified utility function *U(w, w')*, that is because the utility is essential a production of mental activity, and that the agent's mental activity is mainly expressed by belief, desire and intention. So the utility here should be the integrative result of the all mental activities. In decision theory, researchers study negotiation by setting utility function for decision maker. The effective of that method is consistent with ours. As a result, it is reasonable to define the negotiating agent's belief, desire and intention by using unified utility function.

III. PROPERTIES OF BDI-U

After introducing a new logic by means of its syntax and semantics, it is usual to illustrate the properties of the logic by means of a Hilbert-style axiom system. However, no complete axiomatization is currently known for the modal logics that underpins BDI-U. Completeness proofs for modal logics, even in the propositional case, are relatively few and far between [15]. For these reasons, I stay primarily at the semantic level, dealing with valid formulae, rather than attempt a traditional axiomatization.

Axiom 1:

1. If α is a substitution instance of a propositional logic tautology, then $\vDash \alpha$.

2. If $\vDash \alpha \to \beta$ and $\vDash \alpha$, then $\vDash \beta$.

Proof for (1), simply observe that the semantics of the propositional connectives"$\neg$" and "$\to$"are identical to classical logic. Similarly, for (2), which is simply modus ponens, then reasoning is identical to classical propositional or first-order logic.

Next, we turn to the belief operator, *Bel*. This is essentially a normal modal necessity connective, with semantics given via a serial, Euclidean, and transitive accessibility relation [15]. Thus the logic of *Bel* corresponds to the well-known normal modal system "weak-S5"or KD45.

Axiom 2 $< M,V,w >\models Bel(i,(\alpha \to \beta)) \to (Bel(i,\alpha) \to Bel(i,\beta))$

The meaning of Axiom 2 is that if a negotiating agent believes α, and believes $\alpha \to \beta$, then the agent believes β certainly, otherwise he is not supposed to believe $\alpha \to \beta$.

Axiom 3 $< M,V,w >\models Bel(i,\alpha) \to \neg Bel(i,\neg\alpha)$

The meaning of Axiom 3 is that if the negotiating agent believes some proposition is true, then he will not believe it is false. That is to say that the belief of negotiating agent is consistent with itself. Axiom 3 has the following semantic constraint:

Semantic Constraint 3 for $\forall w \in W$, $\exists w' \in W$, so as to $w' \in B_w(i)$. That is to say belief accessibility relation *B* is serial over possible negotiation state set *W*.

Axiom 4 $< M,V,w >\models Bel(i,\alpha,u) \to Bel(i,Bel(i,\alpha,u))$

Semantic Constraint 4 for $\forall w,w',w'' \in W$, if $w' \in B_w(i)$ and $w'' \in B_{w'}(i)$, then $w'' \in B_w(i)$. That is to say belief accessibility relation *B* is transitive over possible negotiation states set *W*.

Axiom 4 is to say that negotiating agent knows beliefs he has.

Axiom 5 $< M,V,w >\models \neg Bel(i,\alpha,u) \to Bel(i,\neg Bel(i,\alpha,u))$

Semantic Constraint 5 for $\forall w,w',w'' \in W$, if $w' \in B_w(i)$ and $w'' \in B_w(i)$, then $w'' \in B_{w'}(i)$. That is to say belief accessibility relation *B* is Euclidian over possible negotiation state set *W*.

The meaning of axiom 5 is that the negotiating agent knows that he doesn't know some facts.

Note that axiom 2 is usually known as the "K" axiom; axiom 3 is known as the "D" axiom; axiom 4 is known as the "4" axiom, and axiom 5 as the "5" axiom.

In the above discussion about the belief related axiom of negotiating agent, axiom 2 and 3 keep the classical pattern of belief axiom, but axiom 4 and 5 integrate the concept of utility. As discussed before, utility is an integrated mental result of belief, desire and intention. As a result, one utility value is not just focused on one mental state, but on a proposition (it can also be regarded as a negotiating affair which the negotiating agent is to deal with). And it will change when the proposition is different. In axiom 3, for example, negotiating agent *i* believes respectively proposition α, β and $\alpha \to \beta$, and it will have three different utility u_1, u_2, u_3 for these three different proposition. For it is meaningless to present different utility in one axiom. As a result, there isn't unified utility expression in the axiom 2 and 3.

