Joint intention-based collaboration

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Abstract: Collaboration plays an important role in multi-agent environments. In this paper, a collaboration model based on joint intention will be proposed. Joint intentions are held by multi-agents to keep a team as a whole and inform shared goal with each other. In terms of BDI theory, we construct the short-term memory (STM) which is an important component in consciousness and memory model (CAM) and provides a powerful condition for collaboration of multi-agents. Dynamic description logic (DDL) is used to describe agents' belief, desires and intentions in this paper.

Keywords: joint intention; collaboration; multi-agent; collaborative intelligence.

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1 Introduction

In artificial intelligence, an intelligent agent (IA) is an autonomous entity which observes through sensors and acts upon an environment using actuators (i.e., it is an agent) and directs its activity towards achieving goals (i.e., it is rational) (Russell et al., 2010). Emerging applications require hundreds of agents to coordinate to achieve a joint goal. So it is drawn increasing attention recently.

Autonomous agents exist in our world which composes a large team, they should share a joint intention. In domains such as disaster response or military operation, agents are required to harmonise activities and make the best use of the resources (Chavez et al., 1997). In the complex, real-time and dynamic environment, agents need to coordinate under the condition of limited time and resource, such as resource allocation, task scheduling, avoid collision and so on (Di Paola et al., 2011).

One popular approach to build IA is via the belief-desire-intention (BDI) architecture (Rao and Georgeff, 1991). That architecture models an agent's acting based on intentions and commitments, which subject to its beliefs. It is well accepted and reflected in the theoretical underpinnings of BDI systems that an agent should not pursue a goal that is impossible to achieve. But as a single BDI cognitive agent, it is not enough to express the social behaviours. On the one hand, multi-agents' social behaviours are not the sum of all the single agents; on the other hand, single agent's social behaviour is not the same as the team behaviours.

The abstraction concept of the joint intention is convenience to support, describe and analyse the social behaviour among the agents. Just as individual intention is defined to be a commitment to having done an action knowingly, joint intention is defined to be a joint commitment to the agents' having done a collective action, with the agents of the primitive events as the team members in question, and with the team acting in a joint mental state (Cohen and Levesque, 1991). In this paper, we point out the limitation about the joint intention, and in order to have a comprehensive understanding of the agents' social behaviours.

It is necessary to have a non-formal talk about the joint intention. In multi-agent systems, agents achieve a formula together. Joint intention embody all agents' joint activity selection, so the selective and joint are the basic factors (Mao et al., 2003). Intuitively, joint intention has the following properties

- *Selective*: Intention is the choice of the agent about the future, it will have affect on its activities.
- *Joint*: Joint intention is that which all the team members want to achieve. As a team member, each one knows it specifically and needs collaboration to achieve.
- *Satisfaction*: The satisfaction makes the notion of a formula being true under an interpretation. Then intention is satisfiable means the intention is achievable.
- *Consistency*: Joint intention is the same as the single agent's intention. Different intentions among the team will make the joint intention conflict. What is more, one agent's belief and intention should consistent.
- *Continuity*: Continuity is one of the properties of joint intention. All the agents will keep their intention until it is impossible to achieve or achieved.

As a background, it is interesting that more mice walk together. Each one should have a intention and what is more, they should have a joint intention.

2 Related work

Intention is the notion to characterise both our action and our mental states in our commonsense psychology (Bratman, 1984). While in a collaboration environment, intentions are not sufficient in that teamwork involves more than just the union of the simultaneous individual actions even if they are coordinated (Cohen and Levesque, 1991). As a joint commitment to act in a shared belief state, joint intention binds team members.

Philosophy and computer science have a very deep and unique relation. There are many perspectives about the intention. Joint intention is a crucial part in mind, which has received surprisingly attention. More recently, Grant et al. (2010) presented a detailed investigation of the general problem of intention revision.

Bratman (1999) has argued that in the case of individuals, intentions play certain functional roles: they pose problems; they rule out the adoption of intentions that conflict with existing ones, and so on.

