On Proactive Delivery of Needed Information to Teammates

John Yen
School of Information
Sciences and Technology
The Penn State University
University Park, PA16802
jyen@ist.psu.edu

Xiaocong Fan
School of Information
Sciences and Technology
The Penn State University
University Park, PA16802
zfan@ist.psu.edu

Richard A. Volz
Dept. of Computer Science
Texas A&M University
College Station, TX 77843
volz@cs.tamu.edu

ABSTRACT

Psychological studies about human teamwork have shown that members of an effective team can often anticipate needs of other teammates and take appropriate actions accordingly. CAST is a teamwork model that enables agents in a team to anticipate information needs of teammates, whether they are software agents or human agents. Based on such needs, agents can choose to assist teammates through proactive communications and information delivery. In this paper, we establish the formal foundation of such proactive behavior using SharedPlan theory. We show that the proactive information delivery behavior of agents can be derived from the assist axiom in SharedPlan theory. This formal foundation of proactive information delivery behavior is critical not only for understanding the underlying assumptions required to justify the behavior but also for studying the impact of an agent's belief about other teammates' observability on the agent's choice for proactive information delivery actions.

1. INTRODUCTION

The shifting from strong agency[14] to team-based agents has been exposing increasing number of challenges in dealing with dynamic team formation, intra-team awareness, joint responsibility, team-wide constraint satisfication, backup (or help) behavior, etc. So far several team agent models have been proposed based either on the joint intention theory[2], such as GRATE*[7], STEAM[13, 9], or on the SharedPlan formalism[6, 4, 5], such as CAST[15, 16]. Each of such models tries to answer one or several of the above mentioned team-specific problems.

Apart from building upon the SharedPlan formalism, another key feature of CAST team model is that it focuses on dealing with human-involved teams. Hence, to some extent, it also reflects influence from studies about human-agent teamwork[10, 12].

When shifting to team-based agents, the key concepts of understanding and modeling team agents should also be shifted from focusing on a single agent to focusing on the whole team. Hence, higher-level attitudes such as proactivity, observability, responsibility should be our main concern. However, we argue one of the main drawbacks of the previous team agent models is that they didn't explicitly incorporate observability and proactivity, even though they might implicitly have such supports in implementation[9, 16].

Observability is a major means for an individual agent to obtain the informational aspect of its mental state. It also facilitates an incremental evolution of a shared mental model of the team activity under concern by a distributed heterogeneous team. Apart from an agent's prior knowledge, most, if not all, the new information of an agent comes from observing the team environment and the behavior of its teammates.

Proactivity can be used to enhance team spirit and improve team performance. First of all, proactivity is an effective way to reduce communication cost. In typical information exchange approaches, each instance of the primitive *ask* is always accompanied with an instance of *reply*. By proactively telling the information needed by another agent, the "blind" *ask* actions could be eliminated and communication cost correspondingly reduced. Secondly, proactivity is a feasible way to meet time-critical team activities. By proactively asking for information it (or asking for others) might need at some near future time points, an agent could respond right away when the time comes, without spending time requesting and waiting for the information. Thirdly, proactivity can assist re-planning under unexpected situations. When an agent[1] has realized the current team goal will be unachievable due to the possible conflicts between the overall team activities and the activities that will be carried out by one or more individual agents, it might proactively request those agents to re-adjust their actions, so that the team goals might become achievable. In addition, proactivity is another way, in addition to observability, to refresh the mental state of a team agent.

In this paper, based on the SharedPlan theory, we extend our previous CAST model to incorporate observability and proactivity. The paper is organized as follows: after an overview of the SharedPlan theory, and review of the previous CAST model, in section 3, we embed observability and proactive communication actions into the SharedPlan theory by means of re-defining the kernel modal operator $Int.To$. Proactive information exchange is studied in section 4, both in cases that mutual beliefs of information needs can be set up successfully, and in cases that such beliefs cannot be set

[1] The other team members might not have realized such fact.

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up. Two sufficient conditions for a liveness property are identified in section 5, and section 6 concludes the paper.

2. BACKGROUND

2.1 Overview of the SharedPlan Theory

The SharedPlan model of collaborative planning [6] was originally extended from Pollack's mental state model of (individual) plans [8] to the cases in which contributions from both agents are necessary to perform a complex action. The theory was further extended in [4, 5] by formalizing the concepts of individual plans and shared plans (either may be complete or partial), and exploring the way in which a shared plan for a team action evolves from its initial partial version, possibly with partial recipe, to a final complete form (with complete recipes for the team action and for all the subsidiary actions at different levels of abstraction).

Since SharedPlan theory tries to avoid introducing group mental state such as joint intention[2], initially, a team's knowledge is highly distributed, where each individual agent has its own prior beliefs. However, it's mandatory that such distributed prior beliefs have shared, thus redundant, parts in order to bind the individual agents together as a team. Such shared prior beliefs (information) are the basis of their team activities, which might include those about domain problems, mutual beliefs about the team structure, mutual beliefs about their commitments, etc.

Based on the prior mutual beliefs about their joint commitments, means-end reasoning procedures (I_SELECT_REC_GR, I_SELECT_AGENT, I_SELECT_SUBGROUP) of each agent will be triggered[2] to form an initial partial shared plan, which entails interagent negotiation and communication as well as individual agent reconciliation. Before the partial plan can evolve into a full plan, a sequence of partial plans (with the same identity) will be generated cooperatively by all the team agents. Each of such partial plans is a snapshot of the agents' mental states, which shows what they mutually agree and what they disagree [3]. The constraints of each snapshot on the team agents' intentions also guarantees a partial plan evolve toward right direction, and all the agents are ready to provide help behavior when necessary.

The treatment of partiality and contracting out actions are claimed to be the major contributions of the SharedPlan formalism. Another distinguished feature, compared with joint intention theory[2], is that SharedPlan theory avoids introducing some notion of collective intentionality, which inherently has its philosophical problems[4].

For agents to act together as a team, "individual intentions to act and mutual beliefs of such intentions are not sufficient for representing the mental state of the participants in collaborative activities"[4], this is exactly the motivation of the introduction of (potential) intention-that. Int.To's directly commit the associated agent to means-ends reasoning and acting, while Int.Th's form the basis for meshing subplans, helping teammates, and coordinating the updates to agent's mental state (ultimately, however, it may lead to Int.To's). An agent can only adopt an $Int.To$ toward the actions for which it is the actor, while an agent might adopt an intention-that which will finally lead to another agent's adoption of some intention to do some particular actions, where the performance of which is a prerequisite for the action of the initial agent. Such asymmetry between Int.to and Int.Th shows that Int.Th is much more powerful than Int.To in carrying out team activities.

The roles Int.Th plays include: (1)prevent agents from adopting intentions that conflict with the existing ones; (2)engender helpful behavior; (3)ensure the meshing of subplans; (4)entail communication obligations in case of action failures, intention reconciliation decisions, and resource conflicts; (5)constrain re-planning in case of failure.

We denote the logical system underpinning the SharedPlan theory as *GS*. The CAST team model in this paper is based on *GS* extended with the axioms needed in dealing with proactivity and observability.

Since the feature of contracting out actions does not fit well in modeling team-based agents [4], we will neglect contracting cases in the following discussions.