Let's begin to discuss axiom about negotiation desire and intention. According to the above assumption, the negotiation desire accessibility relation *D* and intention accessibility relation *I* is serial，as a result, the *Des* and *Int* connectives have a logic that corresponds to the normal modal system KD. However, they are not normal modality operator. So, in BDI-U system, formula $Des(i,\alpha,u)$ and $Int(i,\alpha,u)$ satisfy the following axiom, which is constrained by threshold:

Axiom 6

$$< M,V,w >\models Des(i,(\alpha \to \beta)) \wedge (u_1 \geq \Theta) \wedge (u_2 \geq \Theta) \to (Des(i,\alpha,u_1) \to Des(i,\beta,u_2))$$

Axiom 7

$$< M,V,w >\models Int(i,(\alpha \to \beta)) \wedge (u_1 \geq \Theta) \wedge (u_2 \geq \Theta) \to (Int(i,\alpha,u_1) \to Int(i,\beta,u_2))$$

The utility u_1 and u_2 in axiom 6 and 7 is respectively belong to proposition α and β. The meaning of these two axioms is that if negotiating agent has negotiation desire or intention α, and then β will also be the agent's desire or intention. But this process is constrained by a condition, which is the corresponding utility cannot be less than the agent's utility threshold Θ. The reason for setting this constraint is that desire and intention are not normal modality operator, and the axiom combined with utility effectively avoids side effect, which the normal modality has.

Similar to axiom 3, we have the following two axioms:

Axiom 8 $< M,V,w >\models Des(i,\alpha) \to \neg Des(i,\neg\alpha)$

Semantic Constraint 8 for $\forall w \in W$, $\exists w' \in W$ so as to $w' \in D_w(i)$

Axiom 9 $< M,V,w >\models Int(i,\alpha) \to \neg Int(i,\neg\alpha)$

Semantic Constraint 9 for $\forall w \in W$, $\exists w' \in W$ so as to $w' \in I_w(i)$

IV. PROOF

The axiom proposed above is just a kind of syntax form. The aim of this section is to proof that these axioms is valid under explanation of $M =< W,Ag,B,D,I,U,\Theta,SA,\tau,V >$, which is to discuss the consistency relation between syntax and semantics of BDI-U logic.

For axiom 2, it is equal to proof $< M,V,w >\models Bel(i,(\alpha \to \beta)) \wedge Bel(i,\alpha) \to Bel(i,\beta)$, we can therefore suppose $< M,V,w >\models Bel(i,(\alpha \to \beta))$ and $< M,V,w >\models Bel(i,\alpha)$ for arbitrary $<M,V,w>$; from the semantics of *Bel,* we know that $< M,V,w' >\models \alpha \to \beta$ and $< M,V,w' >\models \alpha$ for all *w'* such that $\forall w' \in B_w(i)$. Hence $< M,V,w' >\models \beta$. Using the semantics of *Bel* again, so we have $< M,V,w >\models Bel(i,\beta)$.

For axiom 3, suppose not. Then for some $<M, V, w>$ we have both $< M,V,w >\models Bel(i,\alpha)$ and $< M,V,w >\models Bel(i,\neg\alpha)$. Since the belief accessibility relation is serial, we know that there will be at least one $w' \in B_w(i)$, and from the semantics of *Bel,* we therefore know that $< M,V,w' >\models \alpha$ and $< M,V,w' >\models \neg\alpha$, hence $< M,V,w' >\models \alpha$ and $< M,V,w' >\not\models \alpha$, which is contradiction.

For axiom 4, assume $<M,V,w>\models Bel(i,\alpha,u)$ for arbitrary <M, V, w>. We need to show that $<M,V,w>\models Bel(i,Bel(i,\alpha,u))$, which by the semantics of *Bel* amounts to showing that $<M,V,w'>\models Bel(i,\alpha,u)$ and $u\geq\Theta$ for all $w'\in B_w(i)$, $u=U(w,w')$, which in turn amounts to showing that $<M,V,w''>\models\alpha$ and $u\geq\Theta$ for all $w''\in B_{w'}(i)$, $u=U(w,w')$. But since the belief accessibility relation is transitive, that is to say for all $w,w',w''\in W$, if $w'\in B_w(i)$ and $w''\in B_{w'}(i)$, then $w''\in B_w(i)$; and because $<M,V,w>\models Bel(i,\alpha,u)$, then by the semantics of *Bel*, we have $<M,V,w''>\models\alpha$, and we are done.

