Knowledge Organization and Logical Description for Multi-Agent Tactical Plan Recognition

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Summary

Recent applications of plan recognition require observing agents whose behavior is reactive, in that the observed agent may be so intelligent as to coordinate their plans. With the analysis of these domain characteristics in military plan recognition, we propose that the multi-agent tactical plan recognition is essentially a problem about abduction, and detail the knowledge organization and logical description by extend the discussion of real military tactical problem which forms the foundation of the logical links between the elements in tactical plan recognition process, finally a recognition algorithm is introduced with the basis of former abduction framework. .

Key words:

plan recognition; knowledge organization; logical description; course of action;

1. Introduction

Since plan recognition is proposed as a special issue by Schmidt [1], it has been widely applied to varied fields. Plan recognition is the process of inferring other agents' plans, based on observations of their interaction with environment. Two classes of plan recognition problem that are generally distinguished as: intended plan recognition and keyhole plan recognition. Keyhole plan recognition' main application is in the fields of natural language understanding, etc. and intended plan recognition lies mainly in cooperative or gaming fields with opposability. Furthermore, plan recognition can be also categorized as plan library based recognition and none plan library recognition. Correspondingly, focus of this paper, tactical plan recognition, appears as a plan library based intention recognition process.

To establish a applicable intention recognition system, task of knowledge acquisition seems critical which should be accomplished by the knowledge engineer and domain expert. However, for the plan recognition technique, foremost task is the organization and logical description of domain knowledge, which builds the fundamental and crucial blocks of the latter recognition. Recently, some representative work have appeared in the intended plan recognition area such as Azarewicz, NATO Data Fusion projects and Tambe, etc [3]. but their work only concerns different part of the problem without common assents to a unified recognition framework which heavily blocks the development and application of intention recognition in relative fields.

Aiming at the current problems above, this paper makes great efforts to establish the knowledge organizing structure and logical description framework for the multi-agent tactical intention recognition based on the analysis of the domain characteristics so as to form a formal theoretic for the latter research.

2. Domain characteristics

Comparing to applications in other fields, the military plan recognition contains more complexity caused by the complexity of war gaming itself. So it's necessary to fully understand the domain characteristics in military field. [4]：

1）The military plan recognition includes the distributive source and agents within the battlefield, the result of recognition is not only a certain agent's actions or intention, but also the multi-agent, group agent and multi-group agent' common tactical intention during the COAs (Course of Actions) of them. So efficient plan recognition should deals much about the agents' autonomy and the cooperation and influence between them.

2）The situation of battlefield evolves with highly dynamic factors, which need the recognition process to concerns much on the dynamic restricts between the agents' actions.

3) The source of uncertainty and its propagation should be fully considered, it include the uncertainty of evidence with the observation and the match between the plan library and evidence which brings the uncertainty propagation and integration. When establishing the plan

library, we should take account of these factors enough.

4）The enemy intention to be recognized may be at strategic, operational or tactical level. Although the fact and trend is that the three levels overlap more and more with each other, comparatively the strategic and operational intention mainly behave as a pure subjective analyzing process which make people hard to model it, so the recognition level for us is still staying at the tactical level.

In conclusion, what the military plan recognition seeks for is the tactical intention of the hostile multi-agents, whose outstanding features appears distributive, dynamic and uncertain. During the plan recognition process the enemy agents would try to cover its latent intention, so it's a typical multi-agent tactical intention recognition problem.

3. General description

In the course of enemy intention recognition, after analyzing the mutual situation the commander may draw a conclusion such as: our commander as the observer, inversely the hostile agents being observed, the observer gives a interpretation 'the agents may wish to achieve the goal (*G*) by a certain plan hypothesis (*H*) ', based on the plan library (*PL*) and the evidence by observation (*O*). So defines:

O as observation set, *PL* as the observed agents' background knowledge, *H* as hypothetical plan set of the hostile agents. Then the tactical intention recognition could be treated as a interpretation for *O* from *H* and *PL*, which embodies an abduction problem composed of a triple <*PL, O, H*>.

Definition 1: $Abduce(PL, O) = H$ iff

1) $PL \not\models O$;

2) $H \cup PL \models O$;

3) $H \cup PL \not\models False$;

4) No subset of *H* have character 1), 2), 3) ;

Description above uncovers the essentials of the multi-agent tactical intention recognition; with the basis of it we could extend analysis of the knowledge organization and logical description which forms the logic base of practical tactical plan recognition.