Cohen and Levesque (1990) extend the intention theory. In the work of Cohen and Levesque (1991), they try to illustrate that, among agents, beliefs, desires and intentions have interrelation. And what is more, they point that joint activity is one performed by individuals sharing certain mental properties.

The account of intention is formulated in a modal language that has connectives of a first-order language. First, they define a weak goal, which is used as an agent's decision method. That is the holding conditions and the give up conditions.

$$\begin{aligned}(WGxyp) &\overset{def}{=} \left[\neg(BELxp) \wedge (GOALx\diamond p)\right] \\ &\vee \left[(BELxp) \wedge \left(GOALx\diamond(MBxyp)\right)\right] \\ &\vee \left[(BELx\square\neg p) \wedge \left(GOALx\diamond(MBxy\square\neg p)\right)\right]\end{aligned}$$

Then define the joint persistent goals

$$(JPGxypq) \stackrel{def}{=} (MBxy\neg p) \wedge (MGxyp)$$
$$\wedge \big(UNTIL\big[(MBxyp) \vee (MBxy\Box\neg p) \vee (MBxy\neg q)\big](WMGxp)\big)$$

where

$$(WMGxyp) \stackrel{def}{=} \big(MBxy(WGxyp) \wedge (WGyxp)\big)$$

Then joint intention can be defined as

$$(JIxyaq) \stackrel{def}{=} \Big(JPGxy\Big(DONExy\big[UNTIL(DONExya)\big(MBxy(DOINGxya)\big)\big]?;\, a\Big)q\Big)$$

Above formulas define the joint intention, but they lack the expression of the selective. Selective is one of the most important properties in joint intention theory.

3 CAM architecture

Since firstly proposed in 1956, AI has made great process and success. Mind is a very important issue in intelligence; it is also a hard problem. A mind model called consciousness and memory model (CAM) is proposed by Intelligence Science Laboratory of Institute of Computing Technology (Shi and Wang, 2011).

CAM is mainly based on consciousness and memory. One of the main tasks in intelligence science is mind modelling which tries to model the human mental activity, such as perception, learning, memory, thinking, consciousness. Here, the mind is defined as thinks, reasons, perceives, wills, and feels. In intelligence science area, a mind model is intended to be an explanation on the problem of how to use a set of primitive computational process to implement some aspects of cognitive behaviours.

Memory is defined as the function of human brain to reflect the things that take places in the past and as knowledge to be used in the future. Because of the existence of memory, people could retain past responses, make present reactions on the basis of the past, and enable the reflections to be deeper and more comprehension. According to the temporal length of memory operation, there are three kinds of human memory: sensory memory, short-term memory (STM) and long-term memory.

The memories are used to store different definition of concepts, actions, events and so on. The STM stores the knowledge or belief about the current world and the goal/sub-goal that the system intend to achieve.

- *Visual model*: From lateral geniculate nucleus (LGN) neuron send their signals to the primary visual cortex V1.
- *Hearing model*: The auditory module is comprised of many states and pathways from ear to brain. Some of the information from the environments and some from its neighbours as a token.
- *Sensory buffer*: A brief storage that store the information.
- *Working memory*: The working memory is located at the prefrontal cortex. It is the central executive of the cognitive entity. It knows the team status, domain knowledge and team conative ability.

- *STM*: It stores the agent's beliefs, goals and intention as the environments changes. It also stores the joint intention.
- *Long-term memory*: It stores semantic, episodic and procedural knowledge, which change gradually.
- *Consciousness*: The primary focus is on global workspace theory, motivation model, attention, and the executive control system of the mind in CAM.
- *Action selection*: It is the process of constructing a complex composite action from atomic actions to achieve a specific task.
- *Response output*: The motor hierarchy begins with general goals, influenced by emotional and motivational input from limbic regions. The primary cortical motor region directly generates muscle-based control signals that realised a given internal movement command.
- *High level cognitive functions*: It includes a class of high level cognitive functions which perform cognitive activities based on the basic cognitive functions supported by the memory and consciousness components of CAM.

