Principal Investigator: **Lucian Vlad Lita**
Center for Automated Learning and Discovery
Carnegie Mellon University
Email: lita@cs.cmu.edu
Phone: (412) 268−1718

Planning Under Uncertainty with Abstraction
Proposal

Abstract

Large multi−agent systems face a number of exponential problems when planning in uncertain worlds. We propose work on an abstraction model that for agent polynomial time planning that has the potential to address the planning time as well as the plan quality. Previous work in abstraction has focused on topologic abstraction usually in deterministic worlds and trades significant world information for abstraction degree. Our proposed model looks at abstraction through world compaction while preserving the world information pertaining to agent plans.

1. Problem Description

We propose work on probabilistic algorithms for agent planning in the Canadian Traveler Problem (CTP). The CTP is the problem of finding a shortest path to a goal location in a graph, where individual edges of the graph might or might not be traversable [BarNoy91]. Whether or not an edge is traversable can only be found out by moving there. Hence, an optimal solution to a CTP is a contingency plan, which offers alternative routes if edges are not available. The CTP differs from other hard planning and optimization problems in that the state of the environment is only partially observable. It can be viewed as a partially observable Markov Decision Process (POMDP) with local and deterministic observations [Kaelbling97, Littman98, Blei99]. Finding an optimal contingency plan is known to be NP−hard.

Our work will focus on an agent planner in a CTP setting, in a world, which involves multiple agents attempting to reach multiple target locations. In practice, due mostly to planning complexity, optimal solutions can only be found for very small graphs (e.g., 10 edges) and a small number of agents (e.g., 3), whereas many practical multi−agent CTP problems possess hundreds of edges and agents.

Fig. 1 Simulation of a multi−agent system during
Hurricane Mitch in Honduras

The CTP plays an important role in many practical problems. A classical example is packet routing in the Internet, where communication nodes might be up or down at random [Itai96]. Clearly, packet routing has to be performed with extremely limited computation, making extensive planning (as proposed here) infeasible. More related to

the work described here is the multi−robot exploration problem [Burgard00, Simmons00, Yamauchi98] where teams of robots jointly explore an unknown environment. Here, the relative speed of the moving agents (robots) is much slower than in the packet routing problem, offering the opportunity for more extensive planning.

The problem that motivates this research is the real life setting where agents (e.g., supply trucks) are tasked to bring emergency supplies to a number of population centers in a country devastated by a natural disaster. The road conditions are unknown. Hence, the optimal solution must offer backups from non−traversable roads. In particular, the natural disaster studied here takes place in October 1998 in Honduras, while and after Hurricane Mitch (Figure 1) destroyed up to 90% of the country's infrastructure in certain regions.

2. Impact

Successful research in planning under uncertainty through world compaction style of abstraction would yield fast algorithms that would perform the equivalent of extensive contingency planning. All agent−based applications such as emergency vehicle networks, robot navigation, army tactics, and even personal digital assistant navigation software, would immediately benefit from this research.

From a theoretical perspective, this research would help develop algorithms for an area not widely studied. The developed algorithms could be further applied to broader POMDP settings with more general problem definitions.

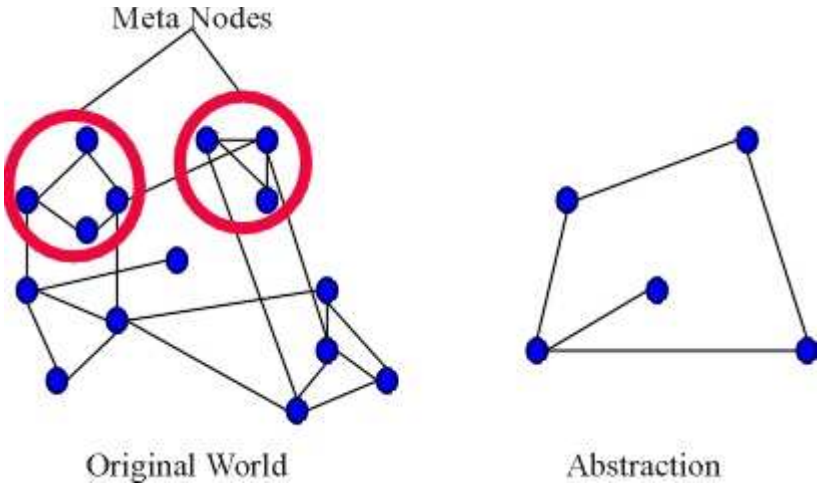

Fig. 2 Nodes in the original world are clustered in meta nodes

3. Approach

Our model proposes a planner that will perform extensive path search not by constructing larger contingency plans, but by compacting the graph representation of the world in polynomial time while obtaining relevant statistics such as: probability to find any path to

reach the goal, expected time it would take the agent to reach the goal, as well as the expected reward the agent would receive upon reaching the goal.

