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LITERATURE REVIEW AND SURVEY

Course Instructor: Dr. Richard Frost

Multi-Agent Oriented Constraint Satisfaction with the ERA Formulation

By,

Dev Minotra

(Minotra@uwindsor.ca, dev.minotra@gmail.com)

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Literature review and survey: Multi-Agent Oriented Constraint Satisfaction with the ERA formulation

Dev Minotra

University of Windsor

Abstract. In distributed multi-agent environments, several problems relating to the co-ordination of agent tasks can be modeled as constraint satisfaction problems. There have been several approaches that have addressed constraint-satisfaction problems [42] in distributed multi-agent environments. The ERA formulation [20] is a new strategy that models the constraint-satisfaction problem as Agents with Reactive Rules, embedded in an Environment. The ERA formulation has been tested on various types of constraint-satisfaction problems such as the satisfiability problem and several other benchmark CSPs. It is an approach that has taken inspiration from the Swarm system, and Cellular Automata. In this survey, research work that focuses on the development of the ERA formulation is covered in detail, and as a part of the same survey, research on related approaches will be discussed briefly.

1 Introduction

ERA [20] is a formulation to deal with constraint-satisfaction problems. The approach is oriented towards developing a framework for constraint-satisfaction in distributed multi-agent environments. However, the authors have claimed that the approach can also be used efficiently, in solving constraint-satisfaction problems that may not be distributed. It has been characterized as a stochastic and incomplete approach, and it can be considered to be a variation of Local Search as well [20]. There have been various approaches that address the problem of CSPs in a distributed environment, out of which ERA is one of them. Ant colonies [29], Particle Swarm [30], and the Distributed Constraint-Satisfaction Problem or DCSP [42], are approaches to solve this class of CSPs. As the ERA formulation may share many characteristics with these approaches in distributed problem solving, this survey will also to highlight some of the work reported in these similar areas. However, the span of coverage on these related approaches is limited because the survey mainly intends to cover research work on the ERA formulation as the main topic of the survey.

In the ERA formulation, the variables are divided among several agents and, each individual agent makes a move based on its predefined behavior. It is the movement of the agents in the environment that corresponds to the solution search in the constraint-satisfaction problem. Agents in the ERA framework are characterized as autonomous, and their movement decisions rely on local information and on simple agent architectures. Their movements, lead to a solution state in a self-organized manner. Liu et al [20] provides descriptions and performance results of this approach.

The authors of the report on the ERA formulation have presented several papers in the area of Autonomy Oriented Computing (AOC), a term coined by the author, Jiming Liu. Autonomy Oriented Computing is a general bottom up approach for problem solving and complex systems modeling. The subject has been covered in a monograph, 'Autonomy Oriented Computing, From Problem Solving to Complex Systems Modeling', by Jiming Liu, XiaoLong Jin and K.C Tsui [14]. In a chapter of the monograph, theoretical aspects of the ERA formulation and results on empirical analyses reported in previous papers are revisited. It should be noted that ERA been referred to as ERE in the book.

The Distributed Constraint-Satisfaction Problem [20] also known as DCSP, is a paradigm to solve the same class of problems. There have been several approaches presented in DCSP, one example is the Asynchronous Weak-Commitment Search [39]. It appears that all approaches in DCSP that have been reported till the year 2000 have been summarized in the review by Yokoo et al, published in the year 2000 [42].

Swarm Intelligence is also a distributed approach for solving CSPs and has inspired ERA. The Discrete Particle Swarm and the Ant Colony System belong to the swarm class. These are nature inspired approaches that were originally used to solve optimization problems [7], but were later studied for their capability in constraint-satisfaction problems as well.

2 Constraint-Satisfaction Problems

Constraint-satisfaction problems are decision problems that are known to be NP-complete. They involve the assignment of values to variables, under a set of specified constraints on how variable values should be related to one another. It is known that a number of problems in artificial intelligence can be formulated as constraint-satisfaction problems. Some examples are, distributed resource allocation, decision support, vision interpretation, circuit diagnosis, job-shop scheduling, meeting-scheduling among many other problems in Computer Science [14]. The number of approaches that have been applied to constraint satisfaction problems is too large to be listed. However, they can be very broadly classified as complete approaches and stochastic-incomplete approaches. Complete approaches are those that may explore the entire potential problem space, and if a solution to the constraint problem is not found, it would report that a solution does not exist. A stochastic-incomplete approach will explore the search space in a random manner, even though it is guided by heuristics. Most stochastic-incomplete approaches are designed to overcome the problem of the time consumption usually involved in a complete approach, however, they do not provide complete solution guarantees, and if a problem is over-constrained, the approach does not discover it. Researchers, in the area of constraint-satisfaction problems, often report the performance evaluations of their approaches, on certain benchmark CSPs. The n-Queens problem and the graph coloring problem are well known benchmark problems. The n-Queens problem involves the placement of 'n' queens on an 'n*n' chessboard, in such a way that no queen attacks another queen. The graph coloring problem involves assigning a color to every node in the graph, in such a way that, no two adjacent nodes could be of the same color, and a limit on the number of available colors is also specified. Over-Constrained problems are those CSPs where a solution to a problem does not exist. In other words, only the removal of one or more constraints may lead to feasible problems. There are approaches that are designed to address over-constrained problems specifically, where the quality of the solution is the main focus of such approaches [12]. An introduction to the area of constraint-satisfaction problems can be given in a chapter of the book - Artificial Intelligence, A Modern Approach [28]. The subject has been covered in detail in the book, Foundations of constraint-satisfaction by Edward Tsang, 1993 [34].

3 Multi-Agent Systems

A multi-agent system is a computational system where agents interact with one another in order to satisfy certain goals. Agents in such systems may be homogenous or heterogeneous. They may have common goals or individual goals [20]. Swarm is a system for implementing multi-agent systems. Swarm involves three key concepts: agents with reactive rules, a living environment, and a schedule for dispatching agents and update changes [20]. Work in the area of multi-agent systems has mainly involved simulating social and biological systems, problem solving, collective robotics, distributed planning etc [20]. Developments in the area of multi-agent systems, goes along with the development of self-organized and decentralized approaches to problem solving. This subject has a potential application in the design and development of amorphous computing systems and large scale mobile sensor networks among many other potential applications. A book, 'Autonomous Agents and Multi-Agent Systems: Explorations in Learning, Self-Organization and Adaptive Computation' by Jiming Liu covers the topic of multi-agent systems in detail.

4 Multi-Agent Oriented Constraint-Satisfaction Problem Using the ERA Formulation

Multi-agent systems involve tasks that can often involve problems that can be modeled as constraint-satisfaction problems. While the need of a distributed approach towards solving these constraint satisfaction problems do arise, it is also a fact that the knowledge of the problem is distributed itself. The multi-agent oriented ERA formulation is an approach that can be applied to such multi-agent environments and it is a swarm like system that offers an alternative to the DCSP approach formulated by Yokoo et al. ERA stands for Environment, Reactive Rules and Agents. While solving CSPs in distributed domains is the main application of ERA, it is also suited to solve constraint-satisfaction problems in a centralized and sequential manner.