4. Knowledge organization and logical description of PL

Multi-agent intention recognition covers different level varying from the single agent to the tactical agent, as a result it comes down to the cognition of low-level agent, multi-agent *COAs* and high-level tactical doctrine. So we can organize the hierarchy of *PL* according to these levels above.

Define *Tac* as tactical doctrine set, *C* as *COA* set, *B* as single-agent action event set, H_{SA} as single-agent plan hypothesis, H_{MA} as multi-agent plan hypothesis, H_{TA} as tactical plan hypothesis, then give:

Definition 2: $PL = Tac \cup C \cup B$ iff

$$B \cup H_{SA} \models O$$
$$B \cup C \cup H_{MA} \models O$$
$$B \cup C \cup Tac \cup H_{TA} \models O$$
$$B \cup C \cup Tac \cup H \not\models False$$

Definition 4.1 briefly depicts the levels of *PL* and its corresponding interpretation for the process of plan recognition. Sections below will detail them and extend the discussion on the modeling and organization of the plan elements within the *PL*.

4.1 Single-agent 'event hierarchy'

Conclude from the angle of task decomposition, each of the distributive agents in battlefield shoulders a certain task which decides its actions, and actions consequently contain the latent intention. To recognize the intention one must establish the PL about the observed agent, and interpret intention with the hypothetical plan. But different agent may have different combat method and pattern, so it leads to different *PLs* accordingly. However the scale of the distributive agents may be too large to make it impossible to establish *PLs* for agents respectively. So clustering and classification need to be introduced.

Assume the battle-space is filled with distributive agents *o*:

$$A = \{o_1, o_2 ... o_k ... o_l\}, 0 < k < l$$

Classify the agents we get the corresponding entity type T_i,

$$Classifier(A) = \{T_i \mid 0 < i < n\}$$

$$\bigcup_i^n T_i = A, \quad \forall i \neq j, T_i \cap T_j = \phi, 0 < i, j < n$$

In the possible agent types there may be some 'abstract type' beyond the types above. For instance: the observation tells that a ship appears, but it's uncertain to say it's a fisher or warship, or it's uncertain to tell it's a mine sweeper or destroyer, in this condition the observation gives us a abstract agent type information 'surface ship'. This example tells us that the agent types forms a hierarchy, where:

$$\forall o, T_j(o) \supset T(o)$$

means type *T* abstracts agent type T_j , and

$$\forall o, T(o) \supset T_1(o) ... \vee T_i(o) ... \vee T_n(o), \text{i=1,2...n}$$

means type *T* includes several type $T_1 ...... T_n$, also we define that there existing no agent *o* or agent type *T*, belongs to the upper abstract type T_i, T_j both :

$$\forall o, \neg T_i(o) \vee \neg T_j(o), i \neq j \quad or$$

$$\forall o, T(o) \supset \neg T_i(o) \vee \neg T_j(o), i \neq j$$

After the classification of the agents, we need to establish the *PL* for the corresponding agent type T_i , the instantiation of T_i have the same *PL*, thereby controls the scale of *PLs* in the plan recognition system.

Work to establish the *PL* is essentially to find the single-agent action sequences exhaustedly and organize them logically. Here we suppose the knowledge acquisition of most ordinary agents is complete, that is to say the single-agent 'event hierarchy' satisfies the close world hypothesis. Then the organization of single-agent *PL* can follow the method proposed by Kautz[2] :

Definition 3 : Each agent type includes independent *PL* as $< T_i, P_i >, B = \overset{n}{\underset{i=1}{\vee}} P_i$, P_i is the knowledge of observer about instantial agents of T_i. it's composed by a series of action event type *E*, to realize the finite search, suppose *E* forms an acylic event hierarchy *P*, *P* decomposes as

$$P_E\, ,P_A\, ,P_{EB}\, ,P_D\, ,P_G\, .$$

（P_E is event type set, P_{EB} is basic event type set, P_A is abstract axioms set, P_D is decompose axioms set, P_G is none-correlative axioms set：

1） $P_A : \forall a, (E(a) \supset E'(a))$

E directly abstract *E'*, a is the agent's action.

