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Agent-Based Coalition Formation in Disaster Response Applications

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***Abstract*— We present an agent-based coalition formation approach for disaster response applications. We assume that agents are operating in a dynamic and dangerous environment, and they need to form convoys to traverse unsafe areas. We introduce a commitment-based convoy model, where the commitments are negotiated between the participant agents. We show that this leads to a complex multi-issue negotiation, with two spatial and two temporal components. We propose an approach for reducing the negotiation space through the creation of discrete offer points, and describe a possible negotiation flow. We validate the model in a scenario using the map of New Orleans flooded by hurricane Katrina.**

***Index Terms*— coalition formation, embodied agent, convoy formation, disaster management**

1. INTRODUCTION

Efficient disaster response requires participants to form teams and coordinate their actions. This process is complicated by a variety of factors:

Dynamic, unpredictable and dangerous environment. In the immediate aftermath of a disaster (such as the hurricane Katrina in New Orleans or the asian tsunami) previously safe areas might become dangerous or unaccessible. The environment might contain new sources of danger in the form of natural obstacles (damaged buildings) or even hostile agents (such as looters or stray dogs).

Dynamic tasks. In rescue missions, tasks appear unpredictably. The discovery of a wounded person at a dangerous location creates a new task with specific logistics, protection and medical aspects. In severe disasters, the number of tasks can greatly exceed the available resources. Occasionally, tasks need to be preempted for higher priority tasks.

Dynamic teams and collaboration patterns. Although some disaster management teams are pre-established, trained together and have a clear pattern of command and control, many teams are assembled on an ad hoc basis, as a response to emerging tasks. Teams are composed from heterogeneous groups of entities: persons, vehicles, service animals, and so on. Team members might not report to the same chain of command, might have communication problems and their interests might not be completely aligned. For instance, the state police and guerilla groups might cooperate in a rescue operation but resume hostilities after the emergency.

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Breakdown in communication lines. In many environments, we normally assume that there is a full connectivity of the mobile agents. Police units normally maintain connection to a central dispatcher over dedicated frequencies. Although it is desirable to maintain this organization in a disaster area as well, in practice, this centralized communication frequently breaks down. For instance, after hurricane Katrina, the policy could use their radios only as pair-to-pair walkie talkies. This prevents the collection global information and centralized command of operations.

Our research group at the Networking and Mobile Computing (NetMoc) laboratory at University of Central Florida is working on a negotiation based coalition formation approach which can be used to assemble ad hoc coalitions in an emergency management scenario. In this paper, we are concentrating on the negotiation regarding convoy formation for mobility in a dangerous environment.

Our assumption in this paper is that forming convoys is always advantageous. This assumption holds in many instances in disaster response applications; for instance many organizations instruct their workers not to go alone in dangerous area. There are, however, several worthwhile exceptions. For instance, a damaged bridge of limited bearing capability might only hold a small number of agents. In other situations it might be necessary to reduce the size of the convoy for achieving stealth or to prevent alarming or offending the local population. Thus, the utility of the convoy might not be super-additive (or even monotonically increasing) with the number of participants. For instance, the stealth of a convoy decreases with its size. These issues are subject of future research of our group.

The environment considered in this paper assumes a 2-dimensional geographic area, where we identify: *safe areas* which are traversable by any agent, *danger areas* which are traversable only by convoys and *unaccessible areas*. The model can be extended in a straightforward way to involve more than three area types which affect the movement of the vehicles in a variety of ways (such as slowing down, requiring higher energy consumption, and so on). In this environment, we consider the actions of a set of *embodied agents*, which have a well-defined physical location and movement capabilities. In practice, these agents can be "RAP" (Robots, Agents and/or Persons). The goal of every agent is to reach a destination location. Beyond disaster rescue, these types of scenarios arise in other applications as well, such as military operations in urban terrain.

The time to reach the destination can be improved by the formation of convoys. In certain cases, the agent can not reach the destination except through joining convoys. We assume the agents *self-interested* but *honest*; the agents keep their negotiated commitments. The notion of building and adhering with commitments [**?**], [**?**] is central for the operations of the system. The embodied agents are using message based communication, which can be either point to point or broadcasted to all other agents in the transmission range.

Negotiation is the process by which a group of agents come to a mutually acceptable agreement on some matter [**?**]. In our scenario, the subject of negotiation is the joining and leaving convoys, and the adaptation of the path of the convoy to the requirements of the agent. The agents are exchanging a set of offers, based on their *offer construction strategies*. The other party is using its *offer evaluation strategy* to make a decision, which can be either to accept the offer, send a counteroffer or terminate the negotiation.

The remainder of this paper is organized as follows. We describe a convoy formation mechanism based on spatio-temporal commitments in Section 2. The process of negotiation through which can agree upon these commitments is considered in Section 3. These concepts are illustrated in an experimental scenario involving a map of New Orleans after it was flooded by hurricane Katrina in Section 4. We survey related work in Section 5 and conclude in Section 6.

2. Convoy formation mechanism

2.1. *Convoy structure and commitments*

In this section we describe a mechanism for the structure of the convoys based on a set of spatio-temporal commitments of the participant agents and the convoy itself. In this section we will see how this mechanism conditions the lifecycle of the convoys. In Section 3 we describe the negotiation process which leads to the adoption of a certain set of commitments.

We define a *convoy* as a coalition of embodied agents which agreed on a common path and schedule. Normally, the agents of the coalition have a common location and speed; however, from a logical perspective, we consider an agent which has agreed to join a convoy and it is on its way to a rendezvous point as part of the convoy.

Formally, a convoy C is described by a set of agents $S = \{A_1, \dots A_n\}$, a leader agent $A_L \in S$, and a set of commitments $G = \{g_1, \dots g_n\}$. The commitments of the convoy can be seen as representing the interests of the participating agents and are expressed as constraints on the path of the convoy. The role of the leader is to negotiate on behalf of the convoy and to determine its path, taking into account its previous commitments G.

