Distributed Information Fusion Agents

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Abstract – *Information fusion is typically data driven and applied to adversarial contexts. Advantages of a goal driven fusion process are emerging. An agent approach to fusion applied to friendly contexts, such as logistics, is presented. Agents are suitable for fusion because they can represent autonomous fusion entities by modelling their capabilities, expertise and intentions. This paper promotes a level 3 centric view of information fusion, and focuses on impact and situation fusion. Extended Contract Net Protocol (ECNP) provides a distributed fusion approach, but has its shortfalls for the fusion domain. Provisional Agreement Protocol (PAP) is an extension of the ECNP. It allows backtracking and a deliberative approach to fusion. Details of PAP are presented.*

Keywords: data fusion, JDL model, λJDL model, information fusion, situation assessment, impact assessment.

1 Introduction

1.1 The λJDL Model of Data Fusion

Lambert [1-3] defines data fusion as the process of utilising one or more data sources over time to assemble a representation of aspects of interest in an environment. Figure 1 illustrates the λJDL revision of the JDL model [4] outlined in [3].

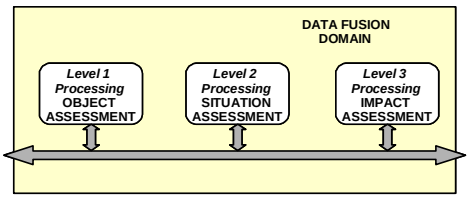

Figure 1. The λJDL Model of Data Fusion.

Lambert [1] defines the elements of the λJDL model in the following way.

- Object fusion is the process of utilising one or more data sources over time to assemble a representation of objects of interest in an environment. An object assessment is a stored representation of objects obtained through object fusion.
- Situation fusion is the process of utilising one or more data sources over time to assemble a representation of relations of interest between objects of interest in an environment. A situation assessment is a stored representation of relations between objects obtained through situation fusion.
- Impact fusion is the process of utilising one or more data sources over time to assemble a representation of effects of situations in an environment, relative to our intentions. An impact assessment is a stored representation of effects of situations obtained through impact fusion.

Machine data fusion arises when we interpret "representation" as "machine representation" in the λJDL model. Machine data fusion is about having machines develop object, situation and impact assessments.

1.2 Impact and Situation Fusion

The bulk of the data fusion community remain heirs to the traditions and techniques of sensor fusion, which is primarily concerned with the use of sensors to form object assessments. This has engendered a *data driven* view of data fusion, under which a data fusion process is understood as a process that assembles assessments of the environment, based on the data provided to it. An alternative perspective is to embrace a *goal driven* view of data fusion. Data fusion is then understood as a process that assembles assessments of the environment, based on its goals. In fusion terms, this represents a transition from a level 1 centric view of data fusion to a level 3 centric view of data fusion.

This paper is primarily concerned with impact and situation fusion. In the early days of data fusion, impact assessments were called "threat assessments" and involved assessments of likely enemy behaviour, given enemy intent. Of course the significance of enemy behaviour to us varies with our own intent and likely behaviour, and so an assessment of the overall effect needs to consider the intent and behaviour of both enemies and ourselves. Moreover, as we expand our attention beyond purely adversarial contexts, an assessment of the effect of a situation will depend upon the intents and associated behaviour of the respective players, be it competitive or collaborative intent and behaviour.

The authors promote multi-agent systems [5] as an appropriate paradigm for impact fusion. [6] offers the following assessment of use of the term "agent".

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Most often, when people in AI use the term "agent", they refer to an entity that functions continuously and autonomously in an environment in which other processes take place and other agents exist.

The remark identifies three key characteristics of agents.

- Embeddedness: agents exist in an environment in which other processes take place and interact continuously with that environment.
- Autonomy: agents operate autonomously within their environment, based upon their own goals.
- Society: agents operate within a society of other agents, which may be human or artificial.

Collectively these characteristics distinguish agent systems from earlier conceptualisations within Computer Science.

To illustrate the application of information fusion agents to impact and situation fusion, we discuss a multi-agent implementation that forms an assessment of behaviour involving a number of agents to effect the movement of military resources. The framework presented is applied to assess our own likely behaviour, but could be extended adversarial contexts to assess likely enemy behaviour, given their intent.