2） P_A: $\forall a, E(a) \supset E_1(a) \vee ... \vee E_n(a)$

event type *E* directly abstracts $E_1 \ldots E_n$;

$$\forall a, \neg E_i(a) \vee \neg E_j(a), i \neq j$$

E_i and E_j both abstract from *E*;

3） P_D :

$$\forall a, (E(a) \supset (E_1(step_1(a)) \wedge ... \wedge E_n(step_n(a)) \wedge r)$$

E decomposes to $E_1 \ldots E_n$, *r* is temporal restricts;

4）Suppose P has no insignificant event, that is: event a must belong to top event type E_{top} or components of other event type:

$$\forall a, E_{ij}(a) \supset E_{top}(a) \vee \exists y_1, E_1(y_1) \wedge (f_{1j}(y_1) = a)...$$
$$\vee \exists y_m, E_m(y_m) \wedge (f_{mj}(y_m) = a)$$

With rules detailed above, we can get the embodiment and extension of single-agent *PL P*. Given the observed agent belongs to T_i with *PL* P_i , then with the new evidence O_i by observation we can work out plan hypothesis H_{SA}, which means:

$$P_i \cup H_{SA_i} \models O_i \text{ and } B = \overset{n}{\underset{i=1}{\vee}} P_i ,$$

$$\text{get } B \cup H_{SA} \models O$$

4.2 Multi-agent COA

Single-agent's action sequences directly indicate the intention of pursuing its goal, so reasonable to say it maybe easy and simple to recognize the single-agent intention by developed battlefield perception. However, in the real war gaming process, recognizing the single-agent's intention is far from enough, it's more critical to recognize the multi-agent's high level goal which lies in the diversified *COAs* of them. So extending discussion to the multi-agent level and fully considering the relations between and contribution to upper tactical goal are far more important[2][6].

In modeling the single-agent plan, Kautz's idea of 'event hierarchy' seems appropriate, when extended to multi-agent level, it may cause some problems. Given:

$$G \supset A(step_1(G)) \wedge B(step_2(G) \wedge C(step_3(G)) \wedge r)$$

the default sequence of action node *A*, *B* and *C* is *Time(A)<Time(B)<Time(C).*

Think at single-agent level, if the occurrence of action A endures a time interval but not instantaneous, then the temporal relation would be no longer 'before or after' choice.

Think at multi-agent level, if actions *A*, *B* are executed by different agent, then *Time(A)>Time(B) or Time(A)<Time(B)* maybe possible both. This would bring the confusion of the action analysis, so the multi-agent *COA* hierarchy should be extended beyond the 'event hierarchy'.

Lemma 1：Define time interval variable $i = < i_s, i_e >$, i_s as starting time, i_e as end time. Relation *r* is the thirteen basic temporal relation:

$$r = \{=, \mathrm{p}, during, overlap, meet, start, finish\}$$

And the latter six converse relation. [5]

Definition 4: Define *a(i)* as the description of action *a* about interval *i*, multi-agent actions *a(i)* constitutes finite set:

$$\Psi = \{a_k(i) \mid k = 1, 2...n\}$$

The temporal relation set between *a(i)* is:

$$R = \{r(a_p(i), a_q(j)), p \neq q, p, q = 1, 2...k\}$$

R satisfy the axioms system ξ :

validity:

$$(i \mathrm{\ r\ } j) \vee \neg (i \mathrm{\ r\ } j)$$

equality:

$$i = i, (i = j) \supset (j = i)$$
$$,(i = j) \wedge (j = k) \supset (i = k), (i = j) \supset (A \equiv A(j/i))$$

reversibility：

$$(i\ r\ j) \equiv (j\ r'\ i)$$
$$r = \{\mathrm{p}, during, overlap, meet, start, finish\}$$

transitivity：

$$(i\ r1\ j) \wedge (j\ r2\ k) \supset i\ (T(r1, r2))\ k$$

totality:

$$i(=, \mathrm{p}, \mathrm{f}, d, d', o, o', m, m', s, s', f, f')\, j$$

exclusivity：

$$\neg(i\ r1\ j) \vee \neg(i\ r2\ j)$$

Axioms system provides the soundness and completeness for *R*.

Definition 5：define multi-agent plan library

$$C = < T, \Psi, R >$$

T is the agent type set included in the COA, Ψ is the instantial agent's *PL* according to *T*, R is the temporal relation set between *a(i)* .

With definition 5, when getting new evidence *O* as multi-agent's actions set *{a(i)}*, conclusions can be made as:

$$B \cup C \cup H_{MA} \models_{\xi} a(i),$$

$$B \cup C \cup H_{MA} \models_{\xi} r(a_p(i), a_q(j))$$

$$\text{Get: } B \cup C \cup H_{MA} \models_{\xi} O$$

4.3 Tactical agent doctrine

Cognition of multi-agent *COA* embodies the process of 'some hostile agent how to do' whereas cognition of tactical doctrines tells a process of 'who do what'. So plan organizing of tactical agent contains mainly work on task decomposition and source distribution [6].