For axiom 5, suppose $<M,V,w>\models\neg Bel(i,\alpha,u)$ for $\forall<M,V,w>$, by the semantics of *Bel*, we have $<M,V,w'>\models\neg\alpha$ and $u\geq\Theta$ for $\forall w'\in B_w(i)$, $u=U(w,w')$. Then for the same reason $<M,V,w''>\models\neg\alpha$ and $u\geq\Theta$ for $\forall w''\in B_w(i)$, $u=U(w,w'')$, but since the belief accessibility relation is Euclidean, we have $w''\in B_{w'}(i)$, hence $<M,V,w'>\models\neg Bel(i,\alpha,u)$, we therefore have $<M,V,w>\models Bel(i,\neg Bel(i,\alpha,u))$.

For axiom 6, it is equal to proof

$$<M,V,w>\models Des(i,(\alpha\rightarrow\beta))\wedge(u_1\geq\Theta)\wedge(u_2\geq\Theta)\wedge Des(i,\alpha,u_1)\rightarrow Des(i,\beta,u_2),$$

we can therefore assume $<M,V,w>\models Des(i,(\alpha\rightarrow\beta))$ and $<M,V,w>\models Des(i,\alpha,u_1)$ for $\forall<M,V,w>$. From the semantics of *Des* we know that $<M,V,w'>\models\alpha\rightarrow\beta$, $<M,V,w'>\models\alpha$ and $u_1\geq\Theta$ for $\forall w'\in D_w(i)$, $u_1=U(w,w')$, hence $<M,V,w'>\models\beta$, from the semantics of *Des* and $u_2\geq\Theta$, so we finally have $<M,V,w>\models Des(i,\beta,u_2)$.

The validity proof for the axiom 7 is identical to the proof for the axiom 6, and the validity proof for the axiom 8 and 9 are identical to the proof for the axiom 3, and they are therefore omitted.

V. PRINCIPLES FOR NEGOTIATION REASONING

The BDI-U logic proposed above is a formal system, whose main function is to provide a theoretical basis for practical design of negotiating agent and multi-agent system. The following work is to study the reasoning principle for agent in negotiation.

From the previous work of Rao and Geogeff [8], we can see that the generation and update of belief, desire and intention is the core problem when a mental state model is to be realized. Similarly, the principle for the agent's negotiation reasoning is mainly to explain the inner relationship between the negotiating agent's belief, desire and intention, and define their cooperation process. The main difference comparing to other previous work is we intents to build a reasoning system suitable for the agent's negotiation behavior, which integrate the utility concepts with the traditional mental states: belief, desire and intention.

A. Negotiation Desire Generation Principle

Negotiation desire plays an important role in the reasoning process of agent's negotiation. It is a connection between agent's belief and intention. The principle of desire generation is coming from the following system axiom.

Axiom NA10 $Des(i,\alpha,u)\rightarrow Bel(i,\alpha,u)$

It is to say: if negotiating agent has negotiation desire α, it then believes that the desire is true and can be realized. In other words, negotiating agent does not have desires which it can not realize. At the same time, the axiom presents that the desires come from beliefs. Therefore, in the software architecture of negotiating agent, if there are data or data structure representing proposition α in the desire base, then the data or data structure is also in the belief base, but $Bel(i,\alpha,u)\rightarrow Des(i,\alpha,u)$ is not right. The axiom is constrained by the following condition:

Constraint NC10 $\forall w\in W$, $B_w(i)\subseteq D_w(i)$

Because the belief accessible relation *B* and desire accessible relation *D* are both serial, that is to say, under arbitrary negotiation state *w*, there is at least one belief accessible negotiation state and one desire accessible negotiation state. As a result, according to the above semantic definition, we can always find corresponding negotiation desire accessible negotiation state set $D_w(i)$ for arbitrary belief accessible negotiation state set $B_w(i)$, and make it satisfy the relation $B_w(i)\subseteq D_w(i)$.