2 Fusion Using Agents

2.1 Fusion Agent Based Model

Figure 2 illustrates our agent information fusion model, which is similar to the fusion tree in [4]. There are two types of agents, Situation Agents (SA) and Fusion Agents (FA). SA are connected to information sources, databases and/or sensors (level 1 of the λJDL model), and process these in order to form *beliefs* about the world. Beliefs are expressed as relations between objects, describing *how the world is taken to be*. They are characteristic of level 2 in the λJDL model. SA communicate these beliefs to FA when requested, to achieve, or contribute to achieving, FA intentions.

FA perform impact and situation fusion (level 2 and 3 of the λJDL model), and communicate the results to other FA, when requested to achieve, or contribute to achieving[1], their intentions. FA have two types of intentions. The first type of intention is to derive some belief about the world, and thus is about understanding how the world is now. This is characteristic of situation assessment. FA seek beliefs from other SA and FA to determine how they might derive this belief. The second type of intention is about understanding how the world could be, which is characteristic of impact assessment. *Behaviours* represent how the world could be. They are actions that can be executed in the current state of the world to achieve some other state. FA seek proposed behaviours from other FA in order to assemble an assessment of the impact that the current situation can have on its intentions due to future actions. FA try to determine how their intentions can be satisfied (or dissatisfied) based on proposed behaviours that can be performed by other FA, where the proposed behaviours that other FA are willing to communicate are based on *their* intentions.

Beliefs and proposed behaviours provided by SA and FA to satisfy the intent of other FA will be referred to as *proposals*. When SA and FA propose beliefs and behaviours, they are called Proposing Agents (*PA*).

There are three types of behaviours. Proposed behaviours are actions that FA offer to perform for other FA. Possible behaviours are all actions that a FA can perform, hence describes its capabilities. Actual behaviour is the execution of some action. The term "behaviours" in the rest of this paper refers to proposed behaviours, unless stated otherwise. FA hold a local plan, comprising a sequence of the behaviours that they expect to perform in the future.

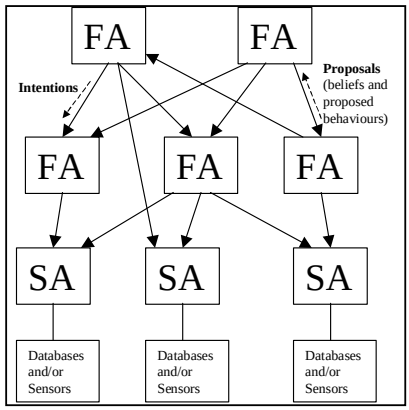

Figure 2. Fusion Agent Based Model, containing Fusion Agents (FA) and Situation Agents (SA).

SA and FA process and provide beliefs and behaviours based on their domain of expertise and capability to perform actions. SA represent entities that provide information and expertise about the current state of the world. Examples include agents that provide information about the weather, fuel holdings and location of enemy assets. FA can represent either entities that provide information or expertise at a higher level of abstraction, and hence uses beliefs from other SA and FA to derive it; or represent and model functional entities, such as organisations and assets, modelling their intentions, behaviours and business processes. Examples include agents that represent friendly or enemy army units, cargo ships and aircraft, and commercial freight companies.

2.2 Domain Characteristics

Agents in our fusion model can be benevolent or self-interested. Benevolent agents act to increase some global,

[1] Adversary FA send proposals to defeat friendly FA intentions. We focus on the friendly case (interaction between friendly FA).

or other agent's, utility, even though its actions may decrease its own utility. It typically occurs, for example, between agents of same organisation. Self-interested agents act to increase their own utility and usually occurs between agents of different organisations or that are competing. Agents may be reluctant to release their information because, for example, it can be proprietary or classified. Our fusion model is an open system, where agents, of indeterminate capability and expertise, may come and go at any time. The fusion domain is dynamic because agent's beliefs, capabilities and intentions are continually changing.

2.3 Agent Approaches to Fusion

Fusion for FA is essentially an agent planning problem. An agent plan specifies which proposals it requires, from which agents, and in what order the proposals are put together (if applicable), in order to achieve its intentions. Two typical approaches to agent planning are classical planning and knowledge approaches.