Definition 6：Define the tactical doctrine set as *Tac*, possible tactical goal set *G* in *Tac*,

$$Tac \supset G_1 \vee ...G_i ... \vee G_n$$

Suppose the final result of *G* to be recognized is one and single, that is:

$$\neg G_i \vee \neg G_j, i \neq j, 1 \leq i, j \leq n$$

Then decompose goal G_i as below:

1） $G_i \supset TA_{i1} \wedge ...TA_{ik} ... \wedge TA_{im} \wedge f_i(k)$

G_i is the possible goal, G_i decompose to TA, the decomposing process contains much subjectivity, so give $f_i(k)$ as power distribution function for TA_{ik} which means the sub-task's role in the realization of G_i.

2） $TA_{ik} \overset{ab}{\supset} \overset{q}{\underset{j=1}{\wedge}} (T_j, f_{ab}(T_j)), 1 \leq j \leq q$

To TA_{ik}, the recognizer should allocate the agent source T_j based on the ability $f_{ab}(T_j)$ needed by TAik ,

As depicted before, the decomposition of tactical goal G_i to TA_{ik} tells that the agent type may have the ability to accomplish the sub-task TA_{ik}, it shows the prior knowledge 'who can do what', then through the instantiation of T_j and matching the *COA* at the multi-agent level, we can link the three levels to a whole plan library for tactical plan recognition. That is:

$$B \cup C \cup Tac \cup H_{TA} \models O,$$

$$PL \cup H \models O$$

5. Recognition algorithm

Based on the discussion about the actual characteristics of real war gaming area, we established a multi-level structure covering from the single-agent actions to high level tactical plan. With this framework a multi-agent plan recognition algorithm can be given as below:

Step1 $PL = Tac \cup C \cup B$ includes:

$Tac \supset G_1 \vee ...G_i ... \vee G_n$

$G_i \supset TA_{i1} \wedge ...TA_{ik} ... \wedge TA_{im} \wedge f_i(k)$

$TA_{ik} \overset{ab}{\supset} \overset{q}{\underset{j=1}{\wedge}} (T_j, f_{ab}(T_j)), 1 \leq j \leq q$

$C = < T, \Psi, R >$

$< T_i, P_i >, B = \overset{n}{\underset{i=1}{\vee}} P_i$

Step2 $O: A = \{o_1 ... o_i ... o_n\}, 0 < i < n$;

$Classifier(A) = T = \{T_i \mid 0 < i < n\}$;

Instantiate $< T_i, P_i >$;

Step3 *if* $T_C \supset T$

（T_C: agent types contained in *COA*）

then

Instantiate $< T_C, P_C >$;

Step4 *Verify* temporal relations with *R*

if

$R \not\models \{r(a_p(i), a_q(j)), p \neq q, p, q = 1, 2...k\}$ *then*

prune $a_p(i)$ *or* $a_q(j)$

Step5 *if* $T_j \supset T_C$, $TA_{ik} \overset{ab}{\supset} \overset{q}{\underset{j=1}{\wedge}} (T_j, f_{ab}(T_j))$

then

Instantiate $(TA_{ik}, G_i) \supset H_{TA}$

Step6 *got new* evidence *O'*

if $PL \cup H_{TA} \not\models O'$

do Step2-Step5

end-if

Step7 *Select* candidate *Plan Hypothesis*

Comparing to the algorithms before, we can found the advantages of our algorithm to others: Firstly, what we want to recognize is the multi-agent tactical goal which involves the complex background of different agent types. Secondly: the action nodes in the basic single agent's PL can be continuous instead of the discrete, instantaneous and none-parallel nodes before. Thirdly: with step4-step5, it realized a pruning process which reduces the plan hypothesis space and improves the speed of recognition.

6 Conclusions

Aiming to establish the basic logical reasoning framework for intended plan recognition, in this paper we analyzed the domain characteristics and presented a three level structure of plan library for tactical plan recognition, and realized a formal description based on the abduction logic.

But our work covers only in the scope of knowledge organization; it only indicates the logical links among the elements involved in the plan recognition process, the results may be a lot of candidate plan hypothesis. So the next step is to mine the uncertainty varying from the battlefield perception to the subjectivity in the task decomposition, and bind the uncertainty with our knowledge structure to dynamically observe and select the comparative best plan hypothesis. This will be the focus of our future work.

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