International Journal of Approximate Reasoning 57 (2015) 44–63

Contents lists available at ScienceDirect

International Journal of Approximate Reasoning

www.elsevier.com/locate/ijar

Time-critical interactive dynamic influence diagram

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ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 13 November 2014
Accepted 19 November 2014
Available online 2 December 2014

Keywords:
Multiagent time-critical decision making
Interactive dynamic influence diagram
Model expansion

ABSTRACT

Multiagent time-critical dynamic decision making is a challenging task in many real-world applications where a trade-off between solution quality and computational tractability is required. In this paper, we present a formal representation for modelling time-critical multiagent dynamic decision problems based on interactive dynamic influence diagrams (I-DIDs). The new representation called time-critical I-DIDs (TC-IDIDs) represents space-temporal abstraction by providing time-index to nodes and the model is defined in terms of the condensed and deployed forms. The condensed form is a static model of TC-IDIDs and can be expanded into its dynamic version. To facilitate the conversion between the two forms, we exploit the notion of object-orientation design to develop flexible and reusable TC-IDIDs. The difficulty on expanding TC-IDIDs is to select a proper time sequence to index nodes in the condensed form so that the expanded TC-IDIDs can be solved efficiently without compromising the quality of the policy. For this purpose, we propose two methods to build the condensed form of TC-IDIDs. We evaluate the solution quality and time complexity in three well-studied problems and provide results in support.

1. Introduction

Time-critical decision problems consider time as an important factor in the decision making process. They are universal in many real-world applications such as route medical decision-support systems [1], shipboard damage control [2], replanning tasks [3], military operations on urban terrain simulations [4] and so on. In order to have sufficient time executing actions, a decision maker is expected to spend a suitable amount of time on modelling decision problems and solving the model. This is a trade-off between the solution quality and computational tractability [5]. Although a complete model may provide exact solutions, a large amount of time in compilation and execution is required.

For time-critical dynamic decision problems, research has been conducted mainly in a single-agent setting [6–8]. In particular, Xiang and Poh [7,9] proposed a formal representation of time-critical dynamic influence diagram (TC-DID). TC-DID not only provides explicit support for modelling temporal processes, but also deals with time-critical situations. The research has been applied successfully to a medical problem on the treatment of cardiac arrest [1]. Although TC-DID is suitable for the single-agent domain, it is difficult to extend it to solve multiagent decision making problems. Since multiple agents may

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http://dx.doi.org/10.1016/j.ijar.2014.11.004
0888-613X/

interact with each other over time, solutions involve a complex process on modelling how the interactions impact their choices. For example, to achieve an instant collaboration in a natural disaster, rescue agents need to consider other agents in the team when they make decisions in real time.

In this paper, we utilize the language of *interactive dynamic influence diagram* (I-DID) [10] to study time-critical dynamic decision making in multiagent settings. I-DID is a probabilistic graphical counterpart of finitely nested interactive POMDP [11] and provides an efficient representation for modelling sequential multiagent decision making under uncertainty. As I-DID stands on the viewpoint of an individual agent and explicitly models other agents into the subject agent's state space, it generalizes dynamic influence diagrams to multiagent settings and can use many standard methods of probabilistic graphical models [12].

One important aspect of time-critical decision analysis is on framing a decision problem, which requires to model the temporal process in an explicit way. Following the same vein as TC-DID, we further formalize I-DID into time-critical I-DID (TC-IDID) by providing time index to each node in the model. This offers a possibility to represent temporal relations of the underlying random variables. For a given domain, a suite of decision models at different levels of space-temporal abstraction may be specified by either domain experts or knowledge engineers, and organized in a knowledge base. The models can only be used for a specific domain because each node corresponds to attributes of the domain and the set of nodes and network structures are fixed in advance [13]. Hence the TC-IDID construction would be intractable in a complex problem domain when we need to expand models over time. We take the notion of object-orientation to facilitate the TC-IDID model development and define the condensed and deployed forms of TC-IDID. The condensed form represents a static model of TC-IDID that will be expanded over time resulting in the deployed form. This follows the spirit of instantiating *class* to construct *object* in the object-orientation design scheme, which reduces the difficulty on building TC-IDID.

As other agents act and observe over time, TC-IDID needs to be updated in order to reflect new beliefs of other agents over environments. Updating models is a complicated process and may result in a computationally intractable TC-IDID model. To reduce the complexity, we need to find a suitable way to specify a condensed form of TC-IDID. Following the concept of subjective equivalence [14], we define ϵ-subjective equivalence between two condensed forms in order to conduct a quantitative measurement on the quality of TC-IDID solutions. In principle, we need to compute all possible condensed forms and select one by indexing which would generate a solvable TC-IDID without compromising the solution quality. An exhaustive search of all condensed forms is definitely not an efficient technique to solve TC-IDID. Even the greedy search may consume much computation on solving TC-IDID with a large number of time steps, which is not feasible in a time pressured situation. To solve TC-IDID efficiently, we propose an entropy-based method which is computationally cheap to select a condensed form. In addition, we formalize the selection strategy and experimentally evaluate the performance of our methods. In three multiagent problems, we show the approach may elicit the condensed form efficiently and strengthen the utilization of TC-IDID in time-critical decision making.

The remainder of this paper is structured as follows. In Section 2, we briefly review necessary background knowledge on I-DIDs and object-oriented paradigm that underlies our work. In Section 3, we formally propose time-critical I-DIDs and its object-orientation design. Furthermore, in Section 4, we implement the greedy method for selecting a suitable condensed form, and proceed to propose the entropy-based method to improve the selection. Meanwhile we conduct the experiments and show positive results on three well-known domains in Section 5. Finally, we discuss relevant works and conclude the paper with some remarks.

2. Background

Our work builds on interactive dynamic influence diagrams and takes the notion of object-orientation design. In this section, we start with a brief review on interactive influence diagrams (I-IDs) for two-agent interactions and their extensions to I-DIDs. More details could be found in the relevant literatures [10,15]. For the clarity, we illustrate the representation of interactive dynamic influence diagrams in the context of the multiagent tiger problem [15].

Example 1 *(Multiagent tiger problem).* Two agents, i and j, intend to open one of two closed doors. A pot of gold is hidden behind one door while one fierce tiger stands behind the other. An agent is rewarded for opening the door that hides the gold but gets hurt for opening the door that is guarded by the tiger. Each agent can choose to open the left door (denoted by OL), open the right door (OR), or listen (L). If an agent opens any door, the tiger will be randomly placed into either of the doors in the next time step; otherwise, the tiger stands still behind the door. On listening, the agent may hear the tiger growling from the left door (GL) or from the right one (GR). Additionally, the agent hears creaks emanating from the left door (CL) or from the right one (CR) if the other agent simultaneously opens either of the doors; otherwise, the agent hears no sound from the doors (S). All observations (such as tiger growling, door creaks or their combinations) are assumed to be noisy. We assume that the actions of the other agent do not directly affect the reward of an agent, but may potentially change the tiger's location.

2.1. Interactive influence diagrams

Influence diagram (ID) [16,17] is a well-known graphical formalism for describing and solving decision making problems. It typically contains chance nodes that represent random variables modelling physical state S, agent i's observations O_i,