Classical planning, or operations research, approach forms plans from *first principles*, i.e. builds plans from scratch by assembling agent's proposals to achieve some intention. Most classical approaches are centralised, requiring information about all agents to be communicated to a single agent for processing. Agents are reluctant to release their information, and to do so may require extensive information from many agents to be communicated. The dynamic nature of the domain will make it difficult to keep information up to date.

A knowledge (or procedural) approach is where plans are defined *a priori* and are hard coded into the agents, rather than developed from first principles. Hence, for a particular intention, an agent knows which proposals are required to achieve the intention and from whom it requires the proposals. This technique may not work well for domains that are unconstrained, dynamic, complex and open, such as our fusion domain. It can be difficult to explicitly define plans for all situations, and requires agents to have knowledge of the existence of other possible agents and their capabilities and expertise at design time, which may not be possible.

The Contract Net Protocol (CNP) [7] is one example of a predominantly knowledge approach. Proposals required to achieve a particular intention are predefined, but which agents must provide it is not. The required proposals, or agent's subgoals, are announced to a set of agents. Agents may offer a proposal, but only proposals that achieves a *complete* subgoal. The proposal that best achieves the subgoal is selected. Fischer et al. showed that using CNP in the transportation planning domain will likely result in a poor plan. The transportation planning domain resembles our fusion domain. A better plan could be obtained if the proposals to achieve a particular intention were determined at runtime (from first principles) based on the capabilities and expertise of other agents at the time [8]. The Extended Contract Net Protocol (ECNP) was developed to do exactly this [8, 9].

3 ECNP

ECNP [8, 9] provides a distributed (decentralised) method for planning via first principles using the reactive means-ends analysis (depth first search) [10] approach. In ECNP, an agent will announce its intentions to a set of agents. Agents may offer proposals to achieve *part of*, or the complete intention. The proposal that best achieves part, or the entire, intention will be selected. The difference between the intention, and the part of the intention achieved by the selected proposal, becomes the new intention to be achieved. This process is repeated until the agent's intention is completely achieved, in which case a distributed plan has been formed.

Allowing partial proposals, i.e. proposals that *may* achieve part of the intention rather than the complete intention, permits the agent to not have to specify exactly how to achieve an intention. Instead, it extracts proposals that may form part of the solution and decides which of them to use, and how to best assemble them, in order to achieve its intention. Agents therefore do not require knowledge of other agent's capabilities and expertise to perform the planning [8], removing the need to communicate extensive or proprietary information. Instead, agents will send proposals that are available at the time, that are relevant to the intention, and that they are willing to offer. Therefore, the conceptual idea behind ECNP is ideal for our domain.

3.1 The Protocol – Impact Fusion

ECNP was developed for the transportation domain, which is essentially an impact fusion problem. It will be explained in the fusion context. FA have an intention, which is the transportation of resources, to be achieved by PA, who can perform part of, or the complete, intention. FA announce the intention to all PA, and PA reply with proposals (behaviours) to transport some or all of the quantity to be transported. FA select the best proposal, based on the ratio of quantity transported for the cost to transport the resources. FA give the PA that sent the best proposal a "temporal grant", so that the PA can hold the proposal until a plan for the rest of the intention (quantity to transport) is resolved. The unselected proposals are given a "temporal reject", causing them to be permanently deleted. If the granted proposal did not cover the complete quantity to be transported, then the remaining quantity will be re-announced as the FA's new intention to be achieved. This process continues until the complete quantity has been accounted for. If the final plan is suitable, FA send the PA with proposals that have a temporal grant for this intention a "definitive grant". PA change their local plans accordingly. If the schedule is not suitable, the PA are

given a "definitive reject", thus reverting to their original local plan without the proposals.

With impact fusion more generally, the intention does not have to be transportation of resources, but can be any state of the world that FA would like achieved. Proposals sent must be behaviours, hence only FA contribute, and could be any actions that PA can perform that they believe can achieve, or partly achieve, the intention.