In CAM, knowledge representation is based on dynamic description logic (DDL) which is an extension of description logic (Shi et al., 2004). It introduces the notion of action into the description logic system in order to support the representation and reasoning of dynamic knowledge (Shi et al., 2004). DDL represents and reasons dynamic knowledge based on the notion of actions. DDL includes TBox, ABox and ActBox. TBox contains intensional knowledge in the form of terminology, and ABox contains assertion knowledge, and ActBox contains all the action.

An atomic action in DDL is a tuple $\alpha \equiv <P, E>$, where

1 $\alpha \in N_A$ is the name of the atomic action.

2 P is a set of formulas which specifies the precondition that should be satisfied when the action is executed.

3 E is a set of formulas that specifies that effect of action execution.

Beside the atomic action, the DDL allows to define the complex actions which are constructed based on atomic actions. The following are the rules to construct complex actions.

$$\pi, \pi' \to \alpha \,|\, \phi ? \,|\, \pi \cup \pi' \,|\, \pi; \pi' \,|\, \pi *$$

where α is an atomic action and ϕ is a formula in DDL. The action in form of ϕ? is named as test action which tests whether ϕ is hold. Action in form of $\pi \cup \pi'$ is named as select action which represents a selection between π and π'. Action in form of $\pi;\ \pi'$ is named as sequence action which represents an action that sequentially executes action π and π'. Action in form of ϕ* is named as iteration action. The iteration action represents an action that iteratively executes action π. The complex action can be used to represent programme control flows. For example, the programme fragment: 'if ϕ? then π else π'', can be rewritten into a complex action $(\phi ?; \pi) \cup ((\neg \phi ?); \pi')$.

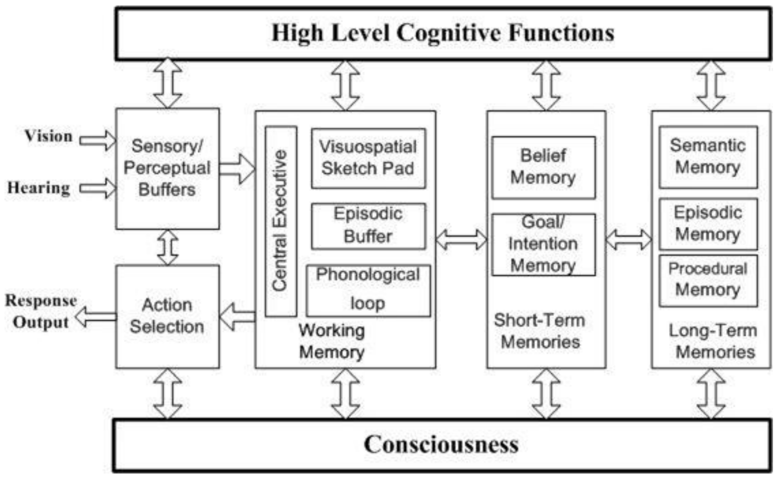
Knowledge base (KB) in DDL can be divided into three components which are TBox, ABox and ActBox. The definitions of TBox and ABox are same as those in description logic. The ActBox is defined as a finite set of definitions on atom actions and complex actions.

The TBox introduces the terminology, i.e., the vocabulary of an application domain, while the ABox contains assertions about named individuals in terms of this vocabulary. The vocabulary consists concepts, which denote sets of individuals, and roles, which denote binary relationships between individuals. In addition to atomic concepts and roles, add DL systems allow their users to build complex descriptions of concepts and roles. Important problems for an ABox are to find out whether its set of assertions is consistent that is, whether it has a model, and whether the assertions in the ABox entail that a particular individual is an instance of a given concept description (Baader, 2003). The ActBox introduces the action to the description logic.

4 DDL-based STM

Memories are the core components of the CAM. Different memory plays different role in the cognitive process; the following section will mainly introduce STM. STM provides agent's beliefs, goals and intention contents. As the dynamic of the environment, they change rapidly.

