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An Intelligent and Unified Framework for Multiple Robot and Human Coalition Formation*

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Abstract

This dissertation develops the ***i***ntelligent-***C***oalition ***F***ormation framework for ***H***umans and ***R***obots (*i-CiFHaR*), an intelligent decision making framework for multi-agent coalition formation. *i-CiFHaR* is a first of its kind that incorporates a library of coalition formation algorithms; employs unsupervised learning to mine crucial patterns among these algorithms; and leverages probabilistic reasoning to derive the most appropriate algorithm(s) to apply in accordance with multiple mission criteria. The dissertation also contributes to the state-of-the-art in swarm intelligence by addressing the search stagnation limitation of existing ant colony optimization algorithms (ACO) by integrating the simulated annealing mechanism. The experimental results demonstrate that the presented hybrid ACO algorithms significantly outperformed the best existing ACO approaches, when applied to three NP-complete optimization problems (e.g., traveling salesman problem, maximal clique problem, multi-agent coalition formation problem).

1 Motivation

Robotic systems have proven effective with recent deployments of unmanned robots in a number of mission situations (e.g., search and rescue, first response, space). Complex mission requirements are often greater than the capabilities of a single agent (human or robotic asset); therefore, multi-agent coalition formation, which intelligently groups agents, is necessary to perform tasks collectively. Coalition formation is an $\mathcal{NP}$-complete problem [Sandholm *et al.*, 1999] and existing research has led to the development of a number of greedy algorithms [Shehory and Kraus, 1998], approximation approaches [Sandholm *et al.*, 1999], and market-based techniques [Shiroma and Campos, 2009]. Greedy algorithms generate coalitions quickly, but do not guarantee solution quality. Approximation algorithms guarantee solution quality, but their high worst case run-time complexities render them inapplicable to real-world situations. Auction-based techniques are inheritably fault-tolerant, but experience high communication overhead and longer convergence time. Therefore, no single class of algorithms is robust and flexible enough to handle a wide spectrum of highly dynamic real-world missions. Therefore, this dissertation primarily contributes to the current state-of-the-art by presenting the *i-CiFHaR* decision making framework that incorporates a library of diverse coalition algorithms, each employing a different problem solving mechanism [Sen and Adams, 2014]. *i-CiFHaR* achieves the desired flexibility and scalability by leveraging a conceptual hierarchical clustering algorithm in order to mine the intricate relationships among the library's algorithms. Finally, the framework accomplishes multi-criteria decision making over the library by employing probabilistic reasoning based on *adaptive* decision networks; thereby, deriving the optimal subset of algorithm(s) to apply to a given uncertain mission. The library of diverse algorithms, coupled with this intelligent algorithm selection capability enables *i-CiFHaR* to generate robust solutions and handle contingencies in a wide variety of dynamic, real-world missions.

Real-world coalition formation often has a greater propensity towards using greedy algorithms that generate acceptable solutions within the stipulated time limitation. Contemporary heuristic-based coalition formation algorithms [Shehory and Kraus, 1998] typically constrain the maximum coalition size up to a maximum limit, k, which can prohibit an effective resource utilization. Therefore, there exists a void in the field of multi-agent systems for greedy algorithms that can scale effectively for large teams of robotic and human assets, without the use of such limited heuristics. The second major contribution of this dissertation fills this gap by presenting two generic hybrid ***s***imulated ***A***nnealing-inspired ***ANT*** colony optimization algorithms, called the *sA-ANT* [Sen and Adams, 2013] and *sA-ANT** that are applicable to a wide spectrum of combinatorial optimization problems, including the traveling salesman problem (TSP), the maximal clique problem, and the multi-agent coalition formation problem.