3.2 ECNP For Situation Fusion

ECNP can also be applied to situation fusion. Intentions can refer to beliefs that FA want to infer or prove about how the world is. PA issue proposals, which are beliefs, to FA when they believe it will achieve, or partially achieve, the FA's intention. There is a fundamental difference between the way proposals in impact fusion and situation fusion need to be handled. Since proposals in impact fusion are behaviours, describing actions that PA can perform, PA need to be notified, or some agreement process needs to be undertaken, if their proposal is to be utilised. This way, FA and PA can commit to the proposal and PA can change their local plan to include the behaviour. Proposals in situation fusion are just beliefs (or information), not actions, and so there is no need to "grant" them. Beliefs are utilised by FA observing them when communicated. No agreement process is required.

Although "granting" may not be necessary in situation fusion, FA will still use it. This will keep the behaviour of FA for impact and situation fusion consistent, having the same protocol for both fusion processes. Notifying PA that a belief they had sent is being used provides them with the knowledge of which beliefs, for which intentions, are being used by whom. This allows PA, for example, to notify the relevant FA if the belief changes.

3.3 Shortfalls of the ECNP

A major shortfall with ECNP is that it does not allow for backtracking, enabling FA to revisit bad choices made in granting proposals. This can occur if FA grant proposals that do not lead to a solution. Backtracking is also required if FA decide to use a deliberative search approach, such as A* [11], to pursue an *optimal* plan to achieve its intention, rather than the (sub-optimal) reactive depth first search approach specified by ECNP. This allows FA to grant another proposal to an intention if it believes that the currently granted proposal will result in a bad solution. ECNP's specification does not accommodate backtracking because it does not allow FA to reject individual proposals that were previously granted. When a definitive reject is received, PA will discard *all* of its proposals that it sent the FA and revert back to its original local plan.

Both FA and PA in ECNP delete proposals that are given temporal rejects. These proposals may be required later if backtracking occurs. If temporal rejected proposals are deleted, then FA will need to re-announce a previously announced intention during backtracking. This may result in FA receiving the same proposals it had received previously, wasting time and communication. Therefore, temporally rejected proposals should be kept.

Temporally rejected proposals, if kept, may not be valid if selected at a later time during backtracking. Beliefs may become false or change. Behaviours, or conflicting behaviours, may have been sent and granted for another intention (by the same or different FA). PA sending FA messages when proposals are no longer available would result in increased communication. A suitable method to describe the persistence of proposals is required.

If intentions are not re-announced during backtracking, then FA may miss out on other, possibly better, proposals that recently became available. Therefore, new proposals should be made available to FA without it having to re-announce its intentions.

ECNP suffers from the eager bidder problem [12]. When PA sends proposals (behaviours) for an intention, they are committed to the proposal even though the proposal has not been granted, and hence cannot make the same proposal, or conflicting proposal, to other FA. If the proposal is rejected, other FA may miss out on the chance to use the proposal that could have been sent to them.

4 Provisional Agreement Protocol

The ECNP will be modified to suit the fusion domain. The new protocol is called Provisional Agreement Protocol (PAP).

4.1 Persistence Policy

To accommodate backtracking, PAP implements a ***persistence policy*** where *agent's intentions and proposals that are communicated are considered persistent unless they reveal otherwise*. When PA send a proposal to a FA, the FA believe the proposal is valid (or active) and that they can grant the proposal, unless the PA reveals otherwise. Conversely, when FA announce an intention to PA, the PA believe that the intention is active (needs to be achieved) and can send proposals for it, unless the FA reveals otherwise. "Reveals", rather than "is told", is used in the definition of the persistence policy to indicate that the originator of a proposal or intention does not inform the relevant agent(s) if the proposal or intention becomes inactive. The originator only informs agents that a proposal or intention is no longer active if they attempt to *use* it. Therefore, if PA make a proposal for an intention that is no longer active, the FA will inform the PA of this belief, and thus the PA may remove the intention from their knowledgebase so that it will not send proposals for it again. Also, if FA grant a proposal from PA that is

inactive, then the PA will inform the FA of this belief, allowing the FA to grant another proposal.

The persistence policy removes the requirement for FA to reject proposals that they do not intend to use, and thus allows the proposal to remain available later for granting if required, assuming it is still active. Eliminating rejection messages between FA and PA will reduce communication. The only rejection messages that are required is to reject a previously granted proposal, which most likely occurs during backtracking.