The commitment of the convoys are related to visiting locations and can be classified as "before" (B) and "after" (A) commitments. A "before commitment" $B(L,t)$ commits the convoy C to arrive to location L *not later than* time t.

$$B(L,t) \in G_C \text{ is satisfied iff } \exists\ t_r \le t, \text{location}(C,t_r) = L \quad (1)$$

An "after commitment" $A(L,t)$ commits the convoy C to leave location L *not sooner than* time t (if the convoy reaches that location sooner, it can, of course wait at the location).

$$A(L,t) \in G_C \text{ is satisfied iff } \exists\ t_r \ge t, \text{location}(C,t_r) = L \quad (2)$$

Intuitively, if two convoys X and Y want to rendezvous at the location L_R, they will agree on a rendezvous time t_R and will take the commitments $A(L_R,t_R) \in G_X$ and $B(L_R,t_R) \in G_Y$ (or the other way around).

We will call a commitment g_1 *stronger than* a commitment g_2 and denote it $g_2 \subseteq g_1$ if every set of actions which satisfies g_1 also satisfies g_2.

Theorem 1:
(a) $\forall L, t_1 \le t_2 \Rightarrow B(L,t_2) \subseteq B(L,t_1)$
(b) $\forall L, t_1 \le t_2 \Rightarrow A(L,t_1) \subseteq A(L,t_2)$

Proof:

(a) Let us consider a series of events such that $B(L,t_1)$ is satisfied. Then, according to the definition, exists $t_r \le t_1$ such that $\text{location}(C,t_r) = L$. However, $t_1 \le t_2$, thus $t_r \le t_2$. Thus, $B(L,t_2)$ is also satisfied, using the same time-point t_r.

(b) Let us consider a series of events such that $A(L,t_2)$ is satisfied. Then, according to the definition, exists $t_r \ge t_2$ such that $\text{location}(C,t_r) = L$. However, $t_1 \le t_2$, thus $t_r \ge t_1$. Thus, $A(L,t_1)$ is also satisfied, using the same time-point t_r. ■

2.2. *An example of convoy formation*

In the following we will discuss the evolution of the commitments throughout the lifecycle of the convoy through an example. We will ignore both the negotiation flow as well as the relative utility of the commitments for the agents; these aspects will be discussed in Section 3.

2.2.1) Before convoy formation: Let us consider two agents X and Y moving from the source locations $SrcX$ and $SrcY$ to their destinations $DestX$ and $DestY$ respectively. Planning their paths in isolation, they reached the conclusion that their expected times to reach their destinations are t_{tx} and t_{ty} respectively. This can be represented through the commitments:

$$\begin{array}{rcl} G_x & = & \{\ B(DestX, t_{tx})\ \} \\ G_y & = & \{\ B(DestY, t_{ty})\ \} \end{array} \quad (3)$$

This state of affairs is represented in Figure 1-a.

2.2.2) Convoy formation agreement: Through mechanisms to be discussed later, the two agents agree to join into a convoy at location L_{join} and separate at the location L_{leave} which they will reach before the time t_{leave}. They agree that the leader of the convoy will be X.

The agents, through the recalculation of the paths, reach the conclusion that by forming a convoy they can reach their destinations at t'_{tx} and t'_{ty} respectively. A simple model of the rational, self-interested agents would require $(t'_{tx} < t_{tx}) \wedge (t'_{ty} < t_{ty})$. This implies $B(DestX, t_{tx}) \subset B(DestX, t'_{tx})$ and $B(DestY, t_{ty}) \subset B(DestY, t'_{ty})$, thus the original, weaker commitments can be removed from the set of commitments of the agents.

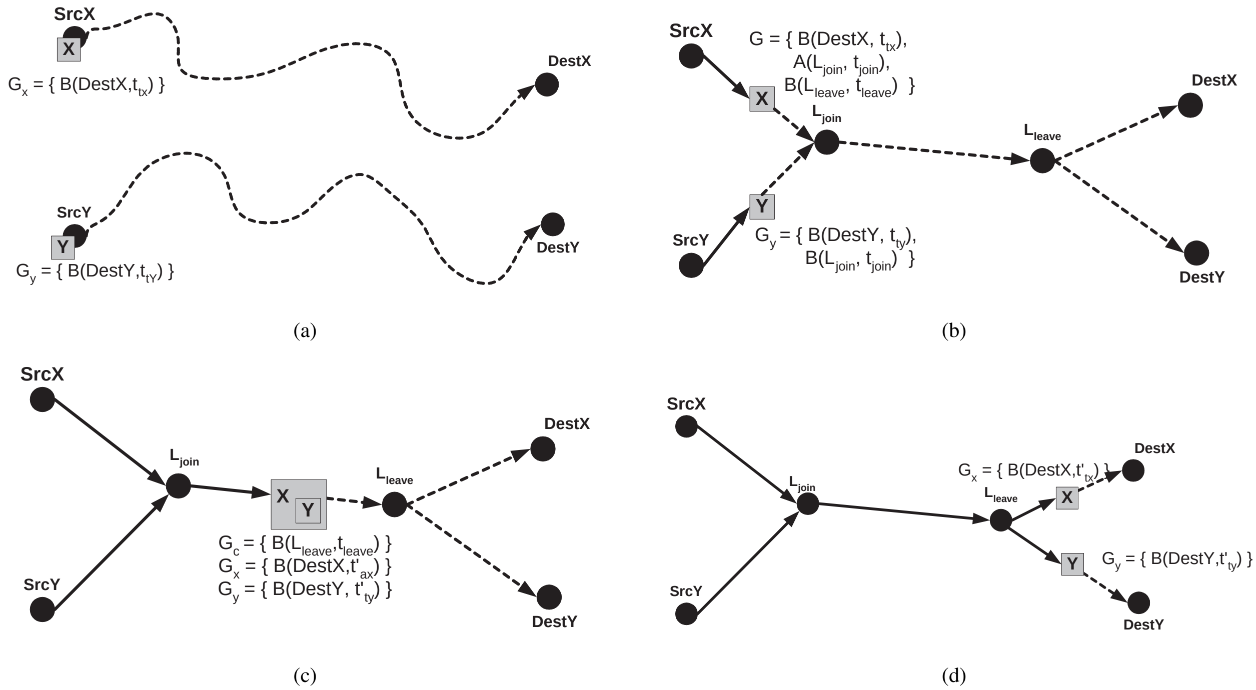

Fig. 1. Four stages of the convoy lifecycle: (a) before convoy formation, (b) after the agreement to join in a convoy, (c) after rendezvous, (d) after leaving the convoy. The previously traversed path is shown as a continuous line, while the current planned path is shown as an interrupted line.