2.2 Review of CAST

CAST [15, 16]was motivated by the observation that effective human teams often exchange information in a proactive way. Psychological studies[10] about human team behavior have suggested that proactive information exchanges and other effective teamwork behaviors are enabled by a shared mental model among team members. The main novelty of the CAST architecture, hence, is that it enables agents not only to develop and update their shared mental model but also to use such models for anticipating potential information needs, proactively exchanging information, and accomplishing other effective team behaviors.

So far CAST answered the following questions pertinent to agent proactivity. The first question is, when an agent generates an intention to send a piece of information that it believes the receivers don't have currently. There are two approaches. One is *sending-on-request*, where information is only sent when an agent received a request from another agent. The other is *sending-on-guard*, where an agent keeps an eye on its teammates (or a small group of teammates it is interested in), and commits to pro_telling once it has realized that the information it has is needed by one of its teammates to fulfill its role.

The second is, what information will be sent in a session of information exchange. For example, suppose $\{p, r, r \to q\}$ and $\{r, p \to q\}$ are splices of the current mental states of agent a and b, respectively, and suppose agent b needs to know if q holds before it can proceed to fulfill its task commitment. Agent a promises to help b friendly. In such case, a can send the direct information q to b after it derives q based on its own reasoning capability. Alternatively, a can also send indirect information, such as p or $r \to q$, to b, assuming b has the appropriate reasoning capability to derive q. Currently, only the former approach is adopted, the latter is the focus of our future work.

MALLET[16], as a team plan language, was designed and used to specify team structures, roles, team plans, actions

[2]From the team's overall point of view, SELECT_REC_GR, SELECT_AGENT, SELECT_SUBGROUP will be triggered.

[3]How much part on which the team agents disagree with each other actually shows how far to go before they can obtain a fully shared plan for the complex action.

[4]Helpful, or assisting, behavior are more reasonable in teamwork context. We assume, actually it's pretty weak in teamwork context, that all the agents that might be involved in a team activity are already in the team. In this mean, it's no longer necessary to include contracting cases.

(pre-conditions, effects, potential actors, etc.), agents and their corresponding observability, etc. All of these specifications are domain and problem dependent. A team plan will be partially instantiated upon execution, and will be evolved into a full shared team plan after all the variable holes in the specifications have been fully instantiated by coordinations and negotiations among team agents.

3. TEAM MODEL OF CAST

Since the CAST team agent model is mainly based on the SharedPlan theory, the mental-state view of plans is implicitly adopted. Likewise, a first-order logic language augmented with necessary modal operators and action expressions is used. For the notions, except for those re-defined explicitly, we refer to [4, 5]. In the following, let TA be the set of all the agents in the team under concern.

We base our analysis on actions, as in [5]. Actions have various associated properties, such as the collection of potential doers, the condition under which the action can be performed, the consequences of performing it, etc. As in [5], we use $\alpha, \beta, \gamma \cdots$ to refer to actions, and assume a set of utility functions can be used to obtain the various properties associated with an action. Specifically, we use $Act_\alpha, pre(\alpha)$ and $post(\alpha)$ to return information regarding the potential doers, the preconditions and effects of α, respectively. More specifically, Act_α returns a set of tuples in the form $\langle Ag_i, level_i, T_i, Cost_i\rangle$[5], where Ag_i is a set of agents capable of performing α, and includes only those agents which really have contribution to the performance of α. T_i and $Cost_i$ are the time duration and cost for Ag_i to perform α, respectively. The value of $level_i$ is either *basic* or *complex* [5], specifying whether α is basic or complex wrt Ag_i. If $level_i$ is *basic*, the action is performable at will with no further decomposition or planning, and $Ag_i = \{G\}$ must be a singleton, i.e., agent $G \in TA$ can do α individually. When Ag_i is not a singleton, then α is a multiple agent action for the agents in Ag_i. When an action is complex, it could be a single agent action (for some agent), or a multiple agent action [6], depending on the actual actors chosen in role assignment. The performance time (period) of an action, which specifies the time duration constraint within which the action must be done, might also vary with its actual actors: (1) actors might differ in their proficiency in carrying out the same action; (2) sometimes, it may take more time for a single agent to do a complex action for lack of cooperations. Moreover, it may take more time for a group of actors because of potential negotiations among them before performance of the action.

All intended actions are planned and performed in some specific context[4]. The context C_α, in which the action α is being done, is a pair $(\Theta_\alpha, IC_\alpha)$, where $\Theta_\alpha = \langle\Psi_\alpha, \Gamma_\alpha\rangle$ is a constraint component with Ψ_α and Γ_α referring to the set of constraints for selecting recipe and reconciling intentions, respectively, and $IC_\alpha = \langle pid, exp\rangle$ is an intentional component where *pid* is the name of the plan by which α is being done, and *exp* accounts for the reason of undertaking *pid*. C_α characterizes different use cases of α.

In CAST, there exist three kinds of actions: domain actions (specific to domain problems), mental actions (planning, evaluating, conflict reconciling, observing, etc.), and communication actions (ask, reply, pro_tell, pro_ask, etc.). We also define action related meta-predicates we need. Let $G \in TA$. Then,

$bSingle(G,\alpha) \triangleq \exists l \cdot \langle\{G\}, l, -, -\rangle \in Act_\alpha \wedge l = \text{“}basic\text{”}$,
$cSingle(G,\alpha) \triangleq \exists l \cdot \langle\{G\}, l, -, -\rangle \in Act_\alpha \wedge l = \text{“}complex\text{”}$,
$SAction(G,\alpha) \triangleq bSingle(G,\alpha) \vee cSingle(G,\alpha)$,
$MAction(G,\alpha) \triangleq \exists GR \subseteq TA \cdot (GR \neq \emptyset) \wedge \langle\{G\} \cup GR, -, -, -\rangle \in Act_\alpha$,
$CAction(\alpha) \triangleq \alpha \in \{ask, reply, pro\_ask, pro\_tell\}$.

Modal operator $Exec(G, \alpha(G, \cdots, t, \cdots), t)$ is used to represent the fact that agent G has the ability to perform action $\alpha(G, \cdots, t, \cdots)$ at time t. $Exec$ applies only to basic-level actions. In the following axiom, (1) says that if an agent currently believes it can perform action α now, it really does it. (2) says that the corresponding effects of an action will hold after the execution of the action.

Axiom 1. (1)$Bel(A, Exec(A, \alpha, t), t) \Rightarrow Exec(A, \alpha, t)$,
(2)$\forall G \in TA, \alpha, t \cdot Exec(G, \alpha(G, \cdots, t, \cdots), t) \Rightarrow post(\alpha(G, \cdots, t, \cdots))$.

We use the modal operator Bel, for which we adopt the axioms $K, D, 4, 5$, where $D, 4, 5$ entail the accessibility relation to be non empty for each possible world, transitive, and Euclidean, respectively. Axiom T (i.e., $\Box p \Rightarrow p$), which corresponds to reflectivity, is for knowledge rather than for beliefs. If T were adopted, we would have the counter-intuitive conclusion: what I believe is true. However, we find that it's acceptable to say "I believe 'what I believe I believe'", hence, the axiom scheme $Bel(A, Bel(A, p, t), t) \Rightarrow Bel(A, p, t)$ [7] is adopted. We use $unknown(A, p, t) \triangleq \neg Bel(A, p, t) \wedge \neg Bel(A, \neg p, t)$ to represent the fact that agent A does not know the state of p at time t.