4.2 Commitment Policy

PAP also implements a ***commitment policy*** requiring that *proposals sent by an agent are not committed to unless granted*. Thus, PA may send proposals for intentions without being committed to them. Therefore, PA may send conflicting behaviours concurrently, to the same or many FA, and are not obligated to update changes in beliefs that have been sent. This permits the elimination of rejection messages, particularly for behaviours, since they do not need to be rejected before they can be used elsewhere. Only one FA may be able to grant a specific behaviour, or one that conflicts with it, from a PA. Hence, the first FA to grant the behaviour can use it. Another benefit of the bid commitment policy is that it prevents the eager bidder problem associated with behaviours. The commitment policy is similar to an approach that Schillo, et al. [12] proposed.

PAP allows FA to reject *individual* proposals that had been previously provisionally[2] granted. This occurs during backtracking to reject a proposal that resulted in an infeasible or bad solution. If a proposal is rejected, the PA will de-commit from the proposal, and in the case of a rejected behaviour, removes it from their local plan.

Intentions announced by FA are stored by the PA for future use, whether they submit a proposal or not. Therefore, PA can submit proposals for a FA intention anytime they believe the intention is active. Announced intentions in PAP specify a deadline, which is the *earliest time* the FA will give a proposal for that intention a provisional grant. Unlike most CNP approaches, FA will accept a proposal after the deadline. A provisionally granted proposal may latter be deemed inappropriate, and so late proposals may be considered and selected. As a result, proposals for an intention can be considered at anytime during the fusion process.

From the PA perspective, storing FA intentions and allowing proposals after the deadline, enables PA to update proposals, either because a proposal that was recently sent became inactive, or because a better proposal becomes available. PA may also make an initial proposal for an intention that was not previously possible when the intention was first announced.

PAP requires more memory than ECNP to store intentions and proposals. Strategies can be implemented to limit the number of intentions and proposals stored in FA and PA memory, such as deleting proposals and intentions that they reveal are no longer active, are old, or that are not relevant or less useful than other intentions and proposals.

4.3 PAP Speech Acts

PAP comprises 5 speech acts. These include *"provisional grant"*, *"provisional reject"*, *"confirm grant"*, *"withdrawn"* and *"provisionally withdrawn"*. The first three are based on ECNP speech acts.

Provisional grant is used by FA to get PA to commit to a proposal it provided, but allows the FA to reject the proposal if it found it inappropriate. It is similar to a tentative booking, done when there is uncertainty at the time that a service will meet an individual's needs. A proposal is given a provisional grant if FA believe it will be part of a solution to its intention, but since a full solution has not been found, the FA cannot guarantee it. On receiving a provisional grant for a proposal, a PA must commit to the proposal. If the proposal is a behaviour, then PA enter it into their local plan, and tag it to indicate that it is provisionally granted. If it is a belief, then the PA will tag it accordingly and perform its commitment obligations with respect to it, such as notify FA if there are changes to the belief. PA may enforce a time limit for which a provisionally granted proposal must be secured before it de-commits from it.

Provisional reject is used during backtracking to reject an individual proposal that was previously given a provisional grant. On receiving a provisional reject for a proposal, PA will de-commit from it. If the proposal is a behaviour, then PA remove it from their local plan.

Confirm grant is used to secure an individual proposal that was previously given a provisional grant. If the proposal is a behaviour, PA will secure it in their local plan. If it is a belief, it will be tagged accordingly, and possibly new (full) commitment obligations pursued. When FA arrives at a plan to achieve its intention, all the provisionally granted proposals in the plan are given a confirm grant to secure the plan.

To explain the last two speech acts, a description of how intentions and proposals in PAP are represented is required. Intentions and proposals have states associated with them. An intention's two possible states are *"active"* or *"withdrawn"*. A proposal's three possible states are, *"active"*, *"provisionally withdrawn"* or *"withdrawn"*. Intentions and proposals can only be in one state at any time.

[2] In the PAP, we use the term provisional(ly) rather then temporal(ly).

An *active intention* indicates that there is not a confirmed solution for the intention, i.e. FA have not found proposals that can achieve the intention and have been given a confirm grant. Hence, FA are still considering proposals to achieve it, and are available for PA to send proposals. A *withdrawn intention* indicates that an intention has found a confirmed solution, was part of an infeasible solution, or is no longer required to be achieved.