In Figure 2 a very simple graph representation of the world is presented. Since optimal planning in the original world presents computational difficulties, abstracting the graph into a clustered representation could potentially generate plans in less time. Our research will explore the different ways of abstraction in order to determine the appropriate methods for graph compaction. Initial abstraction methods will incorporate:

- distance/time information – a set nodes with the property that all nodes reach each other fast enough (e.g. short distances between cities) will have a higher chance of being abstracted together into the same meta node.
- probability information – two nodes connected directly or indirectly through edges with low probability will not be likely to belong to the same meta node in the abstraction process.
- expected reward – combining probability and distance into an approximate expected reward (since the exact reward cannot be computed in polynomial time) will yield scores (rewards) for pairs of nodes.
- connectivity degree – nodes with high connectivity degree will likely form meta nodes with their neighbors.

We intend to experiment with different abstraction levels in order to determine if deeper abstraction yields qualitatively good solutions. Abstraction levels are chained abstraction starting with the original world. With each abstraction, the planning complexity is reduced.

In the event that deeper abstraction is successful we also want to experiment with extreme abstraction where we use abstraction to compute statistics such as expected reward between two nodes, expected time, and probability to reach the goal from the agent location.

4. Results

Previous work on the CTP problem has yielded good results but our recent study also suggests that there is room for improvement, particularly when abstraction is concerned since it is a new way of looking at the planning problem.

4.1 Previous Results

Traditionally, planning problems in deterministic spaces involve finding a path from an agent to its goal. A commonly used algorithm is A* which uses an optimistic and thus admissible measure of goal distance to efficiently find the optimal path [Nilsson82]. In our previous work, we proposed Belief A* BA*, an algorithm based on A* which efficiently, handles planning under uncertainty. BA* searches in the space of all possible plans and produces the best contingency plan over the belief space found under time restrictions. The algorithm generates a contingency plan represented by a tree and not a by a path as in the deterministic case. For practical purposes the BA* implementation

uses memoization to cut down on the planning complexity in a similar fashion to value iteration.

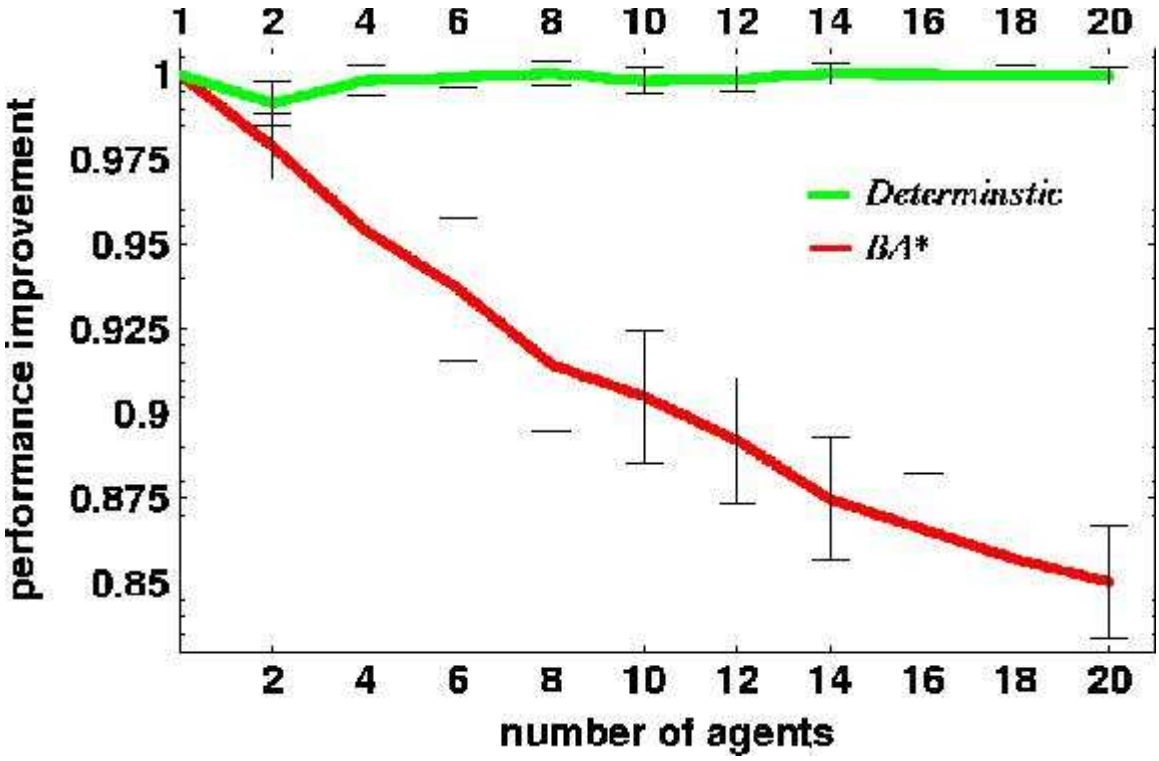

Fig. 3 The performance increases for a multi−agent system using BA*, as the number of agents grows. (performance is measured in relative time, so lower is better)