The axiom proposed above is just a kind of syntax form. We must proof that these axioms are valid under explanation of $M=<W,Ag,B,D,I,U,\Theta,SA,\tau,V>$. That is to discuss the consistency relation between syntax and semantics of BDI-U logic.

Theorem 1: Axiom NA10 is valid over the model $M=<W,Ag,B,D,I,U,\Theta,SA,\tau,V>$

Proof: it is equal to proof $<M,V,w>\models Des(i,\alpha,u)\rightarrow Bel(i,\alpha,u)$, from the semantics of *Des,* we know that for $\forall w'\in D_w(i)$, $u=U(w,w')$, we have $u\geq\Theta$ and $<M,V,w'>\models\alpha$, we can therefore suppose for $\forall w''\in B_w(i)$, according to the semantic constraint NC10 $B_w(i)\subseteq D_w(i)$, we know that $w''\in D_w(i)$, then $<M,V,w''>\models\alpha$, from the semantic definition of *Bel*, we have $<M,V,w>\models Bel(i,\alpha,u)$.

Axiom NA10 is just a system stipulation for describing the mechanism of agent's desire generation. We must deduce realizable reasoning specification from it for further design of practical system. Before the rules are proposed, here gives a system hypothesis.

System Hypothesis: the belief of negotiating Agent can be hold for a longer time than desire and intention. There aren't any maintenance problems of desire and intention in our system. That is to say, one round of negotiation has one round of belief-desire-intention reasoning. If current negotiation is over, then the corresponding desire and intention will be released. They will not affect the next round of negotiation decision. This hypothesis is also useful for the following process of intention generation.

Reasoning Rule NR1 (rule for desire generation):

$$Bel(i,\neg\varphi) \wedge Bel(i,\Diamond\varphi,u) \wedge (u \geq \Theta) \Rightarrow Des(i,\varphi,u)$$

Rule NR1 presents that negotiation desire comes from belief reasoning. Concretely, the desire comes from the proposition which is not true now but will be true in the future. Where, $u \geq \Theta$ indicates that negotiating agent does not make the all proposition satisfying the above condition as negotiation desire, but the proposition must satisfy the constraint of utility threshold. $\Diamond\varphi$ indicates proposition φ is possibly true.

B. Negotiation Intention Generation Principle

As mentioned above, some negotiation desires are selected by decision model, and negotiation desire is generated consequently, this process is supervised by the following axiom.

Axiom NA11 $In(i,\alpha,u) \rightarrow Des(i,\alpha,u)$

That is to say that, if negotiating agent has intention α, then it have got desire to realize α to a certainty. In other words, negotiation intention comes from negotiation desire. Therefore, in the software architecture of negotiating agent, if there are data or data structure representing proposition α in the intention structure, then the data or data structure is also in the desire base, but $Des(i,\alpha,u) \rightarrow In(i,\alpha,u)$ is not right. The axiom is constrained by the following condition:

Constraint NC11 $\forall w \in W$, $D_w(i) \subseteq I_w(i)$

Theorem 2: Axiom NA11 is valid over the model $M = <W, Ag, B, D, I, U, \Theta, SA, \tau, V>$

Proof : it is equal to proof $<M,V,w> \models In(i,\alpha,u) \rightarrow Des(i,\alpha,u)$, from the semantic definition of *Int,* we know that for $\forall w' \in I_w(i)$, $u = U(w,w')$, we have $<M,V,w'> \models \alpha$ and $u \geq \Theta$, we can therefore assume for $\forall w'' \in W$ we have $w'' \in D_w(i)$, from the semantic constraint $D_w(i) \subseteq I_w(i)$, we know $w'' \in I_w(i)$, hence $<M,V,w''> \models \alpha$, from the semantic definition of *Des*, so we finally have $<M,V,w> \models Des(i,\alpha,u)$.

