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THE INTEGRATED AGENT IN MULTI-AGENT SYSTEMS

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In this paper, we characterize the integrated agent in multi-agent systems. The following result is proved: if a multi-agent system is reflexive (symmetric, transitive, Euclidean) then the integrated agent of the multi-agent system is reflexive (symmetric, transitive, Euclidean), respectively. We also prove that the analogous result does not hold for multi-agent system's serial ness. A knowledge relationship between the integrated agent and agents in a multi-agent system is presented.

Keywords: integrated agent, knowledge operators, multi-agent systems, reasoning about knowledge.

1. INTRODUCTION

The theory of knowledge investigates reasoning about knowledge, in particular, reasoning about the knowledge of agents who reason about the world and each other's knowledge. This theory is given in [1], [2], [3], and [4].

A multi-agent system (MAS) is any collection (group) of interacting agents, [1]. Incorporating knowledge and time into MAS is described in [6]. Some important relationships between temporal operators and knowledge operators are given in [5] and [7].

In this paper, we define an integrated agent in MASs. We prove that the integrated agent for an MAS is reflexive (symmetric, transitive, and Euclidean) if the MAS is reflexive (symmetric, transitive, and Euclidean), respectively. We also show that the analogous result does not hold for being serial. Because the fundamental property of knowledge, i.e. an agent knows only the true propositions, does not hold if the agent is not serial, we say that such an agent is a believer (not a knowledger). Well, if we want to build the integrated agent (for an MAS) who is a knowledger, then it is not sufficient for the MAS to be serial. In addition, we present a knowledge relationship between the integrated agent and the agents in an MAS. The relationship states that the integrated agent is more knowledgeable than the agents in the MAS).

The paper consists of four sections and an Appendix containing the proofs. In Section 2, we introduce the basic notions of reasoning about knowledge. The main results, described above, are given in Section 3. Section 4 contains our conclusions.

2. THE BASIC NOTIONS

In this section, we introduce, in accordance with [7], some basic concepts and notations.

Suppose we have an MAS consisting of m agents, named 1, 2,.., m . We assume these agents wish to reason about a world that can be described in terms of a non-empty set P of primitive propositions. A language is just a set of formulas, where the set of formulas PLK that are of interest to us is defined as follows:

(1) The primitive propositions in P are formulas;

(2) If F and G are formulas, then so are $\neg F$, $(F \wedge G)$, $(F \vee G)$, $(F \Rightarrow G)$, $(F \Leftrightarrow G)$, and Ki(F) for all $i \in \{1, 2, .., m\}$, where Ki is a modal operator.

A Kripke structure M for an MAS = {1, 2,.., m} over P is a (m + 2)-tuple M = (S, I, k1, k2,.., km), where S is a set of possible worlds (states), I is an interpretation that associates with each world in S a truth assignment to the primitive propositions in P, and k1, k2,.., km are binary relation on S, called the possibility relations for agents 1, 2,.., m, respectively.

Given $p \in P$, the expression I[w](p) = true means that p is true in a world w in the structure M. The fact that p is false, in a world v of the structure M, is indicated by the expression I[v](p) = false

The expression $(u, v) \in ki$ means that an agent i considers a world v possible, given his information in a world u. Since ki defines what worlds an agent i considers possible in any given world, ki will be called the possibility relation of the agent i.

We now define what it means for a formula to be true at a given world in a structure.

Let $(M, w) \models F$ mean that F holds or is true at (M, w). The definition of $\models$ is as follows:

(a) $(M, w) \models p$ iff I[w](p) = true, where $p \in P$;

(b) $(M, w) \models F \wedge G$ iff $(M, w) \models F$ and $(M, w) \models G$;

(c) $(M, w) \models F \vee G$ iff $(M, w) \models F$ or $(M, w) \models G$;

(d) $(M, w) \models F \Rightarrow G$ iff $(M, w) \models F$ implies $(M, w) \models G$;

(e) $(M, w) \models F \Leftrightarrow G$ iff $(M, w) \models F \Rightarrow G$ and $(M, w) \models G \Rightarrow F$;

(f) $(M, w) \models \neg F$ iff $(M,w) \not\models F$, that is, $(M, w) \models F$ does not hold;

(g) $M \models F$ iff $(M, w) \models F$ for all $w \in S$.

Finally, we shall define a modal operator Ki, where Ki(F) is read: Agent i knows F.

(h) $(M, w) \models Ki(F)$ iff $(M, t) \models F$ for all $t \in S$ such that $(w, t) \in ki$.

In (h) we can see that agent i knows F in a world w of a structure M exactly if F holds at all worlds t that the agent i considers possible in w.

3. THE INTEGRATED AGENT

This section comprises our main results (propositions) regarding the integrated agents.