5 Literature Survey

5.1 Distributed constraint-satisfaction Problems (DCSP)

The DCSP approach for solving constraint-satisfaction problems in distributed multi-agent environments, is an old approach and the first algorithm in the DCSP family was reported in 1992 by Makoto Yokoo et al [41]. The formulation involves multiple agents in a distributed environment, where each agent would assign its allocated variables certain values, and it would communicate with other agents in order to check for constraint violations.

In the year 1992, Makoto Yokoo developed an algorithm known as asynchronous-backtracking and ever since there have been various modifications over this approach [41]. Asynchronous Backtracking and many of its improvisations are complete algorithms that explore the potential solution space entirely. More recently, a number of algorithms have been developed to tackle over-constrained CSPs, by researchers who have worked on DCSPs earlier. Makoto Yokoo, Toru Ishida, Edmund Durfee, Katsutoshi Hirayama, Kazuhiro Kuwabara and Aaron Armstrong are some of the well known researchers in this area of Distributed Constraint Satisfaction Problems. While, there have been several publications in this area of research, this survey provides some of the work done in DCSP.

Asynchronous Backtracking Search, 1992 In the year 1992, Yokoo, Ishida, Durfee and Kuwabara [41] were the first group to identify the problem that is known as the Distributed constraint-satisfaction Problem. They state that this approach is useful in formalizing Cooperative Distributed Problem Solving techniques. They present an approach that is called the asynchronous backtracking search. The authors have referenced 'An Overview of DAI: Viewing Distributed AI as distributed search' [22]. The authors report the results of experiments that compare the performance of the centralized backtracking, synchronous backtracking and the asynchronous backtracking approaches. They state that these approaches were tested on the n-queens problem. They mention that a queen can be assigned to an agent in this algorithm. The authors conclude from their experiments that if local problems are loosely-coupled, asynchronous backtracking outperforms centralized backtracking even if communications are relatively low. The authors finally conclude from their study, that solving DCSPs is worthwhile when the problems solved by the individual agents are loosely-coupled.

Asynchronous Weak-Commitment Search In 1995, Makoto Yokoo reported a new approach based on previous approaches in DCSP, know as the Asynchronous Weak-Commitment Search [39]. The author mentions that this is an improved method to solve Distributed constraint-satisfaction Problems. He refers to the Asynchronous-Backtracking algorithm reported in [41] and the Weak-commitment Search algorithm reported in [38]. He claims that the Weak-Commitment search algorithm has inspired this new approach. The author conducts experiments to compare the min-conflicts heuristic, asynchronous-backtracking algorithm with the asynchronous weak-commitment search. He provides details on how he measures the performances of these algorithms. He applies these algorithms to the distributed n-Queens problem and provides results on a table reporting the performances for values of n ranging from 10 to 1000. Following this, he conducts experiments on the graph coloring problem. In order to test the algorithm on a real-life problem, the he reports the results of experiments on the distributed resource allocation problem. Based on the experiments, he claims that his new approach can solve problems that other algorithms cannot solve and based on the results provided in tables, it appears as if the number of cycles required to solve a problem is less in the new approach as compared to the other two approaches, in all cases. The author claims that asynchronous weak-commitment search is "far more efficient" than the asynchronous backtracking algorithm for solving CSPs. Based on his study, he concludes that a flexible agent organization, where hierarchical order is changed dynamically performs better than an organization where the agent organization is static and rigid.

Dynamic Prioritization of Complex Agents In 1997, Aaron Armstrong and Edmund Durfee reported their study and findings on how the ordering of agents impact the performance of distributed constraint-satisfaction [3]. They make references to past papers on DCSP solving, namely Yokoo[39] and Yokoo[41] and they explore the effect of various heuristics, on the performance of distributed constraint satisfaction. They state "Value ordering heuristics, though important, were not the aim of this research and so were not used. We concentrated instead on the problem of deriving agent ordering heuristics from variable ordering heuristics which have been described in the literature" [41] [2]. The authors report the results of experiments that evaluate the performance of various heuristics on agent-ordering. As mentioned by them, one of their heuristics is a combination of other heuristics, developed by the help of a generation-based Genetic Algorithm. They conclude from their experiments that the combination of heuristics prove to be better than any of the 'pure heuristics'. The authors finally state: "Our empirical investigation using these capabilities has revealed that a good ordering is critical to performance, and that ordering based on the local solution spaces is most effective." The authors conclude that the best heuristics attempt to order agents based on cumulative difficulty of finding assignments to their local variables.

Distributed Partial constraint-satisfaction In 1997, Katsutoshi Hirayama and Makoto Yokoo addressed the problem of over-constrained instances of the distributed constraint satisfaction problems [11]. It appears as if this is the first time the authors have developed an algorithm to specifically address this issue. The authors mention that they introduce the Distributed Partial constraint-satisfaction Problem as a new framework for dealing with over-constrained situations. They report new algorithms for solving Distributed Maximal Constraint Satisfaction Problems, which is an important subset of DPCSPs. They refer to Yokoo [41], and state that the algorithm proposed in that paper may only work for instances where constraints are hierarchically structured, if it has to be used to tackle over-constrained problems. They claim to have tested their two algorithms on random binary distributed CSPs. They claim that both these algorithms have been tested on a 'discrete event simulator' that simulates concurrent activities of multiple agents. They report an analysis on comparisons between SBB and IDB and how they differ in the cost of finding optimal solutions and in terms of their 'anytime curves'. They conclude that the Synchronous Branch & Bound (SBB) is suitable when the optimality of the solution is a concern and the IDB is suitable when a near-optimal solution is required in a short period of time.

Multiple Local Variables In 1998, Makoto Yokoo argued that previous approaches for solving distributed constraint-satisfaction problems cannot efficiently or in a scalable way, allow more than one local variable per agent [37]. The author refers to the previous work on asynchronous weak-commitment search [39] and the new approach is based on this approach, as stated by him. He addresses how the approach can take the advantage of multiple local variables. He makes a reference to the approach presented in [3], to compare that with the new approach being reported.

He performs experiments to compare the performance of his approach with two other approaches namely,

- The asynchronous weak commitment search with agent prioritization using the decaying *nogoods* heuristic as reported in [3].
- Single variable asynchronous weak commitment search.

According to the author, the distributed graph coloring algorithm is used to perform the evaluations on the algorithms. He provides details on how the performance of these algorithms are measured to compare for performance. He claims that the number of interactions in this approach can be decreased and that a bad local solution can be modified without forcing other agents to exhaustively search for their local solutions. From the results of the experiments, the author concludes that the approach presented in the paper proves to be more successful than the simple extension of the asynchronous weak-commitment search, and the algorithm that employs prioritization among agents.