An *active proposal* indicates that the proposal is still available for granting. For a behaviour, this means that PA can place it into their local plan. For a belief, it means that it is still true. A *provisionally withdrawn proposal* indicates that a proposal is not currently available for granting, but may become available at a later time. For a behaviour, this occurs when the behaviour conflicts with another behaviour(s) that was given a provisional grant (but does not conflict with a confirm granted behaviour). The behaviour is therefore not yet fully withdrawn because there is a chance that the provisionally granted behaviour(s) that conflicts with it may be rejected, hence resulting in the behaviour becoming active again. A belief can be provisionally withdrawn, for example, if PA are no longer certain that a belief is true or not, and so may be in the process of fusion themselves to determine its truth. A *withdrawn proposal* indicates that the proposal is no longer available for granting. For a behaviour, this is most likely due to the belief that it conflicts with at least one behaviour that was given a confirm grant, which is unlikely to be rejected, hence the behaviour can no longer be placed into PA local plans. For a belief, PA may have found the belief to no longer be true.

When FA send an intention to (one or more) PA, both the FA and PA store a copy of the intention with the state set to active. If FA withdraw the intention, the state of the intention will be set to withdrawn. Note that withdrawn intentions and proposals may be deleted, and so their absence signifies that their state is withdrawn. Due to the persistence policy, the state of the intention for PA will remain active unless they reveal otherwise. Therefore, if PA, which still believe that a withdrawn intention is active, attempt to send a proposal for the intention, the FA will send back a withdrawn message for the intention. The PA can then set the state of the intention to withdrawn. If FA provisionally grant a proposal for an intention, the intention remains active because the FA may come back to it later during backtracking.

When PA send a proposal for an intention to FA, both the FA and PA store a copy of the proposal with the state set to active. If PA proposals become withdrawn or provisionally withdrawn, then they will change the state of the proposal accordingly. The persistence policy requires that the state of the proposal for FA will remain active unless they reveal otherwise. Therefore, if FA, which still believe that the proposal is active, attempt to provisionally grant the withdrawn or provisionally withdrawn proposal, then PA will send a withdrawn message or provisionally withdrawn message, respectively. FA can then change the state of the proposal accordingly. Withdrawn proposals may be removed, but provisionally withdrawn proposals may become active later. FA can implement strategies for dealing with provisionally withdrawn proposals, i.e. when to grant the proposal again. Later, we present two strategies for two different fusion approaches.

5 Fusion Process and Example

5.1 Definitions

FA must achieve a dynamic set of intentions, which at time t is $I_t=\{i_1, i_2, \ldots, i_n\}$, where i_n is an intention. Temporal constraints can be associated with intentions. The set of PA that can be used to achieve I_t are $PA_t = \{a_1, a_2, \ldots, a_i\}$. $bel(a_j, t)$ and $poss\_behav(a_j, t)$ are functions that provide the set of beliefs and behaviours, respectively, that an agent a_j can *possibly* propose at time t. Possible proposals that may be supplied by agent a_j is given by $poss\_prop(a_j, t) = bel(a_j, t) \cup poss\_behav(a_j, t)$. All possible proposals in the agent (fusion) system at time t is $sys\_poss\_prop(t) = \cup\{poss\_prop(a_j, t) \mid a_j \in PA_t\}$. Temporal constraints can be associated with proposals. Ideally a fusion process could find a plan P_t at time t, where $P_t \subseteq sys\_poss\_prop(t)$, that maximises the achievement, or minimises the dissatisfaction, of I_t, and hence satisfies $\underline{diff(I_t, P_t) = \varnothing}$ [3] & $\underline{\min(diss(I_t,P_t))}$, where functions diff(i, p) outputs the difference between the intention i and the plan p, where p can be one, or set of, proposals, diss(i, p) calculates a measure of the dissatisfaction of the plan p to satisfy intention i, and min(x) minimises x.