3.1 Intend-to and Can get

In this section, we re-define the modal operator $Int.To$ to embed pre-information checking.

As an abbreviation, the notion $Cget$ (can get) is given in the context of beliefs in terms of $Inform$ and $CObs$ (defined later). $Bel(A, Cget(B, I, t'), t) \triangleq Bel(A, Bel(B, I, t'), t) \vee (Bel(A, CObs(B, I, t'), t) \wedge P) \vee (\exists C, t_0 < t' \cdot Bel(A, Inform (C, B, I, t_0, t'), t))$, where P is $Bel(A, Hold(I, t'), t)$ when $A \neq B$, and is $Hold(I, t') \wedge (t = t')$ when $A = B$.

In the following, predicate $needs(G, I)$ ($needs(G, I, \alpha)$) is used to represent the intentional context "agent G needs I" ("agent G needs I to do α") in intentions-that generated from information needs.

We say that an agent $G \in TA$ at t intends to do action α at future time t_α if and only if the following constraints are satisfied by its mental state: (1) Either, in cases that G currently believes it can get the necessary pre-information (or know the preconditions hold) by t_α, at the same time it believes it will carry out the action at t_α and really commit to do it. (2)Or, in cases that G currently believes it will never be able to get the necessary pre-information by t_α, however, it at least has the immediate potential intention-that,

[5]An action may be taken as a basic action for one agent, but may be a complex action for another. In [4], $basic.level(\alpha), single.agent(\alpha), multi.agent(\alpha)$ was taken as common knowledge. Here we still specify such information in an action as common knowledge, but encode it in a more implement-oriented way.

[6]While, in [4], it is assumed an action is either a single, or a complex action, but not both, which doesn't reflect the real world naturally.

[7]The corresponding accessibility relation R is required to be weak reflective ($wRvRv$), rather than reflective (wRw).

by which it tries to make its information needs mutually known, and at the same time, it has a potential intention attitude to do α at t_α, which will eventually be reconciled as $Int.To$, and α will be carried out by G if G can get the needed information by t_α.

Definition 1. $Int.To(G, TA, \alpha, t, t_\alpha) \triangleq$
$[\exists t' \cdot (t \le t' \le t_\alpha) \wedge\ Bel(G, Cget(G, pre(\alpha), t'), t) \wedge$
$[bSingle(G, \alpha) \wedge$
$Bel(G, Exec(G, \alpha, t_\alpha), t) \wedge Commit(G, \alpha, t, t_\alpha)] \otimes$
$[(cSingle(G, \alpha) \vee CAction(\alpha)) \wedge$
clause(2) of definition Int.To in [4]. $]] \otimes$
$[\nexists t' \cdot (t \le t' \le t_\alpha) \wedge\ Bel(G, Cget(G, pre(\alpha), t'), t) \wedge$
$\exists t_m \cdot (t < t_m < t_\alpha) \wedge$
$Pot.Int.Th(G, MB(TA, Need(G, pre(\alpha), t_\alpha)), t, t_m,$
$needs(G, pre(\alpha), \alpha))\ \wedge Pot.Int.To(G, TA, \alpha, t_m, t_\alpha))]$.

As we can see from the definition of $Int.To$, an agent will try to set up mutual beliefs about its needs if it cannot get the necessary information before carrying out some action. An agent might also generate intentions to do something helpful when it received information requests from other agents. However, since such intentions are generated for its teammates rather that for itself, the agent will not try to set up mutual beliefs. In case that a receiver can not get the information for the requester by the time limit, it will selectively choose some appropriate agents to be the helpers by pro_asking.

We use meta-predicate $Need(A, I, t)$ to denote agent A needs information I at future time t. Instead of defining $Need$ directly, we'd rather define it in the contexts of beliefs.

Definition 2. $\forall A, B \in TA, I, t, t' \ge t \cdot$
$Bel(A, Need(B, I, t'), t) \triangleq \exists t_0 \le t$
$[Bel(A,\ \nexists t_1 \cdot (t_0 \le t_1 \le t') \wedge Bel(B, Cget(B, I, t_1), t_0), t) \wedge$
$(\exists \alpha \cdot\ Bel(A, SAction(B, \alpha), t) \wedge Bel(A, (I = pre(\alpha)), t)$
$\wedge Bel(A, Int.To(B, TA, \alpha, t_0, t'), t))] \vee$
$Bel(A, asked(B, A, I, t_0, t'), t) \vee$
$(\exists C \cdot Bel(A, pro\_asked(C, A, B, I, t_0, t'), t))$,
where in $t_0 \le t$, *'=' holds iff* $A = B$.

That is, if A believes B will need I, then either B directly needs it to carry out some actions, or A was asked by B or pro_asked by some agent C to reply B.

CBA ($CBAG$) is used to represent the knowledge an agent has about its own (or its collaborators') ability to perform actions[4]. Since CBA will only be used in the context of Bel or $Int.Th$, it is defined as such.

Definition 3. $M(G', CBA(G, TA, \alpha, R_\alpha, t_\alpha), t) \triangleq M$
$(G', \exists t_0 \le t, t' \cdot (t_0 \le t' \le t_\alpha) \wedge\ Bel(G, Cget(G, pre(\alpha), t'), t_0)$
$\wedge ([bSingle(G, \alpha) \wedge\ Exec(G, \alpha, t_\alpha)] \otimes$
$[(cSingle(G, \alpha) \vee CAction(\alpha)) \wedge$
clause(2) of definition CBA in [4]. $]), t)$,
where $M \in \{Bel, Int.Th\}$, *in* $t_0 \le t$ *'=' holds iff* $G = G'$.

We assume beliefs and intentions persist by default. Beliefs can be changed only when it conflicts with new observed or communicated facts (prefer new information), while an intention can be dropped only when it has already been achieved, or the intention becomes unachievable. The intentions already adopted are preferred to new intentions when reconciling conflicting intentions. The following axiom corresponds to axiom(1) in[5], but with more elaborations. It says that an agent can not intend that p holds at t' if it currently believes p will be impossible by t'.

Axiom 2. $\forall G, p, t, t' > t, IC_p \cdot Int.Th(G, p, t, t', IC_p) \Rightarrow$
$\nexists t'' \cdot (t \le t'' \le t') \wedge Bel(G, Bel(G, \neg p, t''), t)$.

3.2 Observability

We distinguish the abstract concept "observability" and the action *observing*. Observing is a main way for distributed heterogeneous individual agents to obtain information from its teammates and the outside world, as well as a way to facilitate the incremental evolution of shared mental models for team activities. *observing* is the means to achieve observability, while observability is just a special kind of capability, which is denoted by meta-predicate $CObs$ (can observe). $CObs(A, I, t)$ means agent A can observe information (or the truth of proposition) I at time point t.

Like the way $Need$ and CBA were introduced, the capability to observe things in the future might only exist in an agent's belief state. No one knows for sure he can observe something at some future time. It only makes sense to say he (strongly or weakly) *believes* he can observe in the future. Hence, when reasoning about observability, it might be reasonable to involve only those of the form $Bel(A, CObs(B, I, t'), t)$, rather than dealing with $CObs$ directly.