In the year 2000, Hirayama and Yokoo argued that the approach presented in [11], may not be suitable for all types of problems [12]. The authors claim that their series of new algorithms are aimed at solving a new class of Distributed Partial constraint-satisfaction Problems known as the Distributed Hierarchical constraint-satisfaction Problem. The authors also refer to the paper [40] that reviews many of the previous approaches to solve Distributed constraint-satisfaction Problems and they state that their new algorithms being presented here are based on them. The authors claim that they evaluate the performances of the algorithms on Distributed 3 coloring problems. The authors state that the algorithms were implemented on a simulator of 'synchronous distributed system'. They provide an analysis of these algorithms on small sized instances and large sized instances. The authors conclude that their algorithms perform much better than their previous algorithms for finding anytime solutions that are optimal.

In 2003, Modi et al introduced a a new approach to address over-constrained CSPs, known as ADOPT [27]. They stated that "Existing methods for DCOP are not able to provide theoretical guarantees on global solution quality while operating both efficiently and asynchronously". They mention that Distributed Constraint Optimization or DCOP is able to model a large class of multi-agent collaboration problems where a solution can be found within given quality parameters. The authors refer to the book: Distributed constraint-satisfaction: Foundation of Co-Operation in Multi Agent Systems [40] and Hirayama et al [12]. They mention that previous approaches which involve extending the Asynchronous Backtracking Search to solve the over-constrained CSP's, have been applied to only limited types of constraint satisfaction problems. The authors introduce their new method named ADOPT, that addresses the DCOP. The problem being addressed is stated to be a generalization of the Distributed constraint-satisfaction Problem (DCSP). The authors perform experiments on three algorithms:

- Synchronize Branch and Bound.
- Synchronous Iterative Deepening.
- Adopt.

Their comparisons show that Adopt performs better than the other two algorithms. They conclude that a certain class of optimization problems have been solved efficiently and optimally by Adopt and it obtains significant orders of magnitude speed up over distributed branch and bound search.

Summary of Research on DCSP

Author(s)	**Conference/Journal and Year**	**Title of the Paper**	**Main Contributions**
Makoto Yokoo, Toru Ishida, Edmund Durfee and Kazuhiro Kuwabara	Conference on Distributed Computing Systems, 1992	Distributed Constraint Satisfaction for Formalizing Distributed Problem Solving	An approach to formalize Distributed Co-operative Problems has been presented and a first attempt to address distributed constraint satisfaction problems is developed.
Makoto Yokoo	International Conference on Principles and Practice of Constraint Programming 1995	Asynchronous Weak-Commitment Search for Solving Distributed Constraint Satisfaction Problems	The author reports a new method to solve DCSPs by taking inspiration from asynchronous weak-commitment and asynchronous-backtracking.
Aaron Armstrong and Edmund Durfee	International Joint Conference on Artificial Intelligence, 1997	Dynamic Prioritization of Complex Local Agents in Distributed Constraint Satisfaction Problems	The authors present an approach to address agent-ordering heuristics, in order to deal with DCSPs.
Katsutoshi Hirayama and Makoto Yokoo	Principles and Practice of Constraint Programming 1997	Distributed Partial Constraint Satisfaction Problem	The authors address the over-constrained problems in DCSPs and present a ‘Distributed Partial Constraint Satisfaction Algorithm’
Makoto Yokoo	International Conference on Mutliagent Systems 1998	Distributed Constraint Satisfaction Algorithm for Complex Local Problems	A new approach to the DCSP is being presented, where it is claimed that having multiple local variables is an advantage.
Katsutoshi Hirayama and Makoto Yokoo	Fourth International Conference on Multi Agent Systems 2000	An Approach to Over-Constrained Distributed Constraint Satisfaction Problems: Distributed Hierarchical Constraint Satisfaction	The authors address over-constrained constraint satisfaction problems, and propose a modification over previous approaches to DCSP, to tackle over-constrained problems.
Pragnesh Modi, Wei-Min Shen, Milind Tambe and Makoto Yokoo	Proceedings of Autonomous Agents and Multi Agent Systems 2003	An Asynchronous Complete Method for Distributed Constraint Optimization	The authors introduce their new method named ADOPT, that addresses the Distributed Constraint Optimization. This work appears to be similar to the Phd Thesis by Pragnesh Jay Modi, University of Southern California (2003).

5.2 Swarm Intelligence and Ant Colonies

Swarm Intelligence is a general term that refers to nature-inspired computational systems that mimic the behavior of social insects. It is known that social insects show the collective ability to solve problems [6]. The Discrete Particle swarm and the Ant Colony system belong to the Swarm Class. The book, ‘Swarm Intelligence: From Natural to Artificial Systems’ by Eric Bonabeau, Marco Dorigo and Guy Theraulaz [6] serves as a reference to the subject. In 1991, Colorini, Dorigo and Maniezzo reported an approach to solve optimization problems using ant colonies . Significant research in the area of ant colonies in its applicability to optimization problems has been done. More recently, there has been a relatively increasing focus of ant colonies in its applicability on constraint-satisfaction problems. The number of papers that have been published in this area is large, and the survey here covers only a few significant papers.

Ants Can Color Graphs In 1997, Costa and Hertz, presented an ant colony based evolutionary search procedure for tackling assignment type problems. The authors claim that the algorithm repeatedly constructs feasible solutions of the problem by considering the trace factor and the desirability factor. On the basis of experimental results, the authors conclude that their method’s performance proves to be satisfactory as compared to other methods in literature [5].

Recently, in the year 2000, Schoofs et al addressed the issue of whether the ant system can be applied to solve constraint satisfaction problems as well [29]. They refer to the work of [7], where the approach to use ant colonies in discrete optimization is presented. They claim that ant colony systems can be used to solve CSPs, by providing a comparison of their method with other standard approaches in evolutionary computation, in terms of performance. They claim that their approach outperforms all other approaches that are considered for comparisons here.

They provide a comparison-table on the performance of their approach with seven other stochastic approaches. They include performances of the Random-hill-climber, Population-based incremental learning, Mutual information maximizing input clustering, Genetic algorithm with bit-based simulated crossover, Genetic algorithm with adaptive mutation rate, Univariate marginal distribution algorithm and the Bivariate marginal distribution algorithm. The authors claim that their algorithm outperforms all other stochastic approaches that they have tested, both in speed and convergence percentage.

Ant Colonies and Permutation constraint-satisfaction Also in the year 2000, Christine Solnon reported her approach to solve permutation constraint-satisfaction problems, with ant colonies [32]. She refers to the Ant Colony Optimization(ACO) metaheuristic [7],[8] and states that the work being presented is based on the ant colony optimization metaheuristic. This formulation can be placed in the broad class of stochastic and incomplete algorithms. The author introduces the concept of the Ant-p solver by describing how artificial ants walk along the edges of the permutation graph in a stochastic and incomplete way. As it has been stated in this paper, artificial ants communicate in a local and indirect way by laying an artificial 'pheromone' on the edges of the graph that is being searched for the solution to the permutation constraint-satisfaction problem.