This leads to the following set of commitments:

$$\begin{aligned} G_x &= \{ \quad B(DestX, t_{tx}), \\ &\qquad A(L_{\text{join}}, t_{\text{join}}), \\ &\qquad B(L_{\text{leave}}, t_{\text{leave}}) \ \} \\ G_y &= \{ \quad B(DestY, t_{ty}) \\ &\qquad B(L_{\text{join}}, t_{\text{join}}) \ \} \end{aligned} \tag{4}$$

The agents will modify their paths such that they will meet their commitments regarding the join location (see Figure 1-b).

2.2.3) Rendezvous and convoy formation: If both agents successfully kept their commitments regarding the join location, they are able to rendezvous and form a convoy at L_{join}. Once the time-point for a commitment passed, it will be removed from the commitment set.

The convoy, having X as the convoy leader, has the following set of commitments:

$$G_c = \{ \quad B(L_{\text{leave}}, t_{\text{leave}}) \ \} \tag{5}$$

while the interior elements X and Y, have the commitments:

$$\begin{aligned} G_x &= \{ \quad B(DestX, t'_{tx}) \ \} \\ G_y &= \{ \quad B(DestY, t'_{ty}) \ \} \end{aligned} \tag{6}$$

This stage is shown in Figure 1-c.

2.2.4) Leaving the convoy: At the location L_{leave} the agents forming the convoy separate. As the commitment $B(L_{\text{leave}}, t_{\text{leave}})$ was satisfied, it is removed. The two agents are following their own paths to their destinations, with their respective commitments being (see Figure 1-d):

$$\begin{aligned} G_x &= \ \{ \ B(DestX, t'_{tx}) \ \} \\ G_y &= \ \{ \ B(DestY, t'_{ty}) \ \} \end{aligned} \tag{7}$$

2.3. Multi-agent convoys

Our previous example concerned the simplest case, of a convoy formed of two agents, which rendezvous at location L_{join}, and separate at L_{leave}. The model, however, generalizes in a straightforward manner to the case of multiple agents joining and leaving the convoy. Thus, we can define the operation of *merging of two convoys* $C_1 = \{S_1, G_1\}$ and $C_2 = \{S_2, G_2\}$ such that $S = \{S_1 \bigcup S_2\}$ where $G_1 \subseteq G \bigcap G_2 \subseteq G$, that is, the commitments of a merged convoy are stronger than the individual commitments of the participants.

Similarly, a convoy $C = \{S, G\}$ can split in two convoys $C_1 = \{S_1, G_1\}$ and $C_2 = \{S_2, G_2\}$ with $S = \{S_1 \bigcup S_2\}$. Determining the commitments of the successor convoys is a complex problem. Intuitively, the commitments of the larger convoy represent a compromise over the commitments of the constituent agents. It is possible that some subsets S_i of a larger convoy can negotiate a new convoy such that the commitments G_i of the new convoy are stronger on the subset of the locations which are of interest for their participants. Basically, this means that the smaller convoy can have a path more favorable to its participants. In some cases, this might be beneficial to the remainder of the agents $S_2 = S - S_1$, because they might be able to negotiate a stronger commitment for themselves as well.

In other cases, however, the remainder of the agents might actually be worse off. For instance, there might be only one agent remaining, who can not take advantage of the benefits of moving in a convoy. We can use several mechanisms for to avoid this problem. For instance, we can allow the split of the convoy only in cases when the operation is a Pareto optimization (in the sense of improving on the performance of all participants). Alternatively, we can impose penalties on the agents leaving the convoy before the agreed leave point.

Let us note here, that for multi-agent convoys, the number of possible combinations grows very quickly, and the agents will not be able to do an exhaustive search of all the combinations. Due to limited computation capacity, and limited negotiation time, the agreement eventually reached might be suboptimal (and in some cases, not even Pareto optimal). In these situations, agents which have a greater computational power and/or better algorithms can negotiate better deals than agents which lower computational power.

3. Convoy formation through peer-to-peer negotiation

3.1. Convoy formation alternatives

As we have shown in the previous section, the convoy formation mechanism revolves around the commitments of the agents and convoys. Every agent A starts with a basic goal of reaching its destination $DestA$. Through a path planning process, assuming that it is traveling alone, the agent will make a commitment of reaching the destination point before time t_A, $B(DestA, t_A)$. The act of joining a convoy creates new commitments, adding $A(L_{\text{join}}, t_{\text{join}})$ and $B(L_{\text{leave}}, t_{\text{leave}})$ to the commitment of the convoy and $B(L_{\text{join}}, t_{\text{join}})$ to the commitments of the joining agent.

Note that there are multiple approaches through which the agents might end up taking these commitments. It is possible that a centralized command and control center explicitly tasks the agents with certain commitments. In some cases, some level of negotiation might happen between the control center and the agents; at the minimum, the agent needs to confirm whether a certain commitment is feasible. In this paper we consider the case when the convoy formation happens through peer-to-peer negotiation between agents. This is frequently the case in emergency response situations where control centers either do not exist, are out of communication range, or they are not recognized by all the participants. This was the case for all the major recent natural catastrophes: the Katrina hurricane, the south asian tsunami and the Pakistan earthquake.

To be able to correctly reason about the negotiation process, we will assume the participants to be self-interested. This is a correct model even if the individual goals of the participants are, in the global picture, altruistic. For instance, there is a conflict of interest between two rescue teams which are trying to perform rescue operations at locations A and B, but need to form a convoy to traverse a dangerous area.

