

Negotiation-based coalitions in the physical world

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ABSTRACT

We present a negotiation based coalition formation scheme for autonomous agents residing in the physical world. While in the virtual world we can abstract the negotiation into a calculation of rewards and ignore the details of the physical substrate of the negotiation, in the physical world we need to concern ourselves with variables such as the geographical location of the agent, range of the communication devices, path planning, obstacles and hazards, the necessity of co-location and the temporal constraints associated with it. We concentrate on agents with coordinated location and speed (convoys) which can improve their performance by being able to traverse previously inaccessible areas. We assume a model where agents can dynamically join and leave the coalition.

1. INTRODUCTION

Coalition formation between autonomous agents is a relatively well researched topic. We find however, that the techniques developed for purely software agents acting in the virtual world are not immediately applicable to embodied agents acting in the physical world (or a simulation of it).

In this paper we present a series of algorithms for coalition formation of agents acting in the physical world. We will concentrate on a particular type of coalition we will call a *convoy*¹: a set of agents with the same location and movement characteristics. The benefits of participating in a convoy is that convoys can traverse geographic areas inaccessible to individual agents. Agents have individual goals which are tied to geographic locations. Agents are selfish, the decision on joining or leaving a convoy is based exclusively of how the action furthers the goals of the agent. The agents and convoys are using negotiation mechanisms to control the joining and leaving of agents from the convoy, as well as

¹Note that the definition of a convoy does not necessarily imply a convoy of vehicles; it can be agents aboard a vehicle such as a boat, or multiple agents physically joined together.

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the shared goals of the convoy (as reflected in its path and destination).

One example of such a scenario is the search and rescue missions in disaster zones (such as New Orleans after Hurricane Katrina, or the tsunami-affected Asian coastline). A variety of agents are performing a set of operations at distinct geographical locations. The communication services are disrupted, and there are a variety of dangerous areas which can be traversed only by special "convoys" - such as by boat, under the protection of armed guards, with special escorts or in the presence of translators.

2. CONVOY FORMATION MECHANISM

The environment considered in this paper assumes a 2-dimensional geographic area, where we identify: *safe areas* which are traversable by any vehicle and convoy, *danger areas* which are traversable only by convoys and *inaccessible areas*.

In this environment, we consider the actions of a set of *embodied agents*, which have 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 execute a certain task at a destination location. For the purpose of this paper, we assume that these tasks are independent, and the collaboration between agents concerns only the movement towards the destination. We are currently working on negotiation models for the cases when the agents can collaborate in the execution of the tasks as well.

The agents try to reach their destination as soon as possible. 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 agents can communicate wirelessly through message based communication, which can be either point to point or broadcasted to all other agents in the transmission range.

2.1 Convoy models

We define a *convoy* as a coalition of embodied agents which agreed on a common path. We allow a hierarchical structure of convoys to allow operations such as a convoy joining another convoy. For the sake of uniformity, we will consider that individual vehicles are being part of single-vehicle convoys.

A convoy C is described by a set of convoys $S = \{C_1, \dots, C_n\}$, a leader agent $A_L \in S$ and a set of commit-

ments $G = \{g_1, \dots, g_n\}$. The of commitments are usually 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 the agreements G . The commitments of the convoys are related to passing through locations and can be classified as before (B) and after (A) commitments. A “before commitment” $B(L, t)$ commits the convoy to pass through location L *not later than* time t . An “after commitment” $A(L, t)$ commits the convoy to leave location L *not sooner than* time t (if the convoy reaches that location sooner, it can, of course wait in the location). We will call a commitment C_1 *stronger than* a commitment C_2 and denote it $C_2 \subset C_1$ if every set of actions which satisfies C_1 also satisfies C_2 .

THEOREM 1.
 $\forall L, t_1 < t_2 \Rightarrow B(L, t_2) \subset B(L, t_1)$
 $\forall L, t_1 < t_2 \Rightarrow A(L, t_1) \subset A(L, t_2)$

We leave the proof of this theorem as an exercise to the reader.

2.2 Negotiation for an agent joining a convoy

Let us now consider the lifecycle of the embodied agents, and the objectives of the negotiation. Whenever an agent detects the presence of a convoy in its vicinity, it starts a negotiation process. If the negotiation is successful, the agent moves to join the convoy at a rendez-vous point. From then on, the agent moves with the convoy, until the pre-agreed leave point is reached. At the leave point the agent leaves the convoy, and moves independently to the destination. Even while the agent is in the convoy, it might start negotiations with other convoys, or simply consider to leave the convoy on its own. If the agent wants to leave the convoy before the leave point, the agent needs to negotiate for the leaving of the convoy with the convoy leader. If the negotiation is successful, the agent leaves the convoy, and it is free to follow its separate path to the destination, or join a different convoy.

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 .