Definition 4. $Bel(A, CObs(B, I, t'), t) \triangleq$
$\exists R \cdot Bel(A, CBA(B, TA, observing(B, I, t'), R, t'), t)$.

In our model, we assume every team agent has its own initially different, dynamically changing observability. Let $id(I)$ refer to the unique identifier of information (type) I, $Obs(A, t)$ denote the set of agent A's potential observability at t. $Obs(A, t)$ is composed of the identifiers of the information that A is able to acquire by observing, that is, $id(I) \in Obs(A, t)$ iff A is able to observe I at t.

Observing is taken as a kind of atomic, basic-level, single agent actions. It's atomic means the effects can be reflected at once in the agent's current mental state. It's rather complex even though it's basic-level, since *observing* is closely related with an agent's mental attitudes, and its execution might need to follow some routine that involves the collaboration from several components.

To guarantee the action *observing* functions as what it's expected, there are two kinds of constraints that must be satisfied when an agent is going to observe. There are object (information)-related constraints, which are those observation constraints originated from the viewpoint of things being observed. For example, in Wumpus world, in case that the Wumpus is in a cave, it's location can't be observed by the hunters. In addition, there are agent-related constraints, which are independent of the things being observed. For example, in case that a hunter is sleeping, he still can't observe the location of the wumpus even though it is inside the hunter's detecting range. Let $Con(I)$ and $Con(A)$ denote object-related and agent-related constraints, respectively.

From the example, we can see that $Con(A)$ and $Con(I)$ are domain-dependent, and it's an implementation level issue. We can specify a weaker constraint (even the weakest condition $true$) so that the agent can observe information every now and then in case that the information is changing very frequently; or we can specify a stronger precondition (or strongest $false$ to prohibit observability completely), so that the team agents depend more on sharing information rather than on personal observability.

Meta-predicate $Hold(I, t)$ is used as an abbreviation of $Bel(God, I, t)$ ($Hold$s can be taken as assertions from God's belief state). Thus, $Hold(I,t)$ means God knows I will hold (be available) at t, while $Bel(A, Hold(I,t'),t)$ means at t A believes the information I is available at t', which can be obtained by observing. When I is a proposition, $Hold\ (I,t)$ means I is ture at t, $\neg Hold(I,t)$ means $\neg I$ is true at t. When I represents information, $Hold(I,t)$ means the information I is available at t, while $\neg Hold(I,t)$ means I is not available at t, and $\neg I$ stands for "no information of I".

Based on the above notations, the preconditions and effects of *observing* are formally defined as follows.

Definition 5. *For any* $A \in TA, I, t,$
$pre(observing(A,I,t)) \triangleq (id(I) \in Obs(A,t)) \wedge$
$Con(I) \wedge Con(A),$
$post(Observing(A,I,t)) \triangleq ((Hold(I,t) \Rightarrow Bel(A,I,t)) \wedge$
$(\neg Hold(I,t) \Rightarrow Bel(A,\neg I,t))).$

Lemma 1. *For any* $A, B, I, t, t' \geq t,$
$(1) Bel(A, CObs(B,I,t'),t) \Rightarrow$
$(Bel(A, Hold(I,t'),t) \Rightarrow Bel(A, Bel(B,I,t'),t)) \wedge$
$(Bel(A, \neg Hold(I,t'),t) \Rightarrow Bel(A, Bel(B,\neg I,t'),t)) \wedge$
$(unknown(A, Hold(I,t'),t) \Rightarrow$
$Bel(A, \neg unknown(B,I,t'),t),$
$(2) Bel(A, CObs(A,I,t),t) \Rightarrow$
$\neg unknown(A,I,t).$

Proof. By definition 4, we have $\exists R \cdot Bel(A, CBA(B, TA, observing(B,I,t'),R,t'),t)$. Then, by definition 3,
$Bel(A, CObs(B,I,t'),t)$
$\Rightarrow Bel(A, Exec(B, observing(B,I,t'),t'),t)$
$\Rightarrow$ {by axiom(1.2), logical reasoning}
$(Bel(A,(Hold(I,t') \Rightarrow Bel(B,I,t')) \wedge$
$(\neg Hold(I,t') \Rightarrow Bel(B,\neg I,t')) \wedge$
$(Bel(B,I,t') \vee Bel(B,\neg I,t')),t)$
$\Rightarrow Bel(A, Hold(I,t'),t) \Rightarrow Bel(A, Bel(B,I,t'),t)) \wedge$
$(Bel(A, \neg Hold(I,t'),t) \Rightarrow Bel(A, Bel(B,\neg I,t'),t)) \wedge$
$Bel(A, \neg unknown(B,I,t'),t).$
Thus, (1) follows. The proof of (2) is similar, by using axiom(1.1). $\square$

In lemma(1.1), we actually assume an agent always knows there is nothing going wrong with its teammate's observability: when A believes B can observe I at t', then it believes B will eventually get to know the truth of I at t'. Whether A knows B will believe I or $\neg I$ depends on A's belief about the status of I at t'. Lemma(1.2) means an agent can always perform the action *observing* and immediately acquire I if it believes it can observe I right now.

Observability has not yet been carefully explored in teamwork research. We argue that the reason for this might originate from the tangling of such complexities: observability is mental context sensitive, observability is dynamically changing, observability is more confidential than other kinds of information, decision problems like when is the appropriate time for an agent to communicate its observability to others, etc. Moreover, observability is intuitively a capability of individual agents rather than that of a team as a whole. Even though we could virtually take a team as a complex agent, a team's observability might not be easily defined in terms of individuals', which are often initially different, and dynamically changing.

From such complexities, we'd like to extract some (incomplete) axioms, which can hopefully be taken as an initial framework for reasoning observability in our information-exchange teamwork domains.

Initially, only the agent itself can have beliefs of its observability. The agents other than A can only get to know A's observability by A's direct or indirect (*pro_ask*) informing actions. One decision problem is whether to knowingly inform the others about its previous observability (those at past time points). Previous observability might be useful in supporting *ask* (or *pro_ask*): when an agent A needs I, and A knows B could observe I at some time before, A might get I by asking B. However, we argue that in such case, it's more reasonable to directly inform (pro-tell) the others the observing result about I, rather than the fact that "it could observe I", if the size of the observing result is not too large. Hence, if needed, an agent is supposed to only pro_tell the others its (current beliefs about) future observability. Of course, as time goes on, and due to communication delay, A's future observability (wrt. the sending time) might become past observability from B's viewpoint wrt. the current time (i.e., the case of $t' < t$ in definition 4).

Suppose B currently has the belief: $Bel(B, Bel(A, CObs(A,I,t''),t'),t)$ ($t' < t$ for communication delay), then, what else can B infer from it? In case that $t'' < t$, assume $pre(observing(A,I,t_a))$ held continuously for $t' \leq t_a \leq t''$. As time approached t'', A performed observing, then $Bel(B, \neg unknown(A,I,t),t)$ holds. In case that $t'' > t$, assume $pre(observing(A,I,t_a))$ holds continuously for $t' \leq t_a \leq t''$, then B believes A will acquire I at t'', i.e., $Bel(B, \neg unknown(A,I,t''),t)$ will hold. In both cases, the reasoning is based on the assumption of interval stability of A's observability, otherwise, B will not get any useful information.

