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Automated Negotiation for Complex Multi-Agent Resource Allocation

Author

Bo An, *University of Massachusetts Amherst*

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First Advisor

Victor Lesser

Second Advisor

Jim Kurose

Third Advisor

Shlomo Zilberstein

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Abstract

The problem of constructing and analyzing systems of intelligent, autonomous agents is becoming more and more important. These agents may include people, physical robots, virtual humans, software programs acting on behalf of human beings, or sensors. In a large class of multi-agent scenarios, agents may have different capabilities, preferences, objectives, and constraints. Therefore, efficient allocation of resources among multiple agents is often difficult to achieve. Automated negotiation (bargaining) is the most widely used approach for multi-agent resource allocation and it has received increasing attention in the recent years. However, information uncertainty, existence of multiple contracting partners and competitors, agents' incentive to maximize individual utilities, and market dynamics make it difficult to calculate agents' rational equilibrium negotiation strategies and develop successful negotiation agents behaving well in practice. To this end, this thesis is concerned with analyzing agents' rational behavior and developing negotiation strategies for a range of complex negotiation contexts. First, we consider the problem of finding agents' rational strategies in bargaining with incomplete information. We focus on the principal alternating-offers finite horizon bargaining protocol with one-sided uncertainty regarding agents' reserve prices. We provide an algorithm based on the combination of game theoretic analysis and search techniques which finds agents' equilibrium in pure strategies when they exist. Our approach is sound, complete and, in principle, can be applied to other uncertainty settings. Simulation results show that there is at least one pure strategy sequential equilibrium in 99.7% of various scenarios. In addition, agents with equilibrium strategies achieved higher utilities than agents with heuristic strategies. Next, we extend the alternating-offers protocol to handle concurrent negotiations in which each agent has multiple trading opportunities and faces market competition. We provide an algorithm based on backward induction to compute the subgame perfect equilibrium of concurrent negotiation. We observe that agents' bargaining power are affected by the proposing ordering and market competition and for a large subset of the space of the parameters, agents' equilibrium strategies depend on the values of a small number of parameters. We also extend our algorithm to find a pure strategy sequential equilibrium in concurrent negotiations where there is one-sided uncertainty regarding the reserve price of one agent. Third, we present the design and implementation of agents that concurrently negotiate with other entities for acquiring multiple resources. Negotiation agents are designed to adjust 1) the number of tentative agreements and 2) the amount of concession they are willing to make in response to changing market conditions and negotiation situations. In our approach, agents utilize a time-dependent negotiation strategy in which the reserve price of each resource is dynamically determined by 1) the likelihood that negotiation will not be successfully completed, 2) the expected agreement price of the resource, and 3) the expected number of final agreements. The negotiation deadline of each resource is determined by its relative scarcity. Since agents are permitted to decommit from agreements, a buyer may make more than one tentative agreement for each resource and the maximum number of tentative agreements is constrained by the market situation. Experimental results show that our negotiation strategy achieved significantly higher utilities than simpler strategies. Finally, we consider the problem of allocating networked resources in dynamic environment, such as cloud computing platforms, where providers strategically price resources to maximize their utility. While numerous auction-based approaches have been proposed in the literature, our work explores an alternative approach where providers and consumers negotiate resource leasing contracts. We propose a distributed negotiation mechanism where agents negotiate over both a contract price and a decommitment penalty, which allows agents to decommit from contracts at a cost. We compare our approach experimentally, using representative scenarios and workloads, to both combinatorial auctions and the fixed-price model, and show that the negotiation model achieves a higher social welfare.

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