The author provides an empirical evaluation of the approach being presented by comparing test results with another approach known as the ILog solver, a tree search based solver. She reports the experimental evaluation of both these approaches by testing both of them on an HP 715/100 station. She reports comparisons on the N-queens problem, the car sequencing problem and the all interval series problem. The results on these experiments have been presented on comparison tables. She specifies instances where the Ant-p solver reports better efficiency as well as instances where the efficiency is reported to be less.

The author does not make concluding statements regarding the efficiency of the approach, however, the author does mention that the approach being presented is proven to be a constraint-satisfaction problem solver, that can be enhanced with additional work and modifications.

Reported Modifications Later on in the year 2002, Christine Solnon reported a modified version of her previous approach. The author states that her algorithm should be able to solve all constraint-satisfaction problems. A reference on the authors previous paper [31], is made. This paper introduces approaches to boost the algorithm by using Local search and a Preprocessing Step.

The author first provides the results of an experimental study on the preprocessing step. She later provides comparisons on different variations of the ant solver. She compares the ant solver, ant solver with min conflicts heuristic local search (AS MCHLS) and the ant solver with min conflicts heuristic local search and preprocessing step (AS MCHLSP) and presents the results of the experimental comparisons on a table. In addition to this, she later compares all these approaches with the random walk local search on various parametric values of constraint-satisfaction problems. Based on the experiments, she concludes that ants alone can solve constraint-satisfaction problems although they are slow. When ACO is combined with the LS procedure, the performance is boosted. In addition to this, it has also been concluded that the preprocessing step improves the success rate and running time.

Also in the year 2002, Luk Schoofs and Bart Naudts, presented an approach to solve constraint-satisfaction problems using the Particle Swarm system [30]. The approach is usually used to solve optimization problems, but is being presented here to solve CSPs. The authors claim that their algorithm is an adaptation of the approach presented in Kennedy et al [1997].

The authors explain some of the terms and definitions that apply to their approach. They provide details on parameter tuning. They also provide a pseudo code for particle swarm algorithm to solve CSPs and later report 4 modifications that they have made on the particle swarm, to suit the requirements of constraint-satisfaction problems.

First, the authors report the results of experiments to determine a 'quasi-optimal setting'. They state that for every combination of parameter values, the authors perform 10 experiments on different instances of the same problem class. Secondly, they report experimental results that explains, the nature in which the search process get affected by the parameters.

Thirdly, they compare their approach with three other approaches that are mentioned as follows:

- Ant Colonies as reported by [31].
- The Stochastic Hill Climber.
- Generational Genetic Algorithm.

They claim that they compare these approaches by using two metrics: the number of conflict checks until termination, and the success rate. They claim that their approach does not perform better than the other two approaches. The authors also conclude that the Ant Colonies approach has the best success rate as compared to the other two. The authors finally conclude that their approach is suitable to solve randomly generated constraint-satisfaction problems, however, they also state that this approach is not better than the generational genetic algorithm or the stochastic hill climber.

More recently in the year 2003, Hu, Eberhart and Shi reported a particle swarm algorithm to solve permutation optimization problems, and presented a case study on the n-Queens problem (Hu, 2003). The authors claim that there is no previous research that has been done on Particle Swarm Optimizers (PSO) in solving permutation optimization problems. They present a modification of the PSO to solve permutation optimization problems. They provide a theoretical explanation on how a 'permutation set' can be dealt with in addition to an introduction to the n-queens problem. They claim to have added a new velocity and particle updating technique and they also state that a mutation factor is used in order to avoid the algorithm from getting stuck in local minima. They report the results of their experiments on their approach. They report tests on the n-Queens problem. They provide the results of queens from n = 10 to n = 200 queens and a fitness evaluation has been provided for values of n within this range. They provide a graph to express this result.

Secondly, they provide a comparison of the results of their approach with two other approaches:

- The results of the approach presented in Homaifar et al (1992).
- The results of the approach presented in Kilic et al (2001).

The authors conclude from their analysis, that their approach is comparable to Genetic Algorithms. They claim that they have demonstrated that the PSO is effective in solving the N-Queens problems. The authors state that further work can be done to analyze whether the PSO can solve other categories of constraint-satisfaction problems.

Summary of Research on Swarm Intelligence and Ant Colonies

Author(s)	**Conference/Journal and Year**	**Title of the Paper**	**Main Contributions**
Costa and Hertz	The Journal of the Operational Research Society, 1997	Ants Can Colour Graphs	The authors presented an ant colony based evolutionary search procedure for tackling assignment type problem.
Luk Schoofs and Bart Naudts	Proceedings of the 2000 Congress on Evolutionary Computation	Ant Colonies are Good at Solving Constraint Satisfaction Problems	An ant colony based approach to solve CSPs was presented. Comparisons with other stochastic approaches were shown to demonstrate efficiency.
Christine Solnon	European Conference of Artificial Intelligence, 2000	Solving Permutation Constraint Satisfaction Problems with Artificial Ants	Another report on how Ant colonies can solve CSPs has been made, but this time the study has been specifically reported for permutation CSPs.
Christine Solnon	IEEE transactions on evolutionary computation, 2002	Ants Can Solve Constraint Satisfaction Problems	A study on how the Local Search procedure boosts the performance of Ant Colonies on CSP solving is reported.
Luk Schoofs and Bart Naudts	Proceedings of the 2002 congress on evolutionary computation	Swarm Intelligence on Binary Constraint Satisfaction Problems	The authors present an approach to solve binary constraint satisfaction problems using the Particle Swarm.
Xiaohui Hu, Russel Eberhart and Yuhui Shi	Proceedings of the 2003 IEEE symposium	Swarm Intelligence for Permutation Optimization: A Case Study of n-Queens Problem	The study of how Particle Swarm Optimizers can solve permutation optimization problems is reported by a supporting study on then-Queens problem

5.3 Solving Constraint-Satisfaction Problems using the Alife and ERA approach

The ALife and ERA approach is a relatively recent approach to solve constraint-satisfaction problems, and it has been developed by a group of researchers working in the area of Autonomy Oriented Computing. While the Alife approach in CSPs is lesser known, it is the progenitor to the ERA approach that was reported a year later [20]. This section provides a survey on the research conducted in this area.