However, we have to restrict, if not prohibit, our agents from exposing their observability explicitly, otherwise, not only the communication cost will be higher, the agents will also face the decision problems like when is the appropriate time to communicate, etc. Fortunately, it seems negative information about an agent's observability might be more useful than positive ones in supporting help behavior, and such negative information can be implicitly carried over together with information needs. For instance, suppose B get to know A's information need (i.e., $Bel(B, Need(A,I,t'),t)$), then it knows $\exists t_0 < t \cdot \nexists t_1 \cdot (t_0 \leq t_1 \leq t') \wedge Bel(B, Bel(A, CObs(A,I,t_1),t_0),t)$. However, B cannot derive $Bel(B, \neg CObs(A,I,t'),t)$, since in between t_0 and t, A might have realized it can observe I at t'. In another words, an agent cannot infer the other agent's lack of observability only from its information needs. Actually, without any stronger constraints from outside, an agent might never be able to know the other agent's lack of observability in the future. But nor could B believe that A might be able to observe I in the future, otherwise B might not want to provide any help, which might result in the failure of the team activity under concern. Thus, from the whole team's point of view, it's reasonable for B to assume $\neg Bel(B, CObs(A,I,t'),t)$ holds, so that B can commit to appropriate help actions if possible.

Hence, we have the following axiom about observability.

Axiom 3. $(1) \forall A, B, I, t, t' \geq t \cdot Bel(A, Need(B,I,t'),t) \Rightarrow \neg Bel(A, CObs(B,I,t'),t).$
$(2) Bel(A, pre(observing(A,I,t)),t) \Rightarrow$
$\forall t' > t \cdot Bel(A, CObs(A,I,t'),t).$

Axiom(3.2) says an agent believes it can observe I at future (including now) only if it believes it could perform the action "observing" now if it wants. Hence, at t it actually assumes nothing bad will happen in between t and t'. If something bad really happens at $t''(t \le t'' \le t')$ such that $pre(observing(A, I, t''))$ does not hold, then after t'', A will no longer believe it can observe I at t' any longer.

3.3 Proactive communication actions

We identify four kinds of communication actions: ask, $reply$, pro_tell and pro_ask.

Asking: When agent A has no information I, and it knows that such information is needed prior to performing some actions being committed by itself or other agent, A will ask B about I if it happens to know B has such information.

Pro_asking: Both agent A and B have no information I. B knows that A needs I and agent C knows I, but B does not know whether C knows A's information needs (Consider the case where A and B belong to a sub-team committing to action $\beta_1 \in R_\alpha$, at the same time, B and C belong to another sub-team committing to action $\beta_2 \in R_\alpha$). In such case, B will proactively ask C to inform A directly about I.

There is another possible application of pro_ask. An agent might proactively ask information for its own sake, the information, however, is not what it needs right away, but it may need in the future (for example, the information may be a precondition of the actions inside Pot.Int.To.). The study of such case is out of the scope of this paper.

Pro_telling: Agent A has realized(from team plan, observability, etc.) that B needs information I (which may combined with resource/time constraints) that it currently has, A will proactively feed information I to B.

Somehow, pro_telling can be taken as the counterpart of observing, in the sense that by observing, an agent can obtain information from other agents without their conscious (not knowing being observed); while by pro_telling the other agent can get information without knowing where it comes from (not knowing being told).

We take the proactivity of CAST agents as being composed of pro_asking and pro_telling.

For simplicity, we write $ask(.)$ to denote an action, while $asked(.)$ to denote a proposition that represents the fact of a specific occurrence of ask. The same notion goes for the other actions. $ask(A, B, I, t, t')$ means agent A asks B at t for I to be available by t', $reply(A, B, I, t)$ means A replies B with I at t, $pro\_tell(A, B, I, t)$ means A pro_tells B about I at t, and $pro\_ask(A, B, C, I, t, t')$ means A pro_asks B at t to tell C directly about I by t'.

Communication actions are basic actions, they have preconditions and effects. Moreover, we assume each individual team agent has the full individual recipes to carry out all the communication actions. The following axiom is about the precondition and effects of communication actions.

Axiom 4. *For any* $A, B, C \in TA, I, t, t' > t$,
$(1) W(A, B, t, \cdots) \Rightarrow \exists t_A > t \cdot Bel(A, W\text{-}ed(A, B, t, \cdots), t_A) \wedge \exists t_B > t \cdot Bel(B, W\text{-}ed(A, B, t, \cdots), t_B)$.
where $W \in \{ask, reply, pro\_ask, pro\_tell\}$,
$(2) pre(ask(A, B, I, t, t')) = \{Bel(A, Need(A, I, t'), t),$
$\nexists t_a \cdot t \le t_a \le t' \wedge Bel(A, Cget(A, I, t_a), t),$
$\exists t_0 < t' \cdot Bel(A, Cget(B, I, t_0), t)\},$
$ask(A, B, I, t, t') \Rightarrow (\exists t_c > t \cdot Bel(B, I, t_c) \Rightarrow \exists t_d > t_c \cdot Bel(A, I, t_d)),$
$(3) pre(reply(A, B, I, t)) = \{\exists t_1 > t \cdot Bel(A, Need(B, I, t_1), t) \wedge$
$\exists t_0 < t \cdot [Bel(A, asked(B, A, I, t_0, t_1), t) \vee$
$(\exists C \cdot pro\_asked(C, A, B, I, t_0, t_1))], Bel(A, I, t)\},$
$reply(A, B, I, t) \Rightarrow$
$(\exists t_A, t_B > t \cdot Bel(B, I, t_B) \wedge Bel(A, Bel(B, I, t_A), t_A)),$
$(4) pre(pro\_tell(A, B, I, t)) = \{\exists t_1 > t \cdot Bel(A, Need(B, I, t_1), t)$
$\wedge\ \nexists t_0 < t \cdot [Bel(A, asked(B, A, I, t_0, t_1), t) \wedge$
$(\nexists C \cdot pro\_asked(C, A, B, I, t_0, t_1))], Bel(A, I, t)\},$
$pre\_tell(A, B, I, t) \Rightarrow$
$(\exists t_A, t_B > t \cdot Bel(B, I, t_B) \wedge Bel(A, Bel(B, I, t_A), t_A)),$
$(5) pre(pro\_ask(A, B, C, I, t, t')) = \{Bel(A, Need(C, I, t'), t),$
$\exists t_0 < t' \cdot Bel(A, Cget(B, I, t_0), t),$
$\neg Bel(A, Bel(B, Need(C, I, t'), t), t),\ \neg Bel(A, I, t),$
$\nexists t_a \cdot t \le t_a \le t' \wedge Bel(A, Cget(A, I, t_a), t)\},$
$pro\_ask(A, B, C, I, t, t')) \Rightarrow \exists t_c > t \cdot Bel(A, Bel(C, I, t_c), t)$
$\wedge (\exists D \cdot Bel(A, Cget(D, I, t'), t) \wedge Reach(A, D, t') \Rightarrow Bel(C, I, t_c)),$
where by $Reach(B, C, t)$*, we mean* C *can be reached from* B *by some pro_asking chain by time limit* t.

Axiom(4.1) says that the agent carrying out communication actions and the receiver agents know the fact of the actions' being carried out. The other agent C can only get this information by observing or by being informed.