In the remainder of this section, we assume that the convoy formation happens through a peer-to-peer negotiation between two participants. The negotiation is a multi-issue model with the issues at play being $\{L_{\text{join}}, t_{\text{join}}, L_{\text{leave}}, t_{\text{leave}}\}$. Note that two of the issues under negotiation are points in a 2-dimensional space. The main difficulty of the negotiation based convoy formation is that the issues under negotiation are under a complex relationship with each other. Many multi-issue negotiation models assume that the issues under negotiation are the equivalent of the price negotiation for a package of items, or the splitting of multiple pies (for a comprehensive treatment of these kind of negotiations see [**?**]). This is not true in our case. The only way in which the value of an offer can be ascertained is by performing a recalculation of the planned path of the agent. Even then, some of the features of the offer are difficult to quantize. For instance, a convoy might negotiate in such a way that it allows the agent to join, but it maximizes the flexibility of the convoy in taking on future agents. Our implementation of the negotiation uses heuristics in the offer formation process. The heuristics allow us both to encode the objectives of the participants, and to reduce the number of offers interchanged in the course of negotiation. However, every generated offer will be fully evaluated by the convoy and the agent through a recalculation of the paths, to verify the feasibility of the agreement and the exact benefit it offers for the agent.

3.2. Heuristic negotiation objectives

Let us consider the objective of the negotiation. We will denote with $\tau_C(L_1, L_2)$ the time it takes for convoy C to move from location L_1 to location L_2. In the simplest case, at time t an agent A with the destination D_A and current location L_A considers joining a convoy C, which has a current set of commitments G. The agent has its current expected arrival time $t_A = t + \tau_A(L_A, D_A)$. In the first approximation, the agent would join the convoy if it can add to its list of commitments an agreement $B(D_A, t'_A)$ with $t'_A < t_A$, that is, it can reach its final destination faster. However, even if this agreement is not feasible, it might be worth for the agent to join the convoy up to an intermediate location called the *leave point*. A sufficient condition for the agent to be worth joining the convoy until leave point L_{leave} is to have a commitment $B(L_{\text{leave}}, t_{\text{leave}})$ such that $t_{\text{leave}} + \tau_A(L_{\text{leave}}, L_A) < t_A$. This is however not a necessary condition; the agent might plan ahead for joining a different convoy after leaving the current convoy at L_{leave}.

In the following we discuss the interests of the participants regarding the four issues under negotiation L_{join}, t_{join}, L_{leave}, and t_{leave}. Our results are independent of whether the participants are individual agents or convoys of multiple agents. However, the existing set of commitments of the participants significantly affect their interests during the negotiation process. Note, however, that the act of rendezvous involves an asymmetric set of commitments (independently whether the participants are agents or convoys). Without loosing generality, we will assume that one of the participants is the "joined", and will make the $A(L_{\text{join}}, t_{\text{join}})$ commitment, and the other one is the "joiner" which will make the $B(L_{\text{join}}, t_{\text{join}})$ commitment. If a standalone agent A joins an already formed, multiagent convoy C than A will act as a joiner and C as the joined. In case of a smaller convoy merging with a larger one, the smaller convoy will act as the "joiner".

L_{join} **the join location.** The interest of the both participants is to negotiate a join location which is as close to their current location as possible, or to be in the general direction of their respective destinations.

The preferences for the joined participant are: (a) to negotiate a join location L for which it has an $A(L_{\text{join}}, t)$

commitment, (b) a location for which it has a $B(L_{\text{join}}, t)$ commitment, (c) a location which is on the current projected path and (d) a location which is close to the current projected path.

Intuitively, (a) does not involve any new commitment for the joined participant (if it manages to negotiate a join time earlier or the same as the previous commitment), (b) requires only a temporal commitment, without new restrictions on the path of the convoy. A location of type (c) restricts the ability of the convoy to change its path (although its current path remains valid), while a point of type (d) requires the convoy to change its path.

For the joining participant, similar considerations apply, however, the order of the preferences (a) and (b) are reversed due to the different commitments they need to take. Note that if the participant has a $B(L_{\text{join}}, t_x)$ commitment, it can easily take any $A(L_{\text{join}}, t_y)$ commitment with $t_y > t_x$, as its path calculation is based on the assumption of time of arrival at the location L_{leave}.

t_{join} **- the joining time.** Once the agent and the convoy had identified a join location they need to negotiate the join time. In broad lines, the joiner negotiates for the latest possible join time (to increase its safety margin in getting there), while the joined for the earliest time (because that minimizes its commitment in waiting for the agent). The join time has to be at least the minimum time needed by the joiner to reach the join point (the joined participants minimal arrival time is not strictly relevant, as its commitment is to leave after the negotiated time). This is a simple linear negotiation, which (for all other negotiation objectives fixed) can be resolved with a monotonic concession protocol. However, we need to observe that once the hard requirement of $\tau(L_{\text{current}}, L_{\text{join}}) < t_{\text{join}} - t_{\text{current}}$ is met, the rest of the negotiation is only about safety margins. Thus, an agent is more likely to concede on this parameter, which does not affect its predicted performance.

L_{leave} **- the leave location.** For this location, the interest of the joiner is to negotiate a location as close as possible to its final destination (except the case when it is planning to join another convoy on the leave location). The interest of the joined participant is to negotiate, in the order of preference (a) a location for which an existing B commitment exists, (b) a location for which an existing A commitment exists, (c) a point on the current planned path and (d) a point close to the current planned path. Note that the order of preferences for types (a) and (b) is reversed for this point compared to the join point. An additional problem which needs to be considered by the convoy is that at every leave location the resources of the convoy are diminished and at the last leave location we end up with two independent agents, not with a convoy and an agent. Thus, the interest of the convoy might be to negotiate for leave points as far down as possible on its projected path. The ideal organization is a single leave point where all the participant agents leave for their individual destinations.

t_{leave} **- the leave time**. This parameter represents the guaranteed arrival time at the leave location. t_{leave} has a lower bound, limited by the physical time a convoy needs to reach the location on the optimal path, while still meeting its other commitments. The upper bound of this parameter is given by the limit at which it is not worth anymore for an agent to join the convoy $t_{\text{leave}}^{\text{upper}} = t_{\text{current}} + \tau_{\text{agent}}(L_{\text{current}}, L_{\text{destination}}) - \tau_{\text{agent}}(L_{\text{leave}}, L_{\text{destination}})$. Evidently, the interest of the joiner is an earliest possible time - preferably the lower bound. The interest of the joined participant is to minimize its commitment, by committing to as late time as possible. By accepting the lower bound, the convoy is essentially committing that it will not change the path calculated at the conclusion of the current negotiation. This limits its ability to accommodate agents joining in the future.