5.2 Agent Fusion Process

The general fusion process for FA can be described by (refer figure 3):

1. Announce intention *I*, with deadline for receiving proposals.
2. Wait for the deadline to pass, receive proposals $p_1, \ldots, p_j$ for *I*. If no proposals received, go to step 4.
3. Calculate the expected dissatisfaction between p_j and *I*, giving FA some cost measure $c_j = diss(I, p_j)$.
4. Decide on the next proposal p to provisionally grant:
   a. **Depth-first search** – list proposals for *I* $(p_1, \ldots, p_j)$ from lowest to highest c_j. Provisionally grant p at head of list. If the FA receives a withdrawn or provisionally withdrawn message for p, delete p and provisionally grant the next p from the head of the list. If no proposals left, then backtrack – move to previous intention in tree, repeat step (a).
   b. **A*** – scan *all* proposals that have not previously been given a provisional grant (i.e. proposals at leaf

[3] In some circumstances, we may want $\min(diff(I_t,P_t))$.

of tree). Find p with the lowest c. Provisionally reject any provisionally granted proposals that are not along the single path in the tree from the root node (initial intention) to p. Provisionally grant all proposals, which have not already been, that are along a single path from the root node to p, starting from the root node. If the FA receives a withdrawn message for any of the proposals, delete the proposal, and all the proposals and intentions (branches/nodes) following the proposal, repeat (b). If the FA receives a provisionally withdrawn message for any of the proposals, then the proposal, and all the proposals following it, will be removed for the next k iterations from being a candidate for granting, giving the proposal time to become active again (if it does at all), repeat (b).

5. New intention to be achieved is the difference between the *I* and p, $I \leftarrow \text{diff}(I, p)$. If there is no difference, $\text{diff}(I, p) = \varnothing$, the intention *I*, hence FA initial (complete) intention, has been achieved, thus confirm grant all provisionally granted proposals and exit. Otherwise, go to step 1.

FA broadcast their intentions to PA, and the scope of the broadcast depends on the knowledge that FA have of other agent's capabilities and expertise. Provisionally withdrawn proposals are deleted in the depth-first approach because of its reactive nature. Proposals are usually considered only once, unless backtracking occurs, where it will usually be considered again soon after. Rather than wait for the proposal to become active again, if at all, it is more effective to move on with the planning and ignore the proposal. Due to A*'s slower deliberative nature, and that all proposals are considered throughout the planning process, FA may try to grant a provisionally withdrawn proposal during some future iteration.

FA accept proposals for any intention at any time. If FA receive a proposal for a withdrawn intention, it will delete the proposal and send PA a "withdrawn" message, otherwise they will store the proposal. Only one single path in the tree of provisionally granted proposals is allowed in A* because behaviours that may be granted on one path cannot be used, and hence may prevent opportunities for, behaviours in another path in the tree. FA must know how to work out the estimated dissatisfaction cost measure, which must not be an overestimate to find an optimal solution in A*, and the difference between a proposal and an intention. These will be domain specific. The cost measure in A* may include computational and communication costs (effort), in order to produce the best plan with the amount of effort required to create it. This fusion process considers only friendly fusion, i.e. PA assist in achieving FA intention rather than trying to defeat its achievement.

On receiving an intention from FA, PA store it and check whether they have any appropriate proposals to send. This is easy if PA have proposals that can achieve the complete intention, but harder for it to determine if a proposal could potentially contribute to achieving part of the intention. Therefore, PA should be able to determine the *likelihood* that their proposals will form part of the solution, or alternatively, form proposals that have a high likelihood of being part of the solution. The likelihood calculation is domain dependent, and can incorporate PA prediction of both FA cost measure for their proposal, and the cost measure of other possible proposals that may be sent by other PA. Many PA proposals may be candidates. The number of proposals that is sent can depend on factors such as quality of the solution required (more proposals give more options and potentially allow a better solution), communication costs, and computation costs (takes time for PA to form proposals, hence they can only generate a limited number before the deadline). Only the best proposals, based on PA evaluation, should be sent. Other activities of PA can be derived from section 4.3.