An Overview on the ERA algorithm ERA stands for environment, reactive-rules and agents. The ERA algorithm is an approach that involves a multi-agent system that involves a variable or a small group of variables assigned to an agent. Agents are composed of reactive-behaviors that are involved in the assignment of values to variables on the basis of how these reactive-behaviors are defined. The algorithm involves a sequence of time-steps in which each time-step is a cycle in which each agent is allowed to assign a value to its variable(s). The algorithm is a concept that provides a foundation to a parallel and distributed CSP solving. However, it should be noted that the results of experiments that have been reported by the authors are based on experiments that implement a sequential equivalent of the parallel approach. Hence, though ideally one time-step is supposed to allow agents to react in a synchronous manner, the experiments involve sequential series of individual agent reactions and the data that has been provided to agents that guide their decision-making is in the same context as what it would be if this were implemented in a parallel manner. Authors of papers that present the ERA approach state that their method is similar to local-search. Local-search is an algorithm that involves a sequential process of individual variable assignment and it involves incrementally reducing the number of conflicts. The local-search and the ERA algorithm have a common bottleneck: the local-minima. This is a condition where the assignment of variables is such a combination that it is not a solution-state and there is no possibility of further incremental correction to any one variable at one time allowing the total number of conflicts to reduce globally. This bottleneck is usually overcome by the random-move in the ERA algorithm [20]. Modifications to the approach have been made later on.

The ALIFE approach In the year 1999, Jiming Liu and Han Jing reported a method to solve constraint-satisfaction problems by using a nature inspired method known as ALIFE [23]. This work was reported in the conference: 'Intelligent Agent Technology, Systems, Methodologies and Tools'. This was the first time this group of researchers had addressed the gap between constraint-satisfaction problems and multi agent systems. The same group later published similar work in the International Journal of Pattern Recognition and Artificial Intelligence [20]. The authors state that their method is inspired by Swarm, Cellular Automata and Artificial Life. They state that the backtracking approach takes exponential time to solve non-trivial CSPs. They mention that subsequent improvements on the backtracking approaches do not report reasonable runtimes on non- trivial CSPs. They have also stated that the variations of stochastic and heuristic local searches are not capable of addressing all types of CSP's. While DCSPs address the issue of CSPs in distributed domains, according to the authors, their approach can be applied in distributed as well as sequential cases. The authors report the results of several experiments which they conducted to prove the validity of their approach. They performed experiments on values of various parameters and report the corresponding results. They furnish their results with graphs and tables that report runtimes against different parameter values. A linear regression analysis of the runtime has also been provided. The authors conclude that their model can solve the n-queens problem for 'n = 1500' in a 'few time steps'. They have reported that the process of finding a solution is entirely determined by the locality of the agents. They also report that the system dynamically evolves by eliminating poor-strategy agents by selection and contest.

Multi-Agent Oriented constraint-satisfaction In the year 2001, Jiming Liu, Han Jing and Y.Y Tang [20], reported the ERA approach to solve multi-agent oriented constraint satisfaction problems. They claim that previous approaches are not suitable for a wide class of problems. They refer to the Min-conflicts heuristic (Minton et al 2002) and provide a comparison of this with the ERA approach in solving constraint-satisfaction problems. They claim that their method does not suffer from a drawback that the min-conflicts heuristic does. This is the trap of the local minima that the hill climbing system of the min-conflicts heuristic is capable of getting into, as stated by the authors. They state that their method is advantageous over the informed backtracking approach [(Minton et al 2002), in a way that ERA does not 'backtrack'. It has also been mentioned that the informed backtracking approach being a complete approach would not be efficient in terms of search timing. They state that the min-conflicts heuristic and the informed backtracking approaches have a common drawback. In that, it is mentioned that both involve the computation of a variable order, which can be costly considering that it is carried out at each step. They claim that their approach does not suffer from such a drawback.

The authors refer to the Distributed constraint-satisfaction approach [13],[42] and they provide a detailed comparison on how ERA differs from this approach. A table providing a comparison of these two approaches, on several scales of the N -queens problem, is presented. Here, it is shown that ERA outperforms several variations of the distributed constraint satisfaction problems, in terms of the number of steps to reach a solution state for the N-queens problem. The following table that is included by the authors summarizes this result. The numbers indicate the number of cycles involved in reaching the solution state.

Table 1. Comparison Table

N	Asynchronous Backtracking	Asynchronous Backtracking with Min-conflicts Heuristic	Asynchronous Weak-commitment search	ERA
100	510	504	51	22
1000	-	324	30	18
2000	-	-	-	30

Comparison between approaches by Yokoo et al, and Liu et al. Page No. 36 in [20].

Analyses of the performance of this approach on two benchmark problems i.e. the N-queens problem and the Graph Coloring problem are reported. They compare the various modes by which the algorithm can function, under different parameter settings. They evaluate the performance of their heuristic by reporting execution runtimes.

The authors claim that the algorithm takes only three steps to reach a state where 80% of the variables satisfy constraints for most instances of the graph coloring problem and N-queens problem. They also state that, results relating to the efficiency in obtaining a final solution-state on some cases of the graph coloring problem, is relatively low due to the structure of the problem.

MASSAT MASSAT stands for Multi-agent SAT where SAT stands for satisfiability. MASSAT is an algorithm that is similar to ERA but it is focussed to solving satisfiability Problems. In the year 2002, Jiming Liu and Xiaolong Jin [16] addressed the problem of solving Satisfiability problems with their previously reported formulation - ERA. It appears that this is the first formulation to use a self organizing multi-agent system to solve Satisfiability problems. The authors refer to their previous publication that introduces the concept of ERA [16]. The previous paper does not provide results on satisfiability problems. They claim that their approach produces results that are comparable to popular approaches that address this class of problems. It should be noted that a conference publication reports similar work that has been presented at IDEAL, the Third International Conference in 2002 at Manchester, UK [15].

The authors evaluate the performance of the MASSAT on instances of Satisfiability problems taken from SATLIB. They claim that they use two commonly used benchmark problems packages from SATLIB namely uf100 or Uniform Random 3-SAT, and flat-50 or Flat Graph Coloring. They claim that both these packages are cases of 3-SAT problems.

The authors compare the number of 'flips' of other approaches with the number of 'movements' on MASSAT. They provide a rationale behind making this comparison. The authors conclude from their experiments that ERA can be applied to SAT problems and that their approach is comparable and more stable in comparison to other approaches.