3.3. Reducing the negotiation space

One of the difficulties in the practical negotiation process is that while the points of type (a) and (b) are coming from a limited set of discrete choices, the points (c) are coming from a one-dimensional while points (d) from a two dimensional continuum, limited only by the resolution of the raster maps on which the systems operate. This leads to an unrealistically large negotiation space, especially considering the fact that the evaluation of an offer requires the recomputation of the path, and it is, therefore, computationally expensive.

To reduce the negotiation space to a more realistic size, we chose to identify a set of discrete offer points on the convoy path. By restricting the choice of the join and leave locations to the offer points, we guarantee that the negotiation happens over a discrete set of choices. To discuss these points, we need to first clarify the difference between the projected and preferred path of an agent. The projected path of the agent is the currently computed path which the agent will take if it cannot form a convoy. According to our assumption, this is always a path which traverses only safe zones. The preferred path of the agent is the path which the agent would prefer to traverse if it would be in a convoy, it might involve traversing danger zones and it is usually shorter than the projected path. We also introduce the value of the *offer point resolution* δ_{offer} which governs the maximum distance between the offer points.

The set of offer points is composed of:

(i) Points related to which the agent or the convoy already has commitments.

(ii) Special points on the projected and/or preferred path of the agent or convoy. The endpoints of the path, the intersections of the path with the danger zones and the intersections between the path of the agent and the negotiating partner are included first. Whenever the distance on the path between two consecutive points O_1 and O_2 such that the path between them traverses only areas accessible to both negotiation partners is larger than δ_{offer}, a number of equidistant new offer points are introduced on the curve between the O_1 and O_2, such that their distance would be smaller than δ_{offer}.

(iii) Points outside the projected and/or preferred path. For the considered path P we create a series of paths P_i^L and P_i^R where $i = 1, 2, \ldots$, with the P_i^L being an equidistant path at the distance $i \cdot \delta_{\text{offer}}$ at the left of the path P, while P_i^R at the right of the path P. We use the techniques of point (ii) to generate the offer points on these paths.

The use of the offer points allows us to reduce the negotiation to a set of discrete points. Furthermore, the set of

TABLE I

THE CONVOY JOINING SUBPROTOCOL

Id	`ConvoyJoining`
Roles	`CandidateAgent (CA)` `CandidateConvoy (CC)`

Messages	`Beacon (CA → ANY)`
	`JoinOffer (CA → CC)`
	`CounterOffer (CA ← CC)`
	`Accept (CA ← CC)`
	`Confirm (CA → CC)`
	`Terminate (ANY → ANY)`

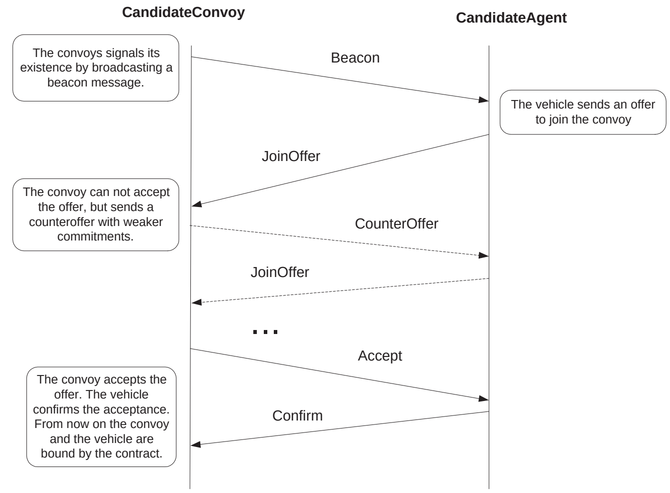

Fig. 2. A typical message sequence for the convoy joining subprotocol

the offer points can be further reduced through heuristics and feasibility checks. For instance, from the points of type (iii), we normally retain only the points which are on the same side of the projected path as the current location of the negotiation partner. Some of the points created through the methods might not be accessible in the current state of the agent, and thus can be removed from the set.

3.4. Convoy joining subprotocol

To describe the negotiation flow we will use the concept of a *subprotocol* [**?**]. A subprotocol is a closed set of *messages*, exchanged by agents acting in certain *roles*, during a *conversation* limited in time. The term closed specifies that any message in the subprotocol will be answered with a message from the same subprotocol. The roles of the subprotocol are indivisible: an agent either implements the complete role, or refuses to participate in the conversation.

The convoy joining subprotocol describes the negotiation process between an agent and a convoy which are acting in the `CandidateAgent` and `CandidateConvoy` roles respectively. The messages of the subprotocol are summarized in Table I. An example message flow of a conversation using this subprotocol is shown in Figure 2. Convoys and agents moving in the field are broadcasting their presence through the Beacon message. Convoys are represented by their lead agent; single agents wishing to form a convoy act as a single agent convoy. Upon receiving the Beacon message, the candidate agent starts the negotiation by sending a JoinOffer message, which contains the $A()$ and $B()$ commitments which the agent wishes that the convoy will accept. The convoy replies with a CounterOffer message, which contains its own terms. If an agent wants to accept the convoys' counteroffer, it sends back the same offer in a JoinOffer message, otherwise it sends a different offer. The convoy can accept the agents offer by sending the Accept message. The agent replies with a Confirm message. At this moment it is considered that the agents have agreed on joining the convoy and accepted the corresponding commitments. At any moment during the negotiation, either participant can end the negotiation by sending a Terminate message.