4.2 Initial Results

We have performed an initial set of evaluations and simulations, which show that very basic abstraction does not reach the performance of a system with no abstraction, but offers a tradeoff in terms of computation time (Fig. 4). This is particularly useful when there are external computation or time limits imposed on planning. The initial results are interesting and suggest that there is much room for improvement.

5. Research Issues

There are several problems with currently developed systems. The fully observable planners eliminate from the problem complexity by assuming that the agent can obtain precise information from the environment. However we are addressing the problem where the agent deals with probabilistic statements as well as with the topology of the world. When applied to partially observable worlds it is easy to observe the pathology of the plans generated.

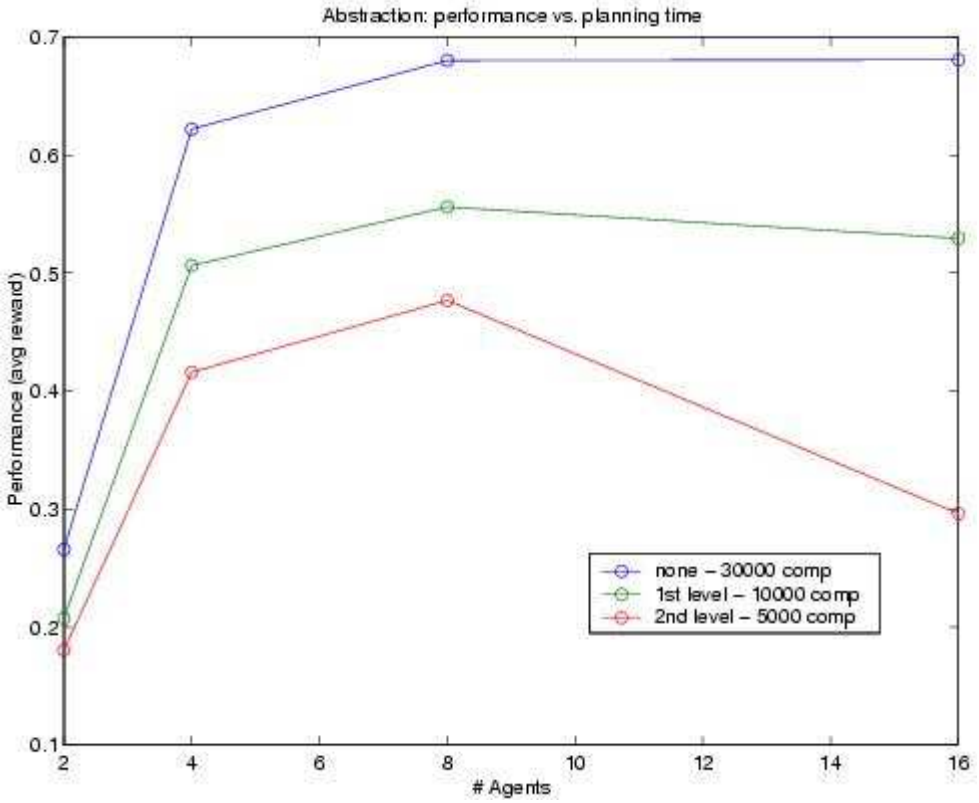

Fig. 4 Tradeoff between performance of a multi−agent system using abstraction and computation time.

The existing agent−based systems, including the BA* presented earlier, can handle a CTP type setting but have major limitations. The most important limitation is scalability. These planners work well with small worlds represented by small graphs (e.g. 10 edges) but when applied to large−scale worlds, they yield inefficient solutions. Since the nature of the problem is non−polynomial, the contingency plans generated are exponential in the number of nodes and edges. Constructing such plans is time consuming, and evaluating these plans in order to generate the best one considered involves extracting and comparing statistics. We propose to solve this problem through abstraction, compacting the graph representation of the world. This proposed solution would avoid the structural complexity while preserving the relevant semantic information.