Deduction 1 $In(i,\alpha,u) \rightarrow Des(i,\alpha,u) \rightarrow Bel(i,\alpha,u)$, corresponding semantic constraint is $B_w(i) \subseteq D_w(i) \subseteq I_w(i)$.

Deduction 1 means if negotiating Agent has negotiation intention α, it then consequentially believes proposition α is true. For example, one negotiating Agent has intention *e* to deal with a negotiation state, it then consequentially choose *e* as a negotiation desire in advance, and believe in itself *e*. Proof is omitted.

Reasoning Rule NR2 (rule for intention generation):

$$Des(i,\varphi,u_1) \wedge Des(i,\psi,u_2) \wedge (u_1 > u_2) \Rightarrow Int(i,\varphi,u_1)$$

Rule NR2 indicates that, if Agent has two incompatible negotiation desires, then it will choose the one with larger utility as the final negotiation intention in this round of negotiation reasoning. The meaning of this reasoning rule is compatible with the constraint of axiom NA11, which is negotiation intention comes from desire. When there are numbers of incompatible negotiation desires, we can use the rule repeatedly to generate the final negotiation intention. The rule plays a very important role in the agent's negotiation reasoning, and supervises directly the design of negotiating agent's architecture.

C. Negotiation Belief Updates Principle

There are two reasons for updating the negotiating agent's belief. One is from the affection of negotiation environment, for example, negotiation message from other negotiating agent, and changes in the decision model and negotiation strategy base, and so on. Another update comes from real time changes of the agent's beliefs during the process of reasoning. It mainly indicates that negotiating Agent need to record the changing process of its own mental states into the belief base. The update discussed here is mainly the latter. The following axiom supervises the process of belief update.

Axiom NA12 $Des(i,\alpha,u) \rightarrow Bel(i, Des(i,\alpha,u))$

Constraint NC12 $\forall w' \in B_w(i)$ and $\forall w'' \in D_w(i)$, then $w'' \in D_{w'}(i)$

Axiom NA12 means that, if negotiating agent has negotiation desire α, it then believe it has the desire. It is to say that the negotiating agent is self-know about desire. Similarly

Axiom NA13 $In(i,\alpha,u) \rightarrow Bel(i, In(i,\alpha,u))$

Constraint NC13 $\forall w' \in B_w(i)$ and $\forall w'' \in I_w(i)$, then $w'' \in I_{w'}(i)$

Theorem 3 Axiom NA12 is valid over the model $M = <W, Ag, B, D, I, U, \Theta, SA, \tau, V>$

Theorem 4 Axiom NA13 is valid over the model $M = <W, Ag, B, D, I, U, \Theta, SA, \tau, V>$

Proof for Theorem 3: it is equal to proof $<M,V,w> \models Des(i,\alpha,u) \rightarrow Bel(i, Des(i,\alpha,u))$;suppose $<M,V,w> \models Des(i,\alpha,u)$ for $\forall <M,V,w>$, from the semantic definition of *Des*, we know $<M,V,w''> \models \alpha$ and $u \geq \Theta$ for $\forall w'' \in D_w(i)$ and $u = U(w,w'')$; from the semantic definition of *Des* and *Bel*, in order to proof $<M,V,w> \models Bel(i, Des(i,\alpha,u))$, we should first proof $<M,V,w'> \models Des(i,\alpha,u)$ for $\forall w' \in B_w(i)$, and then proof $<M,V,w''> \models \alpha$ for $\forall w'' \in D_{w'}(i)$; so we therefore assume for $\forall w' \in B_w(i)$, we have $w'' \in D_{w'}(i)$, which is coming from the semantic constraint NC12.

So we have the following two reasoning rules for updating belief in the design of the negotiating agent's software architecture.

Reasoning Rule NR3 (rule for belief update aiming at desire): $Des(i,\alpha,u) \Rightarrow Bel(i, Des(i,\alpha,u))$

Reasoning Rule NR4 (rule for belief update aiming at intention): $In\ (i,\alpha,u) \Rightarrow Bel(i, In\ (i,\alpha,u))$

The above two rules indicates that the runtime desire and intention data must be saved in the negotiating agent's belief base, which must be guaranteed when the agent's software architecture is designed. When a negotiation is over, according to the system hypothesis, negotiating agent will clean up the desire and intention data in the desire and intention base provisionally. But the data is not deleted completely from the agent's work memory, but transferred to the corresponding data structure of agent's belief base, in terms of rule NR3 and NR4.