While the subprotocol specifies only the exterior view of the negotiation, the participating agents need to maintain their own views of the progress of the negotiation. This can be done through one of the many approaches proposed in the literature: finite state machines, statecharts, Petri nets or others. In our implementation we have used a finite state machine implementation. The finite state machine representing the view of the `CandidateAgent` on the progress of the negotiation is presented in Figure 3. A finite state machine is created for every negotiation process started. The state machines are updated whenever messages are received and sent. The state machine is discarded when a negotiation was terminated, or when an agreement is formed. Additional interconnection between the state machines governs the interaction between the negotiations. This interconnection guarantees that only one accepted offer will be confirmed. Once an accepted offer is confirmed by the agent, it will send terminate messages on all the other negotiations.

4. EXPERIMENTAL RESULTS

We tested our coalition formation algorithms on a realistic scenario based on the environment of New Orleans flooded by hurricane Katrina. The agents were implemented in the YAES simulation environment [**?**]. The physical environment is a 2.0x3.2 km large area of New Orleans, represented through a satellite photo with a resolution of 4 meters/pixel, obtained from Google Maps (Figure 4). The safe, unsafe and unaccessible areas were obtained partially from image processing, and partially manually edited. We assume that the agents are moving at the very slow speed of 4.8 km/hr (which resembles the average pedestrian walking speed [**?**]). The latency in preparing and delivering the messages is assumed to be 1.2 seconds, while the communication range of the agents is 200 meters - realistic for walkie-talkie type device in an urban environment. Note that the agents' speed in this scenario is relatively slow, and it allows for a relatively large number of negotiation rounds, provided that the negotiation is fully computer based and does not require user interaction.

The size of an offer message is very small (on the order of 20 bytes, as it contains only the agent identifier and the binary encoded $A(L,t)$ and $B(L,t)$ values). Considering a message turnaround time on the order of seconds, there is no communication bottleneck in the negotiation, even when hundreds of agents are negotiating simultaneously. The main

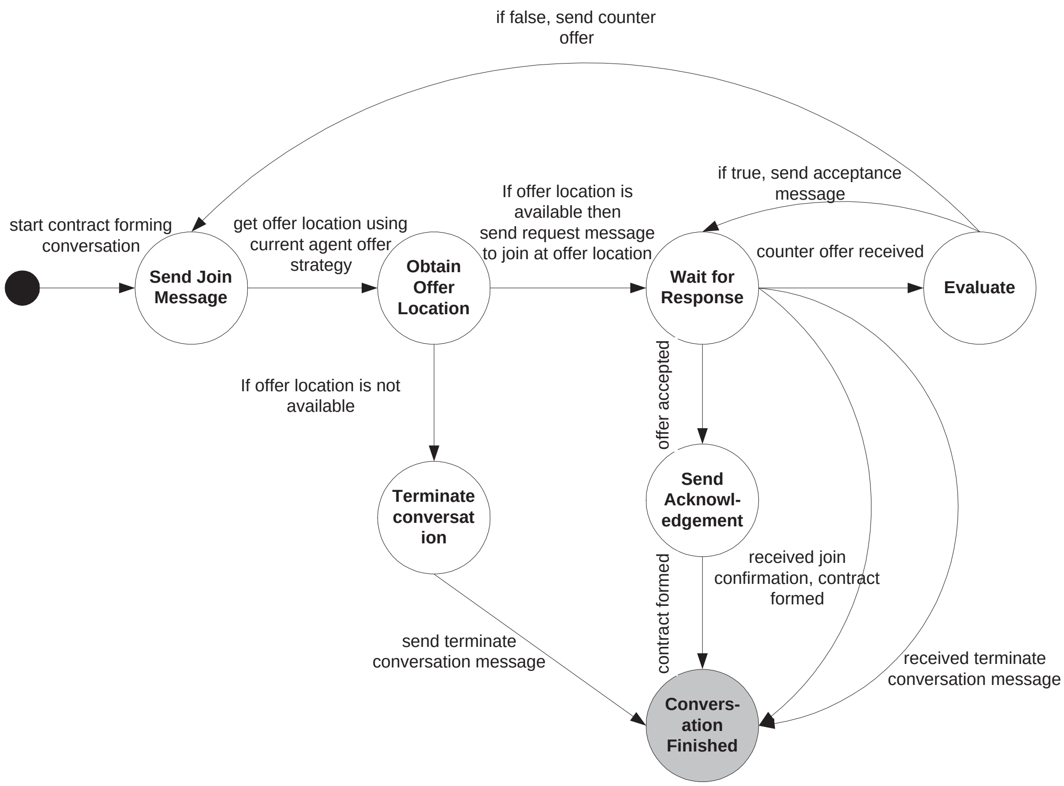

Fig. 3. A finite state machine representing the view of the `CandidateAgent` on the progress of the convoy joining negotiation.

challenge on the scalability of the approach is related to the combinatorial explosion of the number of possible coalitions.

In this simulation, we assume that the offering agent does not have to wait for the other agent at join location. The other agent might want to wait for certain time at offered join location to form the convoy.

In the following sections we present two case studies. The first scenario describes coalition formation between two agents, providing a detailed description of the course of the negotiations and the exchanged messages. The second case study presents a scenario with four agents, and contain more general situations such as cases when a negotiation breaks up without forming an agreement and the formation of multi-agent convoys.

4.1. Two agents coalition formation scenario:

This scenario, shown on Figure 4 considers the movement of two agents from their starting points Start-Agent-1 and Start-Agent-2 to their destination points Dest-Agent-1 and Dest-Agent-2 respectively.

As both agents start moving towards their destination, their initial path goes through the path identified by note 1 and note 2 on Figure 4. The initial path for Agent-1 is roughly 4 km; while for Agent-2, it is 4.7 km. It will take Agent-1 about 50 minutes to reach its destination, while Agent-2 will reach its destination in about 60 minutes. In this scenario, we assume that Agent-2 starts moving towards it destination 5 minutes later than Agent-1.

After traveling some distance, Agent-1 and Agent-2 come within communication range of each other and start negotiations for coordinating their movements. Table II shows the offers and counter offers made during this negotiation process. Please note that the location of the agent is shown as distance in meters from the top left corner of the map.

Offer 1: Agent-2 makes the first offer to Agent-1. It offers a join location constraint for location (608,1036) in 0.7 minutes. The Agent-1 can reach the given location in no less than 2 minutes. Since we assume that the offering agent (i.e Agent-2) is not going to wait, Agent-1 can not possibly agree on this offer. So this offer gets rejected.