Agent-Compromises In 2003, Y.Y Tang, Jiming Liu and Xiaolong Jin [25] considered making a modification to the original ERA formulation [20] in order to remove the drawbacks of the random-move. They state that the random move is supposed to avoid the problem of local minima traps. They claim that this problem of local minima traps, is tackled by a new feature that is being introduced in this paper. They introduce the concept of 'agent compromises' by incorporating a new move called the 'make-compromise' move. They claim that this feature has addressed the structure of the graph coloring problem. They report the results of experiments conducted on benchmark instances of the graph coloring problem. They state that the approach presented in this paper, outperforms the original ERA formulation [20].
First, they perform experiments on the original ERA heuristic on an instance of the graph coloring problem from Donald Knuth's Stanford Graph Base. The authors compare the results of the original ERA algorithm with different parameter values. The parameter being varied is the probability of the random move behavior. They report that each case has been executed 100 times, before the average number of steps is calculated for every case. Based on these results on the original ERA heuristic, the authors state that the random move operation is inefficient.
The second experiment that the authors report is a test on the 'make-compromise' move. This is the new feature that is intended to be added to the original formulation. They perform experiments on the same problem i.e. myciel7.col. These trials are performed on different parameter settings and it has been reported that their new feature does prove to be more efficient. They claim that the number of movements involved in obtaining the solution is reduced by 26% on an average. The variation lies between 14% to 44% according to their report.
Finally, the authors present the results of a third experiment to analyze the overall performance of the new approach. They tested their heuristic on 7 more instances of Graph Coloring Problem's taken from the Donald Knuth's Stanford Graph Base. A table is included that provides a description of the results obtained in this experiment. It indicates a reduction in the number of movements that were required to obtain solutions to these benchmark problems.

Constraint-Satisfaction in Small World Networks Also in 2003, Xiaolong Jin and Jiming Liu [18] reported a study on emergent constraint-satisfaction in small-world networks. The authors state that a number of natural and man-made networks exhibit small-world topologies. They refer to a similar work of theirs reported in [17], at a conference (Autonomous Agents and Multi-agent systems, 2003) and they claim to validate the observations of their previous paper. From empirical results, the author conclude that the small-world badly influence the 4 measurements that have been taken into consideration. A network that has small-properties, decreases the efficiency of solving constraint satisfaction problems. They state that randomness of a network is a key factor in influencing the efficiency of solving generated constraint-satisfaction problems. The authors highlight the main differences between their work and similar work in the past, and they mention what could be the orientation of this research for the future.

A Practical Case Study of ERA Again in 2003, Hui Zou and Berthe Choueiry [45] performed an empirical analysis on the practical applicability of the ERA approach [20]. It should be noted that this work is a part of a master's thesis by Hui Zou at the University of Nebraska at Lincoln [44]. Subsequently, this work was presented at a conference [45] and then at the International Joint Conference in Artificial Intelligence [46]. The authors report an empirical analysis, where they conduct experiments from different networks generated from different lattices.

In Zou et al [46], the authors compare the ERA approach with 2 other approaches on a problem type that has not been addressed in Liu et al [20]. They examine the performance of ERA on both these cases, by comparing it with two other approaches and report their findings and conclusions.

The authors state that their experiments have been made on the problem of assigning Graduate Teaching Assistants (GTAs) to academic courses [46]. They state that, this constraint-satisfaction problem is most of the times over-constrained i.e. it is not solvable. They also describe this as a non-binary CSP. The authors state that some of the instances that have been studied by them are solvable, while some are not. Experimental results on the N-queens problem (N=100), that is addressed in Liu et al[2002] have also been reported in order to be on a common level with Liu et al[20].

The authors experimentally compare the ERA method with:

- Systematic backtracking search with dynamic variable ordering [Glaubius and Choueiry, 2002].
- Hill climbing local search [Zou, 2003].

From the results of various experiments, the authors conclude that ERA performs better than the other two approaches in the case of tight CSP's that are solvable. In addition, they point out that ERA performs poorly when the CSP is over-constrained, as compared to the other two approaches. They state that this problem is a result of a 'deadlock phenomenon' that they claim to have observed in their experiments. They provide a diagram illustrating their observation. They state that their results are an indication that ERA may not be useful in solving real world problems.

Multi-Agent Evolutionary Algorithm for CSPs Very recently in 2006, Jing Liu, Weicai Zhong and Licheng Jiao [1] introduced a new approach to solve CSPs in a multi-agent environment. The description of their new approach includes details on agent behaviors in their environment. They have named it MAEA that stands for Multi-agent evolutionary algorithm.

The authors state that constraint-satisfaction problems are classifiable into two categories i.e. permutation constraint satisfaction problems and non-permutation constraint-satisfaction problems. They state that, the properties of CSPs from this classification, is used to design the behaviors of the agents in their approach. They also claim to use a new encoding method called the minimum conflict encoding, to overcome disadvantages of general encoding methods. They show that their results are better than previous standard approaches to solve CSPs. A reference to [20] is made where the comparison with the ERA approach was needed to be made.

The authors first report their results on an initial set of experiments that are performed on non-permutation CSPs. They report their results on 250 benchmark binary constraint-satisfaction problems and 79 graph coloring problems form the DIMACS challenge. They compare the results of this with 6 other approaches namely, H-GA.1, H-GA.3, SAW, Glass-Box, SSC and ERA. They claim that their approach outperforms all these approaches. Secondly, in order to test the performance of their approach for permutation CSPs, they provide results for the N-queens problem and the Job shop scheduling problem. They claim that their results on the Job-Shop-scheduling problem, is an indicator of MAEA being suitable for practical applications. The authors provide a parameter analysis of the MAEA approach and conclude from their results that their approach is robust and easy to use.

Summary of Research on ERA

Authors	Conference/Journal and Year	Title of the Paper	Main Contributions
Jiming Liu and Han Jing	International Journal of Pattern Recognition and Artificial Intelligence, 2001	ALIFE: A Multi agent computing paradigm for solving constraint satisfaction problems	The first attempt to address the issue of bridging the gap between multi-agent systems and CSPs is made by introducing an approach that works along the lines of Swarm and Cellular Automata.
Jiming Liu, Han Jing and Tang	Artificial Intelligence, 2001	Multi-agent oriented Constraint Satisfaction	A new approach to solve CSP's in a distributed multi-agent environment named ERA is reported. A detailed empirical analysis on the competitiveness of the approach is presented.
Jiming Liu and Xiaolong Jin	International Journal of Pattern Recognition and Artificial Intelligence, 2002	Distributed Problem Solving Without Communication – An Examination of Computationally Hard Satisfiability Problems	Am analysis of the ERA performance on Satisfiability problems is presented.
Yi Tang, Jiming Liu and Xiaolong Jin	Lecture Notes in Computer Science, 2003	Agent Compromises in Distributed Problem Solving	An improvisation on the ERA algorithm on graph coloring problems is reported, by introducing a new make-compromise move.
Xiaolong Jin and jiming Liu	IEEE/WIC, International Conference in Intelligent Agent Technology, 2003	Efficiency of Emergent Constraint Satisfaction in Small-World and Random Agent Networks	An analysis of how multi-agent systems would perform on small-world networks, for constraint satisfaction, has been presented.
Hui Zou and Berthe Choueiry	International Joint Conference in Artificial Intelligence (IJCAI), 2003	Multi-Agent Based Search versus Local Search and Backtrack Search for solving Tight CSPs: A Practical Case Study	A case study on ERA in practical problems has been reported. The performance of ERA in over-constrained problems has been analyzed. This paper is the same work as the Masters Thesis by Hui Zou
Liu, Zhong, Jiao.	IEEE transactions on systems man and cybernetics, 2006	Multi Agent Evolutionary Algorithm for Constraint Satisfaction Problems	A new multi agent approach to solve CSPs has been presented along with detailed comparisons with related approaches

5.4 Concluding Statements

This survey covers research work reported in the area of multi-agent oriented constraint-satisfaction problem solvers, and it specifically focuses on the ERA approach. A number of related approaches have also been included, even though they have not been thoroughly surveyed. I would like to conclude this survey by ending with a few quotes made by authors in this field, on how they intend to orient their future research directions.