Figure 1 Extended architecture of CAM



As illustrated in Figure 1, STM involves two subcomponents, belief memory and goal/intention memory. STM implements the principal aspects of Bratman's (1999) theory of human practical reasoning. There are several reasons for its success, but perhaps the most compelling is that the BDI model combines a respectable philosophical model of human practical reasoning, which has been taken up widely within the agent research community. BDI is a cognitive model developed for programming IAs. Superficially characterised by the implementation of an agent's belief, desires and intentions, it actually uses these concepts to solve a particular problem in agent programming.

Many pre-defined sets of plans stored in a plan library. A plan library will also be included. In our implementation, we use ActBox to express the library. Each plan has preconditions and terminations, then an action expressed.

Belief is updated in a dynamic and uncertain environment. Beliefs are the facts representing what an agent believes about the world. An agent may obtain the beliefs from sensing their world or base on the internal inferences. Belief memory stores agent's current beliefs. Sensors provide inputs to this belief memory in terms of beliefs. The information will be transferred to Abox, by taking the advantage of Tbox, a belief generated.

Goal/intention memory stores agent's current goals and intention.

Desires are that they wish to satisfy. They are goals or some desired end states. Different goals can be achieved, but only one will be selected. With the help of Abox, Tbox and ActBox, desire will be generated.

As the goal selected, then one intention is specified. Intentions refer both to an agent's commitments to its desires and its commitment to the plans that could achieve the goal. Intentions should not to conflict with each other. An intention implies that when committed to achieving a goal, an agent must believe it is committed to that goal. Then agent will use Abox, Tbox and ActBox to generate proper actions.

The central executive is the core in working memory, which drives and coordinates the belief memory and goal/intention memory. All the Abox, Tbox and ActBox are in central executive engineer.

Joint intention theory stipulates what is means for agents to execute actions as a team. This same theory is used to specify formal semantics of communicative acts as an extension of standard speech act theory (Kumar et al., 2002). Joint intention theory is expressed in a modal language, along with operators for propositional attitudes and event sequences. An action expression consists of concurrent actions, sequence actions, test actions, non-determined choices and indefinite choices (Subramanian et al., 2006).

In CAM, the BDI theory implementation is:

1 *Belief*: Belief is the assertion about the named individuals in terms for vocabulary. By using concepts *C* and roles *R*, one can make assertions of the two kinds. First, concept assertions $C(a)$, one states that *a* belongs to *C*, and the second is called role assertions $R(b, c)$, one states that c is a filler of the role *R* for *b*.

2 *Desire*: Desire is the goal that the agent want to achieve. So we can define the goal as: $\mathcal{A}$ is the action set, $\mathcal{L}$ is the formula assertion set, $\mathcal{G}$ is the goal set

- $\mathcal{A} \in \mathcal{G}$, action in set $\mathcal{A}$ is basic action
- if $\varphi \in \mathcal{L}$, achieved $(\varphi) \in \mathcal{G}$
- if $\varphi \in \mathcal{G}$, $\varphi? \in \mathcal{G}$
- if $\delta_1, \delta_2 \in \mathcal{G}, \delta_1; \delta_2 \in \mathcal{G}, \delta_1 \cup \delta_2 \in \mathcal{G}, \delta_1^* \in \mathcal{G}.$

There are three ways to generate the goal.

- System designer sets the goal or the goal will be selected when the system initialising.
- CAM observes the dynamic of the environment and generates the goal.
- CAM generates the goal mainly stem from its inter state

The goal generation rule can be expressed as $\varphi_1, \ldots, \varphi_n \Rightarrow \delta$. $\varphi_1, \ldots, \varphi_n$ is the assert formula, and is the generated goal. When the goal is impossible to achieve, CAM needs to change it. There are three kinds to change the goal

- CAM has the ability to achieve the goal, but as some conditions can not be satisfied, the goal should be change. If the job is an instant one, then CAM should do it in limited time or give up or give the job to another one. If the job is sensitive to agent, and the goal has high priority, then the executing goal changed. If the job has relation to time, then put the job to the job queue.
- If CAM can only achieve partial goal, then CAM drops the remaining part or even give up the goal.