Offer 2: Agent-1 now makes a counter offer for join location (600, 1116) in 0.7 minutes. This time, Agent-2 can reach the join location in 1.7 minutes, so this offer gets rejected too.

Offer 3: Agent-2 has now slightly moved from its previous location. It now make another offer to Agent-1 for join location (648,1032) in 1.3 minutes. The Agent-1 can make to this location in 1.8 minutes. So it rejects the offer.

Offer 4: Agent-1 now makes a counter offer for join location (632,1076) in 1.3 minutes. This time Agent-2 can reach the location in 1.2 minutes, so it agrees with the join location constraint. Next, it evaluates the leave location constraint and finds that it will take it 47 minutes to reach its destination on its own. With the offered path, it will take 1.2 minutes to reach join location, 29 minutes to reach leave location and 9 minutes to reach its destination from leave location. So in total it will take it 39 minutes to reach its destination. Since it is

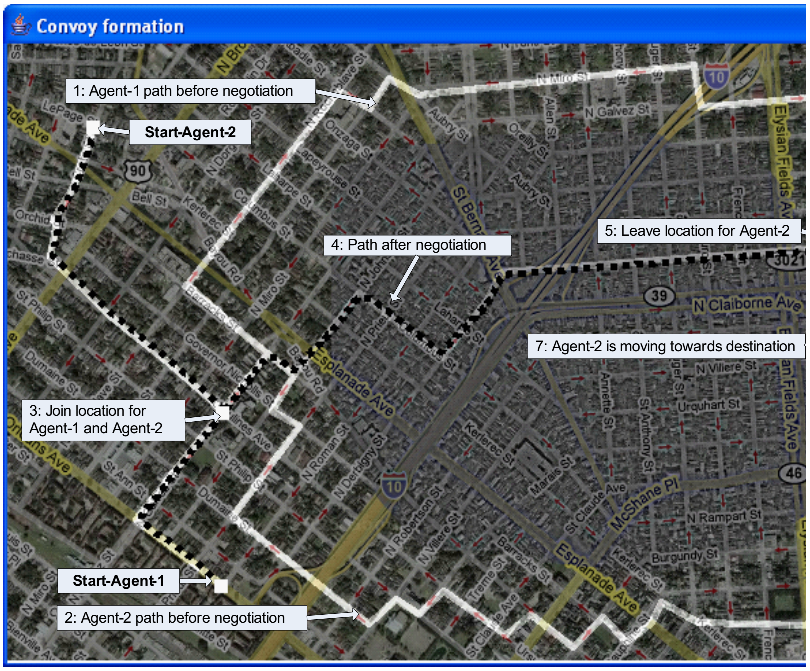

Fig. 4. An example run of the coalition formation algorithm, on a map representing an area of New Orleans flooded in the aftermath of Hurricane Katrina. The area marked in the center of the map is a danger area, which can not be traversed by individual agents, but is accessible for convoys.

Offer No.	Sender	Receiver	Location of the sender (m)	Join constraint $<(m,m),min>$	Leave constraint $<(m,m),min>$
1	Agent-2	Agent-1	(568, 996)	$A((608,1036),0.7)$	$B((2372,1984),27.6)$
2	Agent-1	Agent-2	(568, 1152)	$A((600,1116),0.7)$	$B((2488,576),32.3)$
3	Agent-2	Agent-1	(568, 1000)	$A((648,1032),1.3)$	$B((2376,604),27.6)$
4	Agent-1	Agent-2	(572, 1148)	$A((632,1076),1.3)$	$B((2492,576),29.8)$

TABLE II

THE OFFERS EXCHANGED BETWEEN AGENT-1 AND AGENT-2

lower than the original time (i.e. 47 minutes), it will accept the offer.

Note that for Agent-1 the time to reach destination with this agreement includes 1.3 minutes to reach join location, 29 minutes to reach leave location and 1.1 minute to reach destination from leave location. So in total it will take 31.4 minutes to reach its destination.

Given the very limited communication range, the agents are already in very close proximity during negotiation process. Therefore, we assume that no further negotiation (about join time or leave time) is necessary and conclude the negotiation with the accepted offer becoming the agreement between both agents. Agent-1 becomes the convoy leader (since its offer was accepted) and Agent-2 joins the convoy at agreed join location.

4.2. Four agents coalition formation scenario:

In this scenario, four agents are moving towards their respective destinations. The Figure 5 shows the initial location of the agents and their respective paths before negotiations.

In this scenario, Agent-4 starts moving towards its destination about 17 minutes after Agent-1. As agents start moving towards their destinations, Agent-1 and Agent-3 come within communication range and start negotiation. They do not reach an agreement because the proposed offers from Agent-1 do not make Agent-3 to reach its destination earlier than it can reach on its own. Similarly Agent-3 can not provide any better deal to the Agent-1. As they move along, Agent-1 comes within communication range of Agent-2 and they start negotiation. They soon reach an agreement and form a convoy. The Agent-2 becomes the convoy leader (because its offer was accepted by Agent-1). The Figure 6(a) shows these interactions.

As Agent-1 and Agent-2 move in convoy formation through unsafe region they encounter Agent-4 moving towards its destination Dest-Agent-4. A negotiation takes place between convoy leader Agent-2 and Agent-4 resulting in an agreement to join the convoy. The Figure 6(b) shows these interactions. Agent-3 can also be seen in this snapshot moving towards its destination.

The convoy then splits at agreed location and Agent-1, Agent-2 and Agent-4 start moving towards their respective destinations. The Figure 6(c) shows the splitting of the convoy.

5. RELATED WORK

The field of multi-agent negotiation is influenced by economic models, game theory and artificial intelligence. Jen-

Fig. 5. An example run of the coalition formation algorithm with four agents.