Liu et al:

- "The research ahead will be oriented towards incorporating explicit communication and co-operation mechanisms, and discovering new properties of this approach, in order to solve new types of constraint-satisfaction Problems" Taken from (Liu et al, 2002), in the context of the ERA algorithm.
- "We cannot exempt the agents from the behavior of *random-move*. Although a compromise agent can make the violated neighbor constraints satisfied, the variables changed might not belong to the *primary* variables. This may lead to the different reduction of agent movements. We need further study on the structure of a problem." . Taken from (Tang et al, 2003), in the context of local-minima avoidance and the random-move behavior.

Zou et al:

The authors plan to overcome shortcomings of the ERA formulations by, introducing conflict-resolution strategies to overcome deadlocks. This has been stated in the context of the suitability of the ERA algorithm in over-constrained problems [45].

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APPENDIX : ANNOTATIONS ON MILESTONE PAPERS

[Armstrong et al, 1997]

Research Motivation and Background

The authors report their study and findings on how the ordering of agents impact the performance of distributed constraint satisfaction. They make references to past papers on DCSP solving, namely Yokoo[1995] and Yokoo[1992] and they explore the effect of various heuristics, on the performance of distributed constraint satisfaction. The authors state “Value ordering heuristics, though important, were not the aim of this research and so were not used. We concentrated instead on the problem of deriving agent ordering heuristics from variable ordering heuristics which have been described in the literature, e.g.[Yokoo 1993; Minton et al. 1990]. ”

Description on the Study

The authors first provide a description on Asynchronous-Backtracking and Asynchronous Weak-Commitment Search. They present their algorithm including some of its details. They describe a few agent-ordering heuristics in order to explain how performance optimization is achieved. An example is provided by the authors for an explanation of the approach.

Empirical Evaluations

The authors report the results of experiments that evaluate the performance of various heuristics on agent-ordering. As mentioned by the authors, one of their heuristics is a combination of other heuristics, developed by the help of a generation-based Genetic Algorithm. The authors conclude from their experiments that the combination of heuristics prove to be better than any of the ‘pure heuristics’.

Conclusions

The authors state: “Our empirical investigation using these capabilities has revealed that a good ordering is critical to performance, and that ordering based on the local solution spaces is most effective”
The authors conclude that the best heuristics attempt to order agents based on cumulative difficulty of finding assignments to their local variables.

Directions on Further Research

The authors state that, characterizing the tradeoffs between the benefits of the heuristics and the cost of the local computation, still remains an open problem. The authors state that a better decentralization of the protocol can still be implemented.

Citations:

- Makoto Yokoo, Katsutoshi Hirayama(2000), Algorithms for Distributed Constraint Satisfaction Problems: A review

- Makoto Yokoo, Katsutoshi Hirayama (1998), Distributed Constraint Satisfaction Algorithm for Complex Local Problems

- Modi, Shen, Tambe, Yokoo (2006), ADOPT: Asynchronous Distributed Constraint Optimization with Quality Guarantees

[Hirayama et al, 1997]

Research Motivation and Background

The authors address the problem of over-constrained instances of the distributed constraint satisfaction problems. It appears as if this is the first time the authors have developed an algorithm to specifically address this issue. The authors mention that they introduce the Distributed Partial Constraint Satisfaction Problem as a new framework for dealing with over-constrained situations. The authors mention that they introduce new algorithms for solving Distributed Maximal Constraint Satisfaction Problems, which is an important subset of DPCSPs. They refer to Yokoo [1993], and state that the algorithm proposed in that paper may only work for instances where constraints are hierarchically structured, in order to tackle over-constrained problems.

Authors Description of the Approach

The author provides definitions and descriptions of the Distributed Partial Constraint Satisfaction Problems and the Distributed Maximal Constraint Satisfaction Problem. They mention their two new algorithms: the Synchronous Branch and Bound(SBB) and the Iterative Distributed Breakout(IDB). They provide pseudo-code for these two approaches.

Experimental Evaluations and Conclusions

The authors claim to have tested their two algorithms on random binary distributed CSPs. They claim that both these algorithms have been tested on a ‘discrete event simulator’ that simulates concurrent activities of multiple agents. The authors report an analysis on comparisons between SBB and IDB and how they differ in the cost of finding optimal solutions and in terms of their ‘anytime curves’.
The authors conclude that the Synchronous Branch & Bound (SBB) is suitable when the optimality of the solution is a concern and the IDB is suitable when a near-optimal solution is required in a short period of time.

Directions for Further Research

The authors claim that their future work will include developing more efficient algorithms for DMCSPs and applying this framework to real-life problems.

Citations:

- Makoto Yokoo, Katsutoshi Hirayama(2000), Algorithms for Distributed Constraint Satisfaction Problems: A review

- Modi, Shen, Tambe, Yokoo (2006), ADOPT: Asynchronous Distributed Constraint Optimization with Quality Guarantees

- Katsutoshi Hirayama, Makoto Yokoo, (2000), An Approach to Over-Constrained Distributed Constraint Satisfaction Problems: Distributed Hierarchical Constraint Satisfaction

- Modi, Shen, Tambe, and Yokoo (2003), An Asynchronous Complete Method for Distributed Constraint Optimization

[Hirayama et al, 2000]

Research Motivation and Background

The authors address over-constrained constraint satisfaction problems, and propose a modification over previous approaches to DCSP, to tackle over-constrained problems.
The authors claim that their series of new algorithms are aimed at solving a new class of Distributed Partial Constraint Satisfaction Problems known as the Distributed Hierarchical Constraint Satisfaction Problem. The authors refer to a previous approach, the Distributed Maximal CSP presented in [Hirayama,1997] and state that not all problems are suitable for this approach. The authors propose their new approach, the distributed hierarchical CSP among other new algorithms that are reported in this paper.
The authors also refer to a paper [Yokoo, 2000] that reviews many of the previous approaches to solve Distributed Constraint Satisfaction Problems and they state that their new algorithms being presented here are based on them.

Authors Description of their Approach

The authors provide a description of the distributed hierarchical CSP by making illustrations with examples and figures. The distributed hierarchical CSP is a problem class of the distributed partial CSP, according to the authors.

The authors state that they divide their search process into two parts: the value space search and problem space search. They provide a description of both of these. They mention the new algorithms and provide descriptions on each of these, and also state how they are related to the previous approaches in DCPSs.