$Inform$ is given as an abbreviation of replying or pro_telling information to another agent.
$Inform(A, B, I, t, t') \triangleq [pre(reply(A, B, I, t')) \Rightarrow Exec(A, reply(A, B, I, t'), t)] \wedge [pre(pro\_tell(A, B, I, t')) \Rightarrow Exec(A, pro\_tell(A, B, I, t'), t)]$.

In our model, an agent only believes things that either from its prior set of beliefs, or from being informed or its own observing. Let B_0 be a function that associates each agent with a set of prior beliefs. $\forall p \cdot p \in B_0(A) \Rightarrow Bel(A, p, t_\perp)$, where $t_\perp$ is the starting time point. We have,

Axiom 5. $\forall G, p, t \cdot Bel(G, p, t) \Rightarrow Bel(G, p, t_\perp) \vee (\exists t' \le t \cdot Hold(p, t') \wedge Bel(G, CObs(G, p, t'), t')) \vee (\exists t' < t, G' \cdot Inform(G', G, p, t'))$.

4. PROACTIVE INFORMATION EXCHANGE

In this section, we show how communication actions are instigated to provide needed information proactively.

The following axiom is exactly the help axiom 5 in [4] stated in our notions. It says that if an agent has an intention that some proposition, which it does not believe is true now, should be true at some future time, and it believes it can do something β to help, then it will consider doing β.

Axiom 6. $\forall A, p, t, \beta, t_\beta, t' > t_\beta, C_p \cdot$
$Int.Th(A, p, t, t', C_p) \wedge \neg Bel(A, p, t) \wedge$
$Bel(A, \exists R_\beta \cdot (p \in post(\beta) \wedge CBA(A, \beta, R_\beta, t_\beta)), t) \Rightarrow$
$Pot.Int.To(A, \beta, t, t_\beta)$.

The following axiom plays a key role in connecting information needs with proactive communication actions. It says that, when an agent has realized (been told) that another agent might have an information need, it will generate an intention-that attitude to try to help the other agent. Since the intention is generated for the reason that B will need I at t', the corresponding intentional context is just $needs(B, I)$.

Axiom 7. $\forall A, B \in TA, I, t, t' > t \cdot Bel(A, Need(B, I, t'), t) \Rightarrow Int.Th(A, Bel(B, I, t'), t, t', needs(B, I))$.

4.1 When mutual belief is set up

According to the definition of $Int.To$, when an agent realizes an information need, it will try to set up mutual belief about its need among its teammates. In case that the

$Pot.Int.Th$ can be reconciled to $Int.Th$ [8], such mutual belief will be set up successfully. The following theorem shows how an agent provides help under different situations.

THEOREM 1. $\forall A, B \in TA, I, t, t' > t\cdot$
$Bel(A, Need(B, I, t'), t) \wedge \neg Bel(A, Bel(B, I, t'), t) \Rightarrow$
$[\exists t_r, t_b \cdot (t \leq t_b < t_r \leq t') \wedge$
$\quad Bel(A, Bel(A, pre(reply(A, B, I, t_r)), t_b), t)$
$\quad\quad \Rightarrow Pot.Int.To(A, reply(A, B, I, t_r), t)] \wedge$
$[\exists t_t, t_b \cdot (t \leq t_b < t_t \leq t') \wedge$
$\quad Bel(A, Bel(A, pre(pro\_tell(A, B, I, t_t)), t_b), t)$
$\quad\quad \Rightarrow Pot.Int.To(A, pro\_tell(A, B, I, t_t), t)] \wedge$
$[\exists C \in TA, t_a, t_b \cdot (t \leq t_b < t_a \leq t') \wedge$
$\quad Bel(A, Bel(A, pre(pro\_ask(A, C, B, I, t_a, t')), t_b), t)$
$\quad\quad \Rightarrow Pot.Int.To(A, pro\_ask(A, C, B, I, t_a, t'), t)))]$.

PROOF. Assume $Bel(A, Need(B, I, t'), t)$ holds. By axiom 7, we have $Int.Th(A, Bel(B, I, t'), t, t', needs(B, I))$. By axiom 4, A knows that $Bel(B, I, t')$ might be the effect of communication actions $reply(A, B, I, -)$ or $pro\_tell(A, B, I, -)$. It might also be the result of $pro\_ask(A, C, B, I, -, -)$ if loop-veracity (refer to definition 6) is satisfied by team TA. Since we assume each agent has full recipes for communication actions, there always exists an available recipe R_α for α. For the help axiom 6 to be helpful in our proof, we only need to show $Bel(A, CBA(A, \alpha, R_\alpha, t_\alpha), t)$ holds for some t_α where $\alpha \in \{reply(.), pro\_ask(.), pro\_tell(.)\}$.

To trusify $Bel(A, CBA(A, \alpha, R_\alpha, t_\alpha), t)$, according to definition 3, A's mental state must satisfy the precondition $\exists t' \cdot t \leq t' \leq t_\alpha \wedge Bel(A, Cget(A, pre(\alpha), t'), t)$, i.e., either A can get $pre(\alpha)$ now, or it believes at least it can get to know $pre(\alpha)$ by t_α. The theorem follows directly from the corresponding pre-assumptions and the help axiom 6, which completes the proof. □

COROLLARY 1. $\forall A, B \in TA, I, t, t' > t\cdot$
$Bel(A, Need(B, I, t'), t) \wedge \neg Bel(A, Bel(B, I, t'), t) \Rightarrow$
$[\exists t_r, t_o \cdot (t_r \geq t_o \geq t) \wedge Hold(pre(reply(A, B, I, t_r)), t_o)$
$\quad \wedge Bel(A, CObs(A, pre(reply(A, B, I, t_r)), t_o), t)$
$\quad\quad \Rightarrow Pot.Int.To(A, reply(A, B, I, t_r), t)] \wedge$
$[\exists t_t, t_o \cdot (t_t \geq t_o \geq t) \wedge Hold(pre(pro\_tell(A, B, I, t_t)), t_o)$
$\quad \wedge Bel(A, CObs(A, pre(pro\_tell(A, B, I, t_t)), t_o), t)$
$\quad\quad \Rightarrow Pot.Int.To(A, pro\_tell(A, B, I, t_t), t)] \wedge$
$[\exists C \in TA, t_a, t_o \cdot (t_a \geq t_o \geq t) \wedge$
$\quad Hold(pre(pro\_ask(A, B, I, t_a, t')), t_o) \wedge$
$\quad Bel(A, CObs(A, pre(pro\_ask(A, B, I, t_a, t')), t_o), t)$
$\quad\quad \Rightarrow Pot.Int.To(A, pro\_ask(A, C, B, I, t_a, t'), t)))]$.

PROOF. It follows from lemma 1 and theorem 1. □

From the above corollary we can see that when the current time t approaches t_o, agent A will adopt appropriate potential intention attitude.

4.2 When mutual belief is not set up

However, an agent's $Pot.Int.Th$, which is adopted to set up mutual beliefs about its information need, might not be reconciled to $Int.Th$ due to its conflicting with existing intentions, or whatever other reasons. In such cases, the other agents can't get to know the information needs through being directly informed by the information needers.

An agent can't do anything helpful if it has no idea of the other agents' information needs. The whole team can only expect some potential agent(s) to be able to infer others' needs from its (or their) own point of view. One criteria we provide below is called "pro_telling by lack of action".