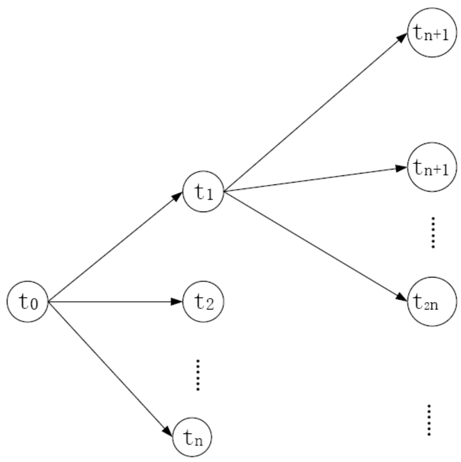
3 *Intention*: Intention is one of the desires that agent wants to achieve. Although one agent has many goals at the same time, only one goal will be selected according to the conditions.

5 Collaboration

Multi-agent systems are computational systems in which a collection of loosely autonomous agents interact to solve a given problem. The BDI approach is one of the major approaches to building agents and multi agent systems. As the given problem is usually beyond the agent's individual capabilities, agent needs to exploit its ability to cooperate and communicate with its neighbours. In that situation, coordination plays a fundamental role, since it allows agents to interact the one with the other in a productive way. To coordinate an interaction between multiple agents, each agent must know its constrains on when to send and receive messages (Robertson, 2004). Some multi-agent systems are referred as intentional systems, so they should have a joint intention.

In the joint intention theory, a team is defined as "a set of agents having a shared objective and a shared mental state". Joint intentions are held by the team as a whole, and require each team member to inform others whenever it detects the goal state change, such as goal achieved or the goal is no relevant.

Figure 2 Joint intention model



Agent joint intention means agent wants to achieve a formula, which corresponds to agent's goal. The formal expression model of the joint intention is a multi-way tree. Points mean time stamp, and line between the points is action. As Figure 2 illustrated the joint intention model.

Before the joint intention, each agent has three basic knowledges: first, each one should select ϕ as its intention; second, each one knows its neighbours who also select the intention ϕ; and last, each one knows they are a team. But how they know each other?

As the agent CAM is based on DDL, there is a DDL knowledge expressing in each agent's working memory's central executive module.

In order to help agent infer from other agents, there is distributed description logic (Borgida and Serafini, 2003). Later, this technology is used to the DDL (Jiang et al., 2006).

There are five basic components: many of the KBs KB_i, KB_j, KB_k, …, distributed Abox, distributed Tbox, distributed ActBox and the inference method.

Definition 1: Given concepts C and E of KB_i and KB_j respectively, and action α and β respectively, bridge rule from i to j is an expression of the following forms:

$i : C \xrightarrow{\sqsubseteq} j : E$; into concept bridge rule

$i : C \xrightarrow{\sqsupseteq} j : E$; onto concept bridge rule

$i : \alpha \xrightarrow{\sqsubseteq} j : \beta$; into action bridge rule

$i : \alpha \xrightarrow{\sqsupseteq} j : \beta$; onto concept bridge rule

An into-bridge rule specifies that C object in KB_i correspond to E object in KB_j, while onto-bridge states that every object in E has a corresponding pre-image in C of KB_i. Bridge rule has direction, that is if i to j has a bridge, we can not simple say that j to i also has a bridge.

Definition 2: If x is an individual in KB_i, while y_1, y_2, … are individuals of KB_j, then

$i : x \longrightarrow y : y$; partial individual correspondence

$i : x \xrightarrow{=} j : \{y_1, y_2, ...\}$; complete individual correspondence

The first kind is x in KB_i corresponds to partial individual expression y in KB_j, then the second kind is x in KB_i corresponds to complete individual expression y in KB_j.