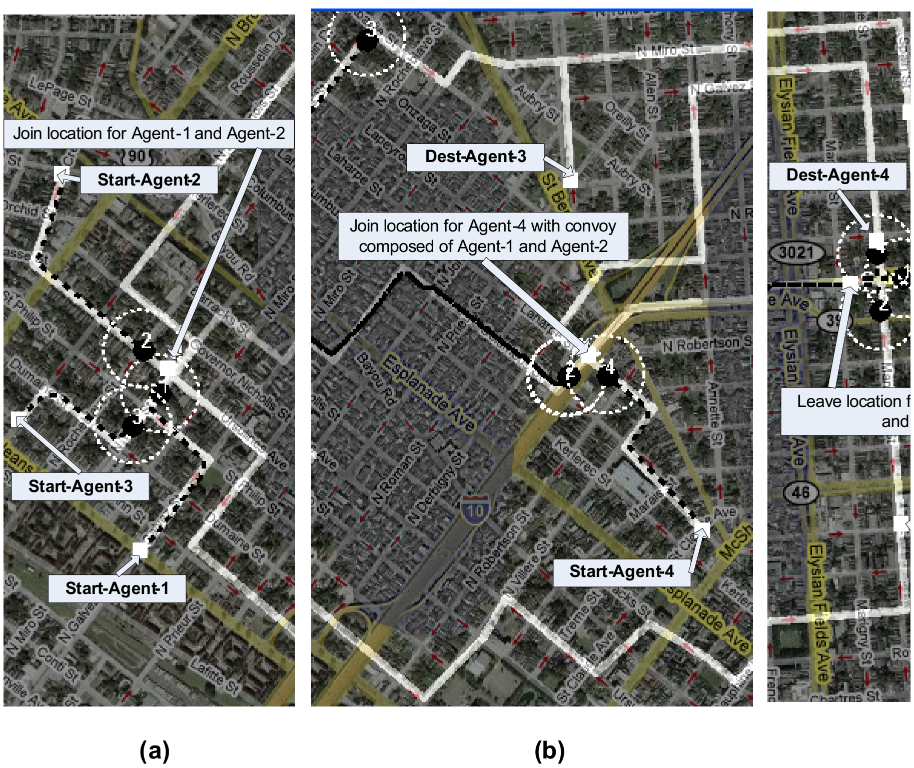

Fig. 6. Snapshots of the simulation: **a)** Agent-1 and Agent-3 can not reach agreement while Agent-1 and Agent-2 reach agreement **b)** The convoy composed of Agent-1 and Agent-2 reaches agreement with Agent-4 **c)** Agent-1, Agent-2 and Agent-4 split to reach their respective destinations

nings et. al [?] defines negotiation as a search process where multiple agents search through the negotiation space to reach agreements and discusses several negotiation models including game theoretic, heuristic based and argumentation based models. Kraus [**?**] provides a more in depth study of strategic negotiations in multi-agent environments.

Coalition formation between agent residing in the physical world has been the object of study of collaborative robotics. One recent effort is the DARPA Software for Distributed Robotics (SDR) program where researchers from SRI International, Stanford University, the University of Washington, and ActivMedia Robotics are designing and implementing a computational framework for the coordination of large robot teams, consisting of at least 100 small, resource limited mobile robots (CentiBOTS) on an indoor reconnaissance task. The Robocup robotic soccer challenge is also a source of research in coalition formation schemes [?]. Alami et al [?] presents a scheme of operating a large number of mobile robots using plan merging paradigm. Their scheme is based on local knowledge and incremental planning in a distributed manner. They attempt to resolve the spatial movement conflicts between mobile robots. Although we have a similar problem domain, our effort differs in that 1) we use negotiations for coordinating the movement and 2) our general goal has been to make mobile agents to agree on a meeting and leaving location rather than resolving the spatial movement conflicts.

Although team formation is frequently considered a centralized activity, where a manager assembles teams based on optimization criteria, several research efforts have dealt with negotiation based team formation models. The DARPA Autonomous Negotiating Teams (ANTS) program was one of the focus points of this effort. Some of these papers are concerned with a multi sensor target tracking problem [?], [?]. Sariel and Balch [?] use an auction based approach for task allocation in multiple robot map exploration problem.

The CoAX - Coalition Agents Experiment series demonstrated the utility of agent technology for coalition operations in a series of technology integration experiments [?], [?].

[?] is one of the classical books on the topic of time constrained negotiation. In our negotiation model, both parties lose if an agreement can not be reached in given time. So both parties are willing to accept any offer (even non-optimal) that can satisfy the join and leave constraints.

Part of our problem domain also resembles with multi-agent meeting scheduling problem. Crawford and Veloso [?] provides a good introduction to existing work in this domain in which the focus has been mainly to make multiple agent agree on a given time slot for a meeting, under static or dynamic user preferences. Our work differs in that our mobile agents schedule for spatial locations under dynamic temporal constraints.

6. Conclusions and future work

In this paper we presented an agent based coalition formation approach for disaster response applications. Agents, representing rescue teams are organizing themselves in convoys to traverse the dangerous areas of disaster environments. We introduced a convoy formation model based on commitments, and a negotiation-based approach which allows the agents to agree on these commitments. This model leads to a multi-issue negotiation model which includes two spatial and two temporal components. We found that this is a challenging negotiation problem, given the large negotiation space and the complexity of the evaluation of the offers. We proposed an approach for reducing the negotiation space through the creation of discrete offer points, and speeding up the offer evaluation through heuristics. We showed the operation of our model in a scenario using the map of New Orleans flooded by hurricane Katrina.

Our future work involves improving the negotiation and offer evaluation approach, especially for cases with large convoys with multiple commitments. Our current approach does not handle co-negotiation, where the value of a certain offer is conditioned by the success of another negotiation. This model is necessary for things such as “convoy hopping”. Our current model assumes that danger areas are known in the moment of negotiation. In disaster rescue scenarios, the knowledge of the dangerous areas is incomplete and in fact, dangerous areas can appear dynamically. A new experience or incoming new information might modify the agents world view even during an ongoing negotiation. Agents might consider levels of dangerousness, and/or probabilities of dangerousness, and negotiate with these assumptions.

Finally, the purely movement and location based model needs to be paired with a task and capabilities based model, which also includes information about the rescue tasks of the participants.

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