Suppose B is the information needer when intending to do $\beta \in \alpha$, and A is a potential information provider. Since the (sub-) team has fortunately maintained a full shared plan for the team action α, A at least has such beliefs: $Bel(A, Int.To(B, \beta, t_0, t'), t)$, $Bel(A, \exists R_\beta \cdot CBA(B, \beta, R_\beta, t'), t)$, and $Bel(A, \exists \rho \cdot \langle \beta, \rho \rangle \in R_\alpha, t)$. Hence, A knows for sure B's doing β is a part of the performance of team action α. If A knows β (then knows its preconditions), then it can initiate either a pro_tell action when it could get the information before too late, or pro_ask actions to propagate such information needs to the others.

The question is how A knows the details of β? In SharedPlan theory, a complex action is supposed to be decomposed hierarchically, but it says nothing about what information goes together with α when a team agent initiates an intention to do α: $Int.To(G, Do(GR, \alpha, t_\alpha), t, t')$. Surely, we can't expect a rational agent knows the details of all the subactions at all different levels of abstraction.

On the other hand, all the team members finally must agree with each other on the recipe R_α even though each individual might only have a partial view of the full recipe. In addition, all the team members must know some sketchy information (the number of the immediate subactions, their respective types, etc.) even though they might not know clearly the details (preconditions, effects, etc.) of these subactions. Moreover, the details of each immediate subaction must be known by at least one agent, if not by all, so that the potential team agent can reasoning about which subaction(s) it is able to do, what's the corresponding effects, etc. And based on such information, the potential agent can manage to achieve agreement among the whole team about its commitment if it really intends to do the action.

To support proactive information exchange in the cases that mutual beliefs of information needs can not be set up, we need go a step further. One feasible solution is, when the specification of a complex action α is transferred among team agents, it might be reasonable to also attach the specifications of all the subactions β_i at the immediate next level as "previewing knowledge" for reference. Thus, we have

AXIOM 8. $\forall GR \subseteq TA, A \in GR, \alpha, t, t_0 < t, t_\alpha > t, R_\alpha, C_\alpha\cdot$
$Bel(A, \forall G \in GR \cdot Int.Th(G, Do(GR, \alpha, t_\alpha), t_0, t_\alpha, C_\alpha), t) \wedge$
$Bel(A, R_\alpha \in Recipes(\alpha), t) \wedge MAction(A, \alpha) \Rightarrow$
$[\forall \langle \beta, \rho \rangle \in R_\alpha, B \in GR \cdot SAction(B, \beta) \Rightarrow$
$\quad \exists \bar{\beta}, Act_\beta, pre(\beta), post(\beta), T, l, c\cdot$
$\quad\quad Bel(A, \beta = \langle \bar{\beta}, Act_\beta, pre(\beta), post(\beta) \rangle, t) \wedge$
$\quad\quad Bel(A, \langle \{B\}, l, T, c \rangle \in Act_\beta, t)]$.

Furnished with such "previewing knowledge", in the performance of α, A comes to be more and more anxious about B's lack of action $\beta \in R_\alpha$. Since A can't wait for the whole team's failure, it will (weakly) assume B might lack the necessary pre-information.

In this case, we also need to assume when any agent A starts to carry out some single action β at t, it will make the fact of its doing β mutually believed, i.e., it will adopt an intention attitude: $Int.Th(A, MB(TA, doing(A, \beta, t)), t, t'$,

[8] There has no intentional conflicts, and some other internal constrains is satisfied, such as it's not overloaded, etc.

$no\_help(A,\beta)$), where t' depends on the communication delay, predicate $no\_help(A,\beta)$ means A needs no help for carrying out β. The following assumption gives a (pseudo-) sufficient condition for an agent to infer that another agent may lack the necessary information to act. It says when there is no more time (ϵ) left before the deadline of the performance of β, A will suppose B might lack the necessary pre-information, and commit to appropriate actions to help according to axiom (6,7).

ASSUMPTION 1. *For some constant ϵ,*
$\forall A, B \in TA, \beta, I, T, t, t' > t, t_0 < t, \Lambda \cdot$
$Bel(A, \beta = \langle -, \Lambda, I, - \rangle, t) \wedge Bel(A, \langle \{B\}, -, T, - \rangle \in \Lambda, t) \wedge$
$Bel(A, Int.To(B, \beta, t_0, t'), t) \wedge Bel(A, (t' - t \leq T + \epsilon), t) \wedge$
$(\nexists t_1 \cdot Bel(A, doing(B, \beta, t_1), t)) \Rightarrow Bel(A, Need(B, I, t'), t).$

As a counterpart of theorem 1, the following theorem shows how the attitudes of intention to pro_ask and pro_tell are adopted by lack of action.

THEOREM 2. $\forall A, B \in TA, \beta, I, T, t, t' > t, t_0 < t, \Lambda \cdot$
$Bel(A, \beta = \langle -, \Lambda, I, - \rangle, t) \wedge Bel(A, \langle \{B\}, -, T, - \rangle \in \Lambda, t) \wedge$
$Bel(A, Int.To(B, \beta, t_0, t'), t) \wedge Bel(A, (t' - t \leq T + \epsilon), t) \wedge$
$(\nexists t_1 \cdot Bel(A, doing(B, \beta, t_1), t)) \wedge \neg Bel(A, Bel(B, I, t'), t) \Rightarrow$
$[\exists t_t, t_b \cdot (t \leq t_b < t_t \leq t') \wedge$
$Bel(A, Bel(A, pre(pro\_tell(A, B, I, t_t)), t_b), t)$
$\Rightarrow Pot.Int.To(A, pro\_tell(A, B, I, t_t), t)] \wedge$
$[\exists C \in TA, t_a, t_b \cdot (t \leq t_b < t_a \leq t') \wedge$
$Bel(A, Bel(A, pre(pro\_ask(A, C, B, I, t_a, t')), t_b), t)$
$\Rightarrow Pot.Int.To(A, pro\_ask(A, C, B, I, t_a, t'), t)))].$

PROOF. By assumption 1, similar to theorem 1. ☐

There are situations where the information I needed by some agent A can only be observed by a few, rather than all, of its teammates (i.e., $pre(id(I))$ and $pre(observing)$ cannot be satisfied by the mental state of some agents). For instance, in aircraft fighting domain, some information about enemy can only be obtained by scouts. Such kind of observability can be specified as prior knowledge, since it's unchangeable during runtime. In RoboSoccer, only the players nearby the football might be able to get the exact location of the ball. However, such kind observability is changing dynamically. Let Ob be a function which returns a set of agents $Ob(I,t) \subseteq TA$ for any information type I, where any agent in $Ob(I,t)$ is able to observe I at appropriate time $t' \geq t$. Due to different specifications for prior knowledge and dynamics, different agents might obtain different results by calling their Ob functions.

The following assumption gives another (pseudo-) sufficient condition, to which we will refer as "pro-acting by lack of observability". It says that when an agent A knows B cannot observe I, A will proactively let B know I timely.

ASSUMPTION 2. $\forall A, B \in TA, \beta, I, T, t, t' > t, t_0 < t, \Lambda \cdot$
$Bel(A, \beta = \langle -, \Lambda, I, - \rangle, t) \wedge Bel(A, \langle \{B\}, -, T, - \rangle \in \Lambda, t) \wedge$
$Bel(A, Int.To(B, \beta, t_0, t'), t) \wedge Bel(A, B \notin Ob(I, t), t) \wedge$
$(\nexists t_1 \cdot Bel(A, doing(B, \beta, t_1), t)) \Rightarrow Bel(A, Need(B, I, t'), t).$

Likewise, the following theorem shows how the attitudes of intention to pro_ask and pro_tell are adopted by lack of observability.