Definition 3: Given a set I of indexes, a distributed Tbox $DTB = \langle \{T_i\}_{i \in I}, \mathfrak{B} \rangle$ contains a set of Tboxes $\{T_i\}_{i \in I}$, and a set $\mathfrak{B} = \{\mathfrak{B}_{i,j}\}_{i \neq j \in I}$ of bridge rules from T_i to T_j. For every $k \in I$, all descriptions in T_k must be in the corresponding the DDL language.

Definition 4: A distributed Abox $DAB = \langle \{A_i\}_{i \in I}, \mathfrak{C} \rangle$ contains a set of Aboxes $\{A_i\}_{i \in I}$ and a set $\{\mathfrak{C}\}_{i \neq j \in I}$ of partial or complete correspondences from A_i to A_j. For every $k \in I$, all descriptions A_k must be corresponding the DDL language.

Definition 5: Given a set I of indexes, a distributed ActBox $DActB = \langle \{Act_i\}_{i \in I}, \mathfrak{D} \rangle$ contains a set of $\{Act_i\}_{i \in I}$, and a set $\mathfrak{D} = \{\mathfrak{D}_{i,j}\}_{i \neq j \in I}$ of bridge rules from Act_i to Act_j. For every $k \in I$, all descriptions Act_k must be corresponding to the DDL language.

Definition 6: A distributed KB is *DKB* = <*DTB*, *DAB*, *DAactB*>. DTB is distributed Tbox, DAB is distributed Abox, and DActB is distributed ActBox.

Now we provide semantics for the distributed agents by using local interpretations, and using relations $\boldsymbol{r}_{ij}$ to their KB.

Definition 7: A distributive interpretation $DI = (\{\mathfrak{I}_i\}_{i \in I}, \boldsymbol{r})$, DI is the KB_i's sematic interpretation. Binary relation $\boldsymbol{r}_{ij} \in \Delta^{\mathfrak{I}_i} \Delta^{\mathfrak{I}_j}$. $\Delta^{\mathfrak{I}_i}$ and $\Delta^{\mathfrak{I}_j}$ are the agent's interpretation domain.

Definition 8: A distributed interpretation $DI = (\{\mathfrak{I}_i\}_{i \in I}, \boldsymbol{r})$, satisfies Tbox $DTB = \langle \{T_i\}_{i \in I}, \mathfrak{B} \rangle$, written $(DI \vDash_d)$. For every $i, j \in I$

$DI \vDash_d i : C \xrightarrow{\sqsubseteq} j : E$, if $\boldsymbol{r}_{ij}(C^{\mathfrak{I}_i}) \sqsubseteq E^{\mathfrak{I}_j}$;
$DI \vDash_d i : C \xrightarrow{\sqsupseteq} j : E$, if $\boldsymbol{r}_{ij}(C^{\mathfrak{I}_i}) \sqsupseteq E^{\mathfrak{I}_j}$;
$DI \vDash_d i : C \xrightarrow{\sqsubseteq} j : E$, if $\mathfrak{I}_i \vDash C \sqsupseteq E$;
$DI \vDash_d T_i :$ if $\mathfrak{I}_i \vDash T_i$;
$DI \vDash_d DTB$, if for every $i \in I$,
$DI \vDash_d T_i$, satisfy every bridge rule in $\mathfrak{B}$;
$DI \vDash_d i : C \sqsubseteq i : E$, if for every distributed interpretation DI,
$DI \vDash_d DTB$ implies $DI \vDash_d i : C \sqsubseteq E$.