2 System Design and Experimental Results

2.1 *i-CiFHaR*: Decision Making Framework

The *i-CiFHaR* framework is a three tiered architecture that includes: (1) User Interaction capabilities, (2) Middle Level Logic Tier, which performs the probabilistic decision mak-

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ing, and (3) Library of algorithms. *i-CiFHaR* leverages an existing taxonomy that defines a comprehensive spectrum of dimensions/features along which the coalition algorithms are classified. The framework computes the utility scores of the taxonomy feature-value features using link analysis and accomplishes the problem dimensionality reduction through *principal component analysis*. *i-CiFHaR* employs an *adaptive* decision network that derives an optimal subset of algorithm(s) to apply to a given mission allocation problem by maximizing the framework's expected utility score. Aiming to achieve real-time algorithm selection and system scalablity, *i-CiFHaR* uses a conceptual hierarchical clustering technique based on COBWEB in order to derive a cluster tree that captures the intricate patterns among the coalition formation algorithms. This clustering allows *i-CiFHaR* to identify and analyze only the most suitable cluster of algorithms for application based on the multiple mission requirements, instead of considering the entire library of algorithms. The effectiveness of *i-CiFHaR*'s decision making capability was realized by applying the framework with nineteen algorithms to a contrasting set of 24 uncertain mission scenarios, when the most suitable subset of algorithm(s) were identified. The integration of the algorithm clustering reduced the computation time from a mean of 16.16 seconds to an average of 5.35 seconds, a 67% improvement.

The major drawback of all the greedy algorithms in *i-CiFHaR*'s library is that they leverage the heuristic of constraining the coalition sizes up to a maximum size, k. The next section describes two swarm-based graph search algorithms that were inspired by the foraging behavior exhibited by swarms of ants and address the aforementioned shortcoming of conventional greedy coalition formation algorithms.

2.2 *sA-ANT* and *sA-ANT** - ACO algorithms

ACO algorithms are biologically inspired search algorithms that simulate the collective foraging behavior commonly exhibited by an ant swarm. Real ants achieve an indirect, local, and environment-based information exchange through the use of pheromones. However, ACO approaches suffer from *search stagnation*, in which the algorithm stagnates in suboptimal solutions. The *sA-ANT* and *sA-ANT** algorithms are important contributions that specifically address the search stagnation drawback by introducing two novel pheromone update policies that deviate significantly from the existing state-of-the-art ACO algorithms through the integration of the simulated annealing methodology.

sA-ANT employs *dynamic searching*, where a dynamically modulating number of ants explore a larger search area during the initial algorithm iterations and gradually converge towards good solutions over time; thereby, effectively resulting in a balanced search exploration and exploitation. This dynamic pheromone deposit scheme increases the likelihood of generating higher quality solutions, without stagnating in local optima. The *sA-ANT** algorithm incorporates a completely different pheromone update policy. *sA-ANT** maintains a repository of good solutions whose size is dynamically modulated during the search process. Each ant solution has an associated fitness value that is computed using the simulated annealing mechanism. Unlike *sA-ANT*, which dynamically modulates the number of ants are permitted to deposit pheromones, *sA-ANT** probabilistically selects the single best fit ant solution to deposit pheromones based on its solution quality. Furthermore, the algorithm permits quality based stochastic forgetting of poor solutions. Equipped with a high initial annealing temperature and a slow annealing schedule, both algorithms avoid stagnating in a local optima; thereby, addressing the undesirable search stagnation problem commonly encountered with existing ACO approaches.

sA-ANT and *sA-ANT** were successfully applied to the multi-agent coalition formation problem, where the algorithms generated high utility coalitions for teams comprising up to 200 agents within ≈ 2 minutes, without restricting the coalition sizes. Furthermore, the novel algorithms were also applied to two other $\mathcal{NP}-$complete problems in order to demonstrate their effectiveness in solving generic combinatorial optimization problems. The presented algorithms outperformed existing state-of-the-art ACO approaches [Stützle and Hoos, 2000] without leveraging any daemon actions (local search, pheromone re-initialization), when applied to the TSP. The experimental results demonstrate that the presented algorithms generated significantly shorter tour lengths, when applied to TSP instances of up to 198 cities. The algorithms computed maximal cliques of higher mean sizes, when applied to the Maximal Clique problem using graphs of up to 1000 nodes and having an edge density of 0.9. Both algorithms exhibited a very high search exploration capability across all three NP-complete problems; thereby, demonstrating their ability to solve a variety of optimization problems.

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