Let MAS = {1, 2, .., m} be a multi-agent system. Additionally, let M = (S, I, k1, k2,.., km) be a Kripke structure for the MAS. The integrated agent for the MAS, denoted ia(MAS), is defined by $kia = k1 \cap k2 \cap .. \cap km$.

What an agent knows is a consequence of the properties of the associated possibility relation, [5].

Let $kj \subseteq S \times S$ be a possibility relation of an agent j .

(Ref) kj is reflexive iff (for all $t \in S$)[$(t, t) \in kj$];

(Symm) kj is symmetric iff (for all $u, v \in S$)[(u, v) kj implies $(v, u) \in kj$];

(Tra) kj is transitive iff (for all $t, u, v \in S$)[$(t, u) \in kj$ and $(u, v) \in kj$ implies $(t, v) \in kj$];

(Euc) kj is Euclidean iff (for all $t, u, v \in S$)[$(t, u) \in kj$ and $(t, v) \in kj$ implies $(u, v) \in kj$];

(Ser) kj is serial iff (for all $t \in S$)(for some $u \in S$)[$(t, u) \in kj$].

An agent $j \in MAS$ is reflexive (symmetric, transitive, Euclidean, serial,) iff his possibility relation ki is reflexive (symmetric, transitive, Euclidean, serial,), respectively. An MAS is reflexive (symmetric, transitive, Euclidean, serial) iff every agent in the MAS is reflexive (symmetric, transitive, Euclidean, serial), respectively.

Proposition1

If MAS is reflexive (symmetric, transitive, Euclidean), then ia(MAS) is reflexive (symmetric, transitive, Euclidean), respectively.

Proposition1 says that the integrated agent ia(MAS) for a multi-agent system MAS is reflexive if the MAS is reflexive. This very fact also holds for symmetric, transitive, and Euclidean MASs.

Proposition2

Implication: If MAS is serial, then ia(MAS) is serial does not hold.

Proposition2 states that the fact given in Proposition1 does not hold for the serial property, that is, there exists a multi-agent system MAS that is serial and its integrated agent ia(MAS) is not serial.

From now on we suppose that F is an arbitrary formula in PLK. We also write ia instead of ia(MAS).

Proposition3

Let M=(S,I,k1,k2,..,km,kia) be a Kripke structure for MAS={1,2,..,m,ia}. Then,

(true) If MAS is reflexive, then $M \models Kia(F) \Rightarrow F$;

(positive introspection) If MAS is transitive, then $M \models Kia (F) \Rightarrow Kia (Kia (F))$;

(negative introspection) If MAS is Euclidean, then $M \models \neg$ Kia (F)$\Rightarrow$Kia ($\neg$Kia (F));
(not) If MAS is symmetric, then $M \models F \Rightarrow$ Kia ($\neg$Kia ($\neg$F));
(contradiction) If MAS is serial, then $M \models \neg$Kia (False).

The (true) part of Proposition3 says that if the integrated agent ia for a reflexive multi-agent system MAS knows F, then F is true; the (positive introspection) part states that if the integrate agent ia for a transitive MAS knows F, then he knows that he knows F; the (negative introspection) part says that if the integrated agent ia for an Euclidean MAS does not know F, then he knows that he does not know F; the (not) part states that the integrated agent ia for a symmetric MAS knows that he does not know $\neg$F if F is true; finally, the (contradiction) part says that ia for a serial MAS does not know a contradiction, named False.

Now we characterize what we mean when we say that one agent is more knowledgeable than another agent.

Let i, j be two agents in an MAS and let M be a Kripke structure for the MAS. We say that agent j is more knowledgeable than agent i, denoted j ▸ i, iff

$M \models Ki(F) \Rightarrow Kj(F)$, for each formula F in PLK.

Accordingly, for all formulas F in PLK: if agent i knows F, then agent j knows F, too.

Proposition4

Let ia be the integrated agent for an MAS. Then, (for all $k \in$ MAS)[ia ▸ k].

This proposition states that the integrated agent ia knows more than any agent in the MAS. This result can be applied when developing (building) a reliable multi-agent system. The idea is as follows: if we have a multi-agent system MAS, then, based on the desirable goals or problems that need to be solved by the MAS, we decompose the MAS to multi-agent systems, MAS1, MAS2, ..MASt, where MAS = MAS1 $\cup$ MAS2 $\cup$ .. MASt. For each multi-agent system MASk, k = 1, 2, .., t, we build the integrated agent ia(MASk), respectively. Now, if the co-operation among MAS1, MAS2, .., and MASt is jeopardized at some point in time because, for example, some agent in MAS1 does not function properly (a 'dead' agent), then that agent can be replaced by the integrated agent ia(MAS1).

4. CONCLUSIONS

We have defined the integrated agent in multi-agent systems. We have stated that the integrated agent is reflexive (symmetric, transitive, Euclidean) if the corresponding multi-agent system is reflexive (symmetric, transitive, Euclidean), respectively.