Definition 9: A distributed interpretation $DI = (\{\mathfrak{I}_i\}_{i \in I}, \boldsymbol{r})$ satisfies the elements of a $DAB = \langle \{A_i\}_{i \in I}, \mathfrak{C} \rangle$ according for the following clauses. For every $i, j \in I$

$DI \vDash_d i : x \longrightarrow j : y$, if $y^{\mathfrak{I}_i} \in \boldsymbol{r}_{ij}(x^{\mathfrak{I}_i})$;
$DI \vDash_d i : x \xrightarrow{=} j : \{y_1, y_2, ...\}$, if $\boldsymbol{r}_{ij}(x^{\mathfrak{I}_i}) = \{y_1^{\mathfrak{I}_i}, y_2^{\mathfrak{I}_i}, ...\}$;
$DI \vDash_d i : C(a)$, if $\mathfrak{I}_i \vDash C(a)$
$DI \vDash_d i : P(a, b)$, if $\mathfrak{I}_i \vDash P(a, b)$
$DI \vDash_d i : A_i$, *i*ff $DI \vDash_d i : \pi$, for every assertion $\pi = C(a), P(a, b)$ in A_i;
$DI \vDash_d i : DAB$, if for every $i \in I$
$DI \vDash_d i : A_i$ satisfies every individual correspondence in $\mathfrak{C}$.
$DI \vDash_d i : C(a)$, if for every distributed interpretation $\mathfrak{C}$,
there is $DI \vDash_d DAB$ implies $DI \vDash_d i : C(a)$;
$DI \vDash_d i : P(a, b)$, if for every distributed interpretation $\mathfrak{C}$,
there is $DI \vDash_d DAB$ implies $DI \vDash_d i : P(a, b)$.

Definition 10: A distributed interpretation $DI = (\{\mathfrak{I}_i\}_{i \in I}, \boldsymbol{r})$ satisfies Tbox $DActB = \langle \{Act_i\}_{i \in I}, \mathfrak{D} \rangle$, written $(DI \vDash_d)$. For every $i, j \in I$

$DI \vDash_d i : \alpha \xrightarrow{\sqsubseteq} j : \beta$, if $r_{ij}(\alpha^{\Im_i}) \sqsubseteq \beta^{\Im_j}$;

$DI \vDash_d i : \alpha \xrightarrow{\sqsupseteq} j : \beta$, if $r_{ij}(\alpha^{\Im_i}) \sqsupseteq \beta^{\Im_j}$;

$DI \vDash_d i : \alpha \xrightarrow{\sqsubseteq} j : \beta$, if $\Im_i \vDash \alpha \sqsubseteq \beta$;

$DI \vDash_d Act_i$: if $\Im_i \vDash Act_i$;

$DI \vDash_d DActB$, if for every $i \in I$, $DI \vDash_d ActB_i$, satisfy every bridge rule in $\mathfrak{D}$;

$DI \vDash_d i : \alpha \sqsubseteq i : \beta$, if for every distributed interpretation DI,

$DI \vDash_d DActB$ implies $DI \vDash_d i : \alpha \sqsubseteq \beta$.

Definition 11: A distributed interpretation $DI = (\{\Im_i\}_{i \in I}, \boldsymbol{r})$ satisfies *DKB* =<*DTB*, *DAB*, *DActB* > written as $DI \vDash_d DKB$, iff *DI* satisfy $DI \vDash_d DTB$, $DI \vDash_d DAB$, $DI \vDash_d DActB$.

For the inference, we can let the distributed KB to a uniform KB. Then all the KBs looks like a single one.

Through the bridge, agents can mutual know the intention and mutual know they are in a team and require collaboration.

6 Conclusions

It is necessary for the multi-agent environment to consider the collaboration. At this point, we have exhibited the multi-agent collaboration problem based on joint intention. Joint intention characteristic is that each agent should have joint intention which they know and have the demand to collaboration. STM is one of the three memories of the CAM system which supports the BDI theory. It contains two parts, one is belief memory and the other is goal/intention memory. In order to support the distributed attributes, we use the bridge rule based on DDL. We utilise the distribute DDL theory to transform the distributed KB to a uniform one, *DKB* =<*DTB*, *DAB*, *DActB* >.

Now we are working on the parallel reasoning for multi-agent system which will be applied to the brain machine integration.

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