In fact, it is important to save the departed desire and intention data for the system's run and maintenance. First, the saved data is meaningful for constructing the agent's explanation mechanism, which is necessary for the users to believe in the agents. At the same time, desire and intention data is important character data for building historical negotiation case, which is significant for adding reactive function to the system. For example, case based reasoning negotiation.

VI. CONCLUSION

For negotiation is a combination of logic and utility, the theoretical model supporting for the negotiation behavior of agent need to combine the utility concept with the agent's mental states. BDI-U logic combined with utility provides theoretical foundation for agent's negotiation behavior, and for the analysis, design, realization and other software engineering activity of automated negotiation system. The research result of this paper will be meaningful for the development of a practical automated negotiation system, and will be helpful for the research of interaction and communication mechanism for multi-agent negotiation.

So, the further researches under the logic frame will proceed in two directions. One is applying the decision principles and reasoning rules to design and develop the negotiating agent's software architecture. Another is applying the semantics model of BDI-U logic system to design multi-agent negotiation communication language.

REFERENCES

[1] C. Bartolini, C. Preist and N. R. Jennings, A software framework for automated negotiation. *Software Engineering for Multi-Agent Systems III: Research Issues and Practical Applications*, Springer Verlag 2005, LNCS 3390: 213-235,.

[2] A. R. Lomuscio, M. Wooldridge and N. R. Jennings, "A classification scheme for negotiation in electronic commerce", Int Journal of Group Decision and Negotiation 2003, 12 (1): 31-56.

[3] V. Tamma, M. Wooldridge, and I. Dickinson. An Ontology for Automated Negotiation. *In Proceedings of the Workshop on Ontologies in Agent Systems,* Bologna, Italy, 2002, 7.

[4] N. R. Jennings, P. Faratin, A. R. Lomuscio, S. Parsons, C. Sierra and M. Wooldridge. Automated negotiation: prospects, methods and challenges. *Int. J. of Group Decision and Negotiation*, 2001, 10(2):199-215.

[5] Shaheen S. Fatima, Michael Wooldridge, Nicholas R. Jennings. Bargaining with Incomplete Information. *Annals of Mathematics and Artificial Intelligence,* 2005, 44(3):207-232

[6] E. H. Gerding, R. K. Dash, D. C. K. Yuen and N. R. Jennings. Optimal bidding strategies for simultaneous Vickrey auctions with perfect substitutes. *Proc. 8th Int Workshop on Game Theoretic and Decision Theoretic Agents*, Hakodate, Japan, 2006:10-17

[7] M. Wooldridge. An Introduction to Multi-Agent Systems. John Wiley & Sons (Chichester, England), 2002

[8] Rao A S, Georgeff M P. Modeling rational agents within a BDI-architecture. *In: Proc KR-91, San Mateo, CA: Morgan Kaufmann Publishers*, 1991: 473-484

[9] Hu Shan-li, Shi Chun-yi. An Improved Rational Agent-BDI Model. *Journal of Computer Research & Development*, 2000, 1137(19): 1125-1129

[10] Van Der Hoek W, Wooldridge M. Towards A Logic of Rational Agents. *In Logic Journal of the IGPL*, 2003, 11(2):133-157

[11] Nash J F. The Bargaining Problem. *Econometrica*, 1950, 18:155-162

[12] Xu Jin-hui, Shi Chun-yi. A Model of Mental States Combined with Utility for Agents. *Journal of Software*, 2000, 11(11):1522-1526

[13] Xu Jin-hui, Shi Chun-yi. One Mechanism of Social Commitment Based on Belief-Desire-Intention and Utility. *Journal of Software*, 1999, 10(8): 829-834

[14] B. Chellas. Modal Logic: An Introduction. *Cambridge University Press: Cambridge, England*, 1980.

[15] Michael J. Wooldridge. Reasoning about Rational Agents. *The MIT Press: Cambridge, Massachusetts/London, England*, 2000.

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