5.3 Example

A simple example of the (depth-first) fusion process using PAP applied to a logistics (transportation) domain follows (refer figure 3). FA intention ***I*** is to move fuel from Cairns to Sydney (impact fusion), hence "move(fuel, Cairns, Sydney)" is announced. Proposals p_1, p_2 and p_3 are received. FA provisionally grants FA1's proposal p_3 to move fuel from Cairns to Townsville, move(fuel, Cairns, Townsville), where FA1 represents a commercial freight company. The difference between the intention ***I*** and the proposal p_3, move(fuel, Townsville, Sydney) (I_1), is the new intention to be achieved, and is announced. Two proposals are received, move(fuel, Townsville, Brisbane) (p_5) and move(fuel, Townsville, Newcastle) (p_4), from FA3 and FA2 respectively. FA2's proposal is provisionally granted, and the intention move(fuel, Newcastle, Sydney) (I_2), is announced. No proposals are received by the deadline, and so FA assumes no solution exists. Backtracking occurs, FA2's proposal p_4 is provisionally rejected, FA3's proposal p_5 is provisionally granted, and the intention move(fuel, Brisbane, Sydney) (I_3) is announced.

On receiving FA intention, FA4, which represents a C130 (military cargo plane), realises it can perform the complete intention if it can land at Sydney airport. This becomes FA4's new intention to achieve (situation fusion), hence "land(C130, Sydney)" is announced (not shown in figure 3). FA4 receives two proposals, "land(C130, ?X) *if* length(?X, >1000) & weather(?X, not_windy)", and "land(?Y, ?X) *if* length(?X, >2000) & weather(?X, clear) & weight(?Y, <500)" (?X and ?Y are variables), from SA1 and SA2 respectively. FA4 provisionally grants the first proposal because it is more specific, and the new intention (difference) is announced, which is "length(Sydney,

>1000) & weather(Sydney, not_windy)". FA4 receives length(Sydney, 2000) from SA2 and weather(Sydney, not_windy) from FA5, satisfying FA4's intention. FA4 confirm grants the relevant proposals, and submits the proposal move(fuel, Brisbane, Sydney) (p_6) to FA. FA receives the proposal and provisionally grants it. FA intention has been achieved, and thus the relevant proposals are given a confirm grant.

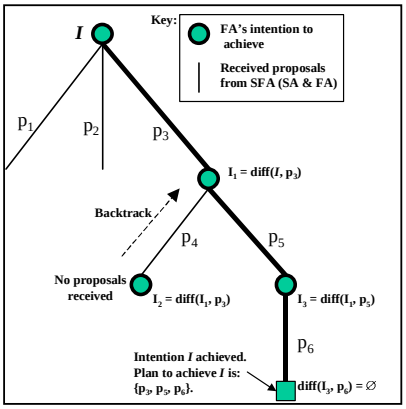

Figure 3. Illustration of FA fusion process using PAP.

5.4 Implementation

One of our domain applications of information fusion is logistics planning [13], focussing on distributed transportation scheduling. Details are beyond the scope of this paper. A prototype was developed using the ATTITUDE [14] agent programming language, using the depth-first approach. The scenario comprises one FA, with a task to move fuel between Melbourne and Sydney, and three PA. Using PAP for our particular scenario produced the optimal transportation schedule. The time that PAP takes to find a solution depends mainly on the proposal deadline (that should be based on the time taken for TA to form and send proposals), accuracy of FA cost measure, the amount of backtracking required, and the size of the intention (i.e. number of proposals required to find a solution). Due to space restrictions, a formal evaluation of PAP cannot be presented. We are currently setting up a much larger scenario, with 2 FA and over 15 PA.

6 Conclusion & Acknowledgements

Agents provide a suitable technology for information fusion, facilitating distributed goal driven fusion. We presented an agent based fusion model, where agents model fusion entities capabilities, expertise and intentions. Agents perform fusion based on their intentions. They co-operate with each other to extract the relevant information in order to achieve their intentions. We applied fusion to friendly contexts, and to the logistics domain.

Extended Contract Net Protocol (ECNP) provides a distributed (decentralised) fusion approach, but has its shortfalls for the fusion domain. This includes in inability for backtracking during the fusion process. Provisional Agreement Protocol (PAP) is an extension of the ECNP. Five speech acts, together with policies regarding the persistence and commitment of agent proposals and intentions, are proposed. This permits backtracking and a more deliberative approach to fusion. Implementation details and an example were presented.

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