Let us consider the objective of the negotiation. 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 P , called the *leave point*. One sufficient condition for the agent to be worth joining the convoy until leave point L_{leave} is to have a commitment $B(L_{leave}, t_{leave})$ such that $t_{leave} + \tau_A(L_{leave}, L_A) < t_A$. This is however not a necessary condition; the agent might plan ahead for the joining a different convoy after leaving the current convoy at P .

A successful negotiation for an agent joining a convoy will add two commitments to the convoys' set of commitments: a commitment $A(L_{join}, t_{join})$ for the join location of the agent, and a commitment $B(L_{leave}, t_{leave})$ for the leave location of the agent.

Thus, the negotiation between the convoy and the agent is a multi-objective negotiation, with the <

$L_{join}, L_{leave}, t_{join}, t_{leave} >$ quadruplet being the minimal negotiation set. In addition to these four objects, the negotiation might involve cost, penalties for contract breaking or other temporal constraints. In the following, we will briefly discuss the four negotiation objectives and their interrelationships.

L_{join} the location to join the perspective convoy. The interest of the agent is to negotiate a join location which is as close to its current location as possible, or to be in the general direction of the destination. The preferences of the convoy are (in order of preference) (a) to negotiate a join location L for which he already has an $A(L, t)$ commitment, (b) a location for which it has a $B(L, t)$ commitment, (c) a location which is on the current projected path of the convoy and (d) a location which is close to the current projected path of the convoy. Intuitively, (a) does not involve any new commitment for the convoy (if it manages to negotiate a join time earlier or the same as than the current 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 ok), while a point of type (d) requires the convoy to change its path. These preferences will be inevitably reflected in the negotiation strategy of the convoy. One additional complexity is the number of negotiation choices. 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. To reduce the negotiation space to a more realistic size, we chose to identify *segment locations* on the convoy path. These locations have special properties, such as they are situated on the intersection between safe and danger zones, or on the intersection between the convoys path and the agents path. In the first pass, we can eliminate the points which are not feasible because of one of the following reasons:

- (i) The convoy has already passed that segment location.
- (ii) The vehicle can not reach the segment location before the convoy passes it.
- (iii) The segment location is unreachable by the vehicle (e.g. if it lies within a safe region surrounded by unreachable and danger zones).

t_{join} - the joining time. Once the agent and the convoy had identified its join location they need to negotiate the join time. In broad lines, the agent negotiates for the latest possible join time (to increase its safety margin in getting there), while the convoy 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 agent to reach the join point (the convoys minimal arrival time is not strictly relevant, as its commitment is to be arrive 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 with Zeuthen strategy. However, we need to observe that once the hard requirement of $\tau(L_{current}, L_{join}) < t_{join} - t_{current}$ is met, the rest of the negotiation is only about safety margins. Thus an agent is more likely to concede in this parameter, which does not affect its predicted performance.

L_{leave} - the leave location. For this location, the interest of the agent 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 choices of the convoy are, 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. Similarly to the join location, for types (c) and (d) we consider segmentation approaches. 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 depart for their individual destinations.

t_{leave} - the leave time. This parameter represents the guaranteed arrival time at the leave location. This parameter 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 $t_{leave}^{upper} = t_{current} + \tau_{agent}(L_{current}, L_{destination}) - \tau_{agent}(L_{leave}, L_{destination})$. Evidently, the interest of the agent is an earliest possible time - preferably the lower bound. The interest of the convoy 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 its current path. This limits its ability to accommodate agents joining in the future.

2.3 Related Work

Coalition formation between objects residing in the physical world has been addressed by several researchers. Recently, [2] presents a coalition formation scheme in a Robocup team. [1] presents a scheme of operating 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 spatial movement conflicts between mobile robots using this approach. Although we have a similar problem domain, our effort differs in that 1) we use negotiations for coordinating the movement 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.

Several research efforts like [9, 4] have used negotiation for forming teams of agents. Most of this work concerned agents residing in the virtual world. From the efforts which concern the physical world, we mention the DARPA Autonomous Negotiating Teams (ANTS) program. [8], used negotiation for resource allocation in multi sensor target tracking problem. A negotiation protocol for resource allocation problem in a multi-sensor based target tracking application is presented in [6]. [7] uses an auction based approach for task allocation for multiple robots exploring a map.

The negotiation process in our domain has to be time constrained. [5] is one of the classical papers on this topic. 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. [3] provides a good introduction to existing work in this domain. The focus in this domain has been mainly to make multiple agents agree

on a given time slot for meeting, under static or dynamic user preferences. Our work differs in that our mobile agents schedule for spatial locations under dynamic temporal constraints.

3. CONCLUSIONS

In this paper we presented an approach for negotiation based coalition formation in the physical world. We find that many of the formal negotiation models are applicable, but the constraints of the physical world, such as temporal and spatial distances, communication constraints, as well as real-time operation requirements add new requirements. The model presented was simulated for convoy formation on real world maps. Future work include extending the coalition model to task oriented domains, development of better algorithms for real-time operation as well as implementation on physical embodied agents.

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