THEOREM 3. $\forall A, B \in TA, \beta, I, T, t, t' > t, t_0 < t, \Lambda \cdot$
$Bel(A, \beta = \langle -, \Lambda, I, - \rangle, t) \wedge Bel(A, \langle \{B\}, -, T, - \rangle \in \Lambda, t) \wedge$
$Bel(A, Int.To(B, \beta, t_0, t'), t) \wedge Bel(A, B \notin Ob(I, t), t) \wedge$
$(\nexists t_1 \cdot Bel(A, doing(B, \beta, t_1), t)) \wedge \neg Bel(A, Bel(B, I, t'), t) \Rightarrow$
$[\exists t_t, t_b \cdot (t \leq t_b < t_t \leq t') \wedge$
$Bel(A, Bel(A, pre(pro\_tell(A, B, I, t_t)), t_b), t)$
$\Rightarrow Pot.Int.To(A, pro\_tell(A, B, I, t_t), t)] \wedge$
$[\exists C \in TA, t_a, t_b \cdot (t \leq t_b < t_a \leq t') \wedge$
$Bel(A, Bel(A, pre(pro\_ask(A, C, B, I, t_a, t')), t_b), t)$
$\Rightarrow Pot.Int.To(A, pro\_ask(A, C, B, I, t_a, t'), t)))].$

It's easy to see that *pro_tell*(*pro_ask*) will be potentially committed when $A \in Ob(I,t)$ ($A \notin Ob(I,t)$).

5. LOOP VERACITY

In this section, We identify two sufficient conditions for a liveness property: if an agent needs I (which might be (part of) the precondition of some action α), and there is some agent in the team who knows I, then under what conditions can the agent eventually obtain I.

THEOREM 4. *Given an agent team $T_1 \subseteq TA$. $Int.To(A, T_1, \alpha, t, t_\alpha)$, $\nexists t_0 \cdot t \leq t_0 \leq t_\alpha \wedge$ $Bel(A, Cget(A, pre(\alpha), t_0), t)$, $\exists C \in TA \cdot \exists t_c < t_\alpha \cdot Bel(C, Cget(C, I, t_c), t)$, and suppose the mutual belief of $Need(A, pre(\alpha), t_\alpha)$ can be set up among T_1. We have $\exists t' \cdot Bel(A, I, t')$, if either of the following conditions hold: (1). $C \in T_1$, (2). $C \notin T_1$, but $\exists B \in T_1$ such that $Reach(B, C, t_\alpha)$ holds.*

PROOF. (1) When $C \in T_1$, it will get to know A needs I from A's intention to set up mutual beliefs among T_1, then A will know I after being replied by C. (2) Since all the agents in T_1 will know A's information needs, and all of them are trying to provide help, each agent who's mental state satisfies the precondition of *pro_ask* will commit to do it. By assumption, B will eventually reach C and instigate C to reply A. ☐

The problem is how we can be sure the agent holding the necessary pre-information of some team action is reachable from within the (sub-) team performing the action.

Suppose A pro_asks B to help C based on its false belief that B has the information I which C will need. Since B does not have I, likewise, B might pro_ask D (hopefully B will not pro_ask A to help C since B might infer that A does not have I from being pro_asked about I by A) to help C based on its false belief that D has I. Then, a pro_asking loop occurs when D pro_asks A to help C also based on its false belief (such loop might involve more than three agents). In such case, C will never get I since A, B, and D keep kicking the ball to the other.

One way to get around such dilemma is to constrain the team agents to avoid the above loops. The following definition of "loop veracity" gives us a necessary condition. Let $distinct(S)$ means the elements in set S are distinct from each other.

DEFINITION 6. *[Loop-Veracity]* $Lvera(TA, I, t_o) \triangleq$
$\forall i \cdot \forall A_1, \cdots, A_i \in TA, t_1, t^1, \cdots, t_i, t^i \cdot (3 \leq i \leq |TA|) \wedge$
$\bigwedge_{j=1}^{i-1} [(t_j \leq t^j < t_o) \wedge Bel(A_j, Cget(A_{j+1}, I, t^j), t_j)] \wedge (t_i \leq t^i < t_o) \wedge Bel(A_i, Cget(A_1, I, t^i), t_i))) \wedge distinct(\{A_1, \cdots, A_i\})$
$\Rightarrow \exists t, t' \cdot (t \leq t' < t_o) \wedge \bigvee_{j=1}^{i} Bel(A_j, Bel(A_j, I, t'), t).$

It seems even this necessary condition is too strong for a team to maintain dynamically. However, it is only used in the specification of the effect of *pro_ask*. In deciding what to do to make $Bel(C, I, t')$ become true, agent A might consider doing *pro_ask* if possible, even though the result might not be what it expected.

6. CONCLUDING REMARKS

This paper, by refining the general SharedPlan theory[6, 4, 5], tries to establish a formal foundation for proactive information delivery behavior of team-based agents. It is critical not only for understanding the underlying assumptions required to justify the behavior but also for studying the impact of an agent's belief about other teammates' observability on the agent's choice for proactive information delivery actions.

More specifically, it has the following contributions. First, proactivity, which is taken as a combination of pro_telling and pro_asking is, for the first time, studied formally based on the SharedPlan theory. We have shown that pro_telling and pro_asking can be used as help behavior not only in cases that the mutual beliefs about information needs can be set up successfully, also in cases that information providers can infer the potential information needs by other agents' lack of actions

Second, observability is embedded into the SharedPlan theory smoothly. Even though the introduction of observability can be traced back to many years ago, the topic of team agents' observability has not attracted much concerns in the teamwork research field. The most related works on observability is the COM-MTDP model[9], which might be the first work towards formally treating observability in teamwork domain. COM-MTDP model is a framework proposed to facilitate the analysis of optimality and complexity of team decisions, where observability, together with communication cost, was selected as one measurement dimension. In COM-MTDP, each agent is supposed to have a pre-specified set Ω_i as its observation domain, from which the agent will choose for each world state during execution, where Ω_i may "include elements corresponding to indirect evidence of the state (sensor reading) and actions of other agent"[9]. However, it is assumed observing is the only way to obtain information(belief), while proactive information exchange was not taken into consideration.

In addition, we also prove a liveness property that holds under either of two sufficient conditions. Theoretically, if the loop veracity constraint can be satisfied by an agent team, any information needs can also be satisfied eventually if there exists an information provider. In practice, even though a team does not satisfy the loop veracity constraint, all the team agents could also assume it holds personally, so that potential help behavior (pro_asking) might be committed towards the common team goal–the performance of team actions.

In this paper, we only considered the case of inferring information needs from the precondition of single agent actions before an agent can really commit to do the actions. Since the preconditions of a multiple agent action might not be known completely by any single participator, and the satisfaction of parts does not entail the satisfaction of the whole precondition [9]. Even though we might find some situations where the problems can be solved at the shared plan level, we would rather postpone such topics to our future work.

[9]The problem of handling distributed constraint satisfaction is an open question in computer science.

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