We have also shown that the analogous result does not hold for multi-agent system's serial ness, that is, there exists a multi-agent system that is serial and its integrated agent is not serial. After these results, we stated that: if the integrated agent for a reflexive multi-agent system knows F, then F is true; if the integrated agent for a transitive multi-agent system knows F, then he knows that he knows F ; if the integrated agent for an Euclidean multi-agent system does not know F, then he knows that he does not know F; the integrated agent for a symmetric multi-agent system knows that he does not know ¬F if F is true; the integrated agent for a serial multi-agent system does not know a contradiction. Lastly we have shown that the integrated agent knows more than any other agent in the multi-agent system. This result can be applied when building a reliable multi-agent system as was described in Section 3.

APPENDIX

Proof (Proposition1)

Assume that MAS is reflexive (symmetric, transitive, Euclidean). We would like to show that ia(MAS) is reflexive (symmetric, transitive, Euclidean), respectively.

It follows, from our assumption, that each agent in MAS = {1, 2, .., m} is reflexive (symmetric, transitive, Euclidean), that is, all the possibility relations, k1, k2, .., km, are reflexive (symmetric, transitive, Euclidean). Therefore, $kia = k1 \cap k2 \cap .. \cap km$ is reflexive (symmetric, transitive, Euclidean), that is, ia(MAS) is reflexive (symmetric, transitive, Euclidean), as we wanted to show.

Proof (Proposition2)

We need to show that A: [if MAS is serial, then ia(MAS) is serial] does not hold.

Let MAS = {1, 2} be a multi-agent system, where the Kripke structure for the MAS is: M = (S, I, k1, k2), S = {w1, w2}, I is an arbitrary interpretation, k1 = {(w1, w1), (w1, w2)}, and k2 = {(w2, w2), (w1, w2)}. We can easily see that the MAS is serial.

The integrated agent ia(MAS) for the MAS is defined by $kia = k1 \cap k2$ = {(w1, w2)}. Because kia is not serial, we obtain that ia(MAS) is not serial, as desired.

In addition, if we define interpretation I in such a way that $(M, w1) \models F$ and $(M, w2) \not\models F$, then we have that $(M, w2) \models Kia(F)$ and $(M, w2) \not\models F$. Accordingly, ia knows F at w2 in M even though F does not hold at w2 in M . Next, we have that $(M, w2) \models Kia(F)$ and $(M, w2) \models Kia(\neg F)$, that is, $(M, w2) \models Kia(F \wedge \neg F)$, that is, $(M, w2) \models Kia(False)$. It follows that ia does not distinguish F from ¬F, and therefore ia is completely useless.

Proof (Proposition3)

The proof follows from Proposition1 (this paper) and Proposition(Ref), Proposition(Tra), Proposition(Euc), Proposition(Symm), and Proposition(Serial) in [5].

Proof (Proposition4)

We need to show that (for all $k \in MAS$)[ia ▸ k] holds.

Let $j \in MAS$ be an arbitrary agent in MAS. We would like to prove that ia ▸ j.

It follows, from the integrated agent definition, that kia $\subseteq$ kj. Suppose that

A: M $\models$ Kj(F). We would like to show that B: M $\models$ Kia(F). To show B we need to show C: (M, w) $\models$ Kia(F), for all w $\in$ S. Therefore, let t $\in$ S be an arbitrary world in S. We prove that D: (M, t) $\models$ Kia(F). Let v $\in$ S be an arbitrary world such that (t, v) $\in$ kia. We need to prove E: (M, v) $\models$ F. Because (t, v) $\in$ kia and kia $\subseteq$ kj, we obtain (t, v) $\in$ kj. Now, it follows, from A, that (M, t) $\models$ Kj(F), that is, (M, v) $\models$ F, that is, E holds. Therefore, D holds, that is, C holds, that is, B holds, and finally ia ▸ j holds, as we wanted to show.

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INTEGRIRAJUĆI AGENT U VIŠEAGENTNIM SUSTAVIMA

Sažetak

U ovom članku karakteriziran je integrirajući agent u višeagentnim sustavima. Dokazan je sljedeći rezultat: ako je više agentni sustav refleksivan (simetričan, tranzitivan, Euklidov), onda je integrirajući agent danog višeagentnog sustava refleksivan (simetričan, tranzitivan, Euklidov), respektivno. Također, dokazali smo da analogan rezultat ne vrijedi u slučaju serijabilnosti višeagentnog sustava. Konačno, karakteriziran je odnos između znanja integrirajućeg agenta i korespondentnog više agentnog sustava, gdje je dokazano da integrirajući agent zna više od bilo kojeg agenta u višeagentnom sustavu.

Ključne riječi: integrirajući agent, operatori znanja, više agentni sustavi, rezoniranje o znanju.