Another limitation directly related to the size of the environment is the quality of the plans. Current probabilistic planners produce contingency plans that are evaluated based on reward obtained after the plan was executed, or based on an expected reward. However, since these plans are exponential in the number of edges, the size of the generated plans grows quickly and is limited by the computation power of the engine running the planning. This implies that even with a very good heuristic, the plans cannot consider most of the good paths tot he goal, and must rely on the paths already discovered – which might be representing of the average path or not. Further, assuming that the planner produces several paths to the goal, the plans would generate long but

narrow paths that don't branch out and don''t interconnect. In a realistic world, paths would intersect and would be dependent on each other. Thus the quality of the plan varies greatly from one world and situation to another.

Our research will address that limitation but will also have to choose among abstraction and compaction methods. These abstraction methods for uncertain worlds have not been yet established, and our work will explore a wide range of graph compaction techniques based on connectivity, probability, time, and expected reward.

6. Goals

The proposed research will focus on agent based planning algorithms in partially observable worlds. The aim is to build an abstraction–based planner that would posses the following properties:

- Fast planning time – the planner would be capable of producing in polynomial time
- Scalability – the planner would perform well in large size environment (high number of edges).
- High quality – the agent would be able to produce a good plan while maintaining a short planning time.
- Statistic extraction – extracting world characteristics based on agent location and goal
- Multi–agent integration – agents with abstraction based planners must work well within a multi–agent framework.

As a long–term goal, depending on the degree of success with meeting the goals above, we intend to investigate a multi–agent system where individual agents that share the abstraction task. This might yield a much faster, potentially continuously updating distributed planner.

7. Working Plan

The time frame consists of a sequential set of steps that we need to take in order to develop the abstraction algorithms for uncertain environments:

- During the first two weeks we will re–implement the basic abstraction techniques in the literature, test them, and evaluate them for comparison with later methods. This is also going to be our framework.
- During the next two weeks we will experiment with different, new abstraction techniques based on probabilistic quantities. Also, for each technique, if it applies we will calculate the time/space complexity and evaluate the feasibility of such technique in practice.
- Another week will be spent on evaluating the new abstraction techniques on small graphs, comparing them with optimal solutions (that can be found exhaustively on these graphs).
- We will use the remainder of the time to evaluate the new abstraction techniques on large scale, realistic graphs such as parts of Honduras by comparing them to other

techniques. Simulating plan execution is also required to test the performance of the plans generated by abstraction.
- If time permits we will also look into the multi−agent aspect of planning with abstraction. Then we will explore a distributed abstraction/compaction strategy using a variable number of agents.

Summary

The problem of planning under uncertainty has been studied very little due to its complex nature. We intend to offer new algorithms and methods from the abstraction perspective for planning in uncertain environments. We plan to do this via graph compaction and statistics extraction from the graph representation of the world.

If successful, this research would contribute to the field of planning under uncertainty with a new set of algorithms, and potentially promising results. In practice this research would benefit every system that uses any kind of probabilistic planning or any system that has to plan in an uncertain environment.

References

- Blei, D. M. and Kaelbling, L. P. (1999). *Shortest Paths in a Dynamic Uncertain Domain,* IJCAI Workshop on Adaptive Spatial Representations of Dynamic Environments.
- Burgard, W. and Fox, D. and Moors, M. and Simmons, R. and Thrun, S. (2000). *Collaborative Multi−Robot Exploration*, Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)
- Yamauchi, B. and Langley, P. and Schultz, A.C. and Grefenstette, J. and Adams, W. (1998). *Magellan: An Integrated Adaptive Architecture for Mobile Robots*, Institute for the Study of Learning and Expertise (ISLE)
- Simmons, R. and Apfelbaum, D. and Burgard, W. and Fox, D. and Moors, M. and Thrun, S. and Younes, H. (2000). *Coordination for Multi−Robot Exploration and Mapping*, Proceedings of the AAAI National Conference on Artificial Intelligence
- Matari, M. J. (1997). Reinforcement Learning in the Multi−Robot Domain, Autonomous Robots, 4, pg 73−83
- Nilsson, N. J. (1982). *Principles of Artificial Intelligence*, Springer Publisher, NY
- Bar−Noy, A. and Schieber, B. (1991). *The Canadian Traveler Problem,* Proceedings of the 2nd ACM−SIAM Symposium on Discrete Algorithms.
- Itai, A. and Shachnai, H. (1996). Adaptive Source Routing in High−Speed Networks, Journal of Algorithms, 20, pg 218−243
- Kaelbling, L.P. and Littman, M.L. and Cassandra, A.R. (1998). *Planning and Acting in Partially Observable Stochastic Domains*, Artificial Intelligence, 101:1−2, pg 99−134