Evaluations and Conclusions

The authors claim that they evaluate the performances of the algorithms on Distributed 3 coloring problems. The authors state that the algorithms were implemented on a simulator of 'synchronous distributed system'. They provide an analysis of these algorithms on small sized instances and large sized instances.
The authors conclude that their algorithms perform much better than their previous algorithms for finding anytime solutions that are optimal.

Directions on Further Research

The authors state that the approach presented in [Yokoo, 1998], that involves multiple local variables per agent, could be used in the value space search part of the algorithm. They state that their future work will involve evaluating the performance of this extension.

Citations:

- Modi, Shen, Tambe, Yokoo (2006), ADOPT: Asynchronous Distributed Constraint Optimization with Quality Guarantees

- Modi, Shen, Tambe, and Yokoo (2003), An Asynchronous Complete Method for Distributed Constraint Optimization

[Hu et al, 2003]

Research Motivation and Background

The authors claim that there is no previous research that has been done on Particle Swarm Optimizers(PSO) in solving permutation optimization problems. They present a modification of the PSO to solve permutation optimization problems. The authors report their study on the n-Queens problem specifically. The authors refer to pervious work done on PSOs. They refer to the work of Eberhart et al [1995], and Kennedy et al [1995].

Authors Description of the Algorithm

The authors provide a description of the particle swarm optimizer and provide a pseudo code of the PSO. They provide a theoretical explanation on how a 'permutation set' can be dealt with in addition to an introduction to the n-queens problem. The authors claim to have added a new velocity and particle updating technique and they also state that a mutation factor is used in order to avoid the algorithm from getting stuck in local minima.

Empirical Analysis and Report

The authors report the results of their experiments on their approach. They report tests on the n-Queens problem. They provide the results of queens from n = 10 to n = 200 queens and a fitness evaluation has been provided for values of n within this range. They provide a graph to express this result.

Secondly, they provide a comparison of the results of their approach with two other approaches:

- The results of the approach presented in Homaifar et al [1992]
- The results of the approach presented in Kilic et al [2001]

Conclusions Made by the Authors

The authors conclude from their analysis, that their approach is comparable to Genetic Algorithms. They claim that they have demonstrated that the PSO is effective in solving the N-Queens problems. The authors state that further work can be done to analyze whether the PSO can solve other categories of constraint satisfaction problems.

Citation

- MF Tasgetiren, M Sevkli, YC Liang, G Gencyilmaz (2004), Particle Swarm Optimization Algorithm for Permutation Flowshop Sequencing Problem.

[Liu et al, 2001a]

Research Motivation and Background

The authors present an approach to bridge the gap between multi agent systems and constraint satisfaction problems. They address the problem of multiple agents sharing the same environment having to comply with several constraints, which is also called a distributed constraint satisfaction problem (DCSP). They state that their approach is not just limited to Distributed CSP’s but it could also be applied to CSPs in general. They state that their method is inspired by Swarm, Cellular Automata and Artificial Life.

Remarks made on other approaches to solve constraint satisfaction problems

The authors, in their introductory section of the paper mention a few words about other approaches:

- They state that the backtracking approach takes exponential time to solve non trivial CSPs.
- The authors mention that subsequent improvements on the backtracking approaches do not report reasonable runtimes on non trivial CSPs.
- They have mentioned that the variations of stochastic and heuristic local searches are not capable of addressing all types of CSP’s.

- They have named a few variations of Distributed Constraint Satisfaction problem solving approaches by Yokoo et al, such as asynchronous weak commitment search and asynchronous backtracking. The authors claim that their approach does not restrict their application domain to Distributed CSPs only.

Description of their approach

The authors provide a description of their approach by providing the definitions to various terms that are being used in this paper. They provide a description to model the N-queens problem and also include a few diagrams. They provide a Pseudo code on their approach, specifically to solve the N-queens problem, and later provide a Pseudo code for solving other CSP’s in general.

Empirical Results

The authors report the results of several experiments that they have conducted to prove the validity of their approach. They perform experiments on values of various parameters and report the corresponding results. They furnish their results with graphs and tables that report runtimes against different parameter values. A linear regression analysis of the runtime has also been provided.

Conclusions

The authors conclude that their model can solve the n-queens problem for n = 1500 in a ‘few time steps’. They have reported that the process of finding a solution is entirely determined by the locality of the agents. They also report that the system dynamically evolves by eliminating poor-strategy agents by selection and contest.

Further Studies that the authors intend to accomplish

The authors claim that further research can be done in this area. Specifically, problems on values of N much larger than the one reported here is intended to be addressed in the future. They state that more evolvable strategies, reproduction and mutation mechanisms could be incorporated to making the approach more efficient. There could be an experimental analysis on how this approach can be applied to other CSPs.

Citations:

- Jiming Liu, Han Jing, and Y.Y Tang (2001) , Multi-Agent Oriented Constraint Satisfaction

- Jiming Liu, Xiaolong Jin, K.C Tsui (2005), Autonomy Oriented Computing: From Problem Solving to Complex Systems Modeling

[Liu et al, 2001b]

Research Motivation

The authors present a new approach to solve constraint satisfaction problems in distributed multi-agent environments. They claim that previous approaches are not suitable for a wide class of problems. They propose a new approach that is named ERA or Environment, Reactive rules and agents. They refer to [Liu et al, 2001].

Background Area and similar approaches

The authors state that ERA is a distributed technique to solve a CSP. The heuristic belongs to the class of stochastic and incomplete approaches, in which completeness is usually traded off for obtaining solutions in a timely manner. Several algorithms that belong to this general class, and a few complete algorithms as well, are being referred to in this paper for performance comparisons. The authors state that their basic formulation is similar to Swarm-like systems and have referred to Ant based optimization systems [Dorigo et al, 1999, 1991]. It has been mentioned by the authors that ERA is similar to these approaches in a way that all of them function with Agents and Reactive rules in the presence of an Environment.

Comparisons with approaches reported by Minton et al [2002]

The authors refer to the Min-conflicts heuristic [Minton et al 2002] and provide a comparison of this with the ERA approach in solving constraint satisfaction problems.

Authors Remarks on Min-conflicts heuristic: The authors claim that their method does not suffer from a drawback that the min-conflicts heuristic does. This is the trap of the local minima that the hill climbing system of the min-conflicts heuristic is capable of getting into, as stated by the authors.

Authors Remarks on Informed Backtracking: The authors claim that their method is advantageous over the informed backtracking approach [Minton et al 2002], in a way that ERA does not 'backtrack'. It has also been mentioned that the informed backtracking approach being a complete approach would not be efficient in terms of search timing.

General Remarks: The authors state that the min-conflicts heuristic and the informed backtracking approaches have a common drawback. In that, it is mentioned that both involve the computation of a variable order, which can be costly considering that it is carried out at each step. The authors claim that their approach does not suffer from such a drawback.

Comparisons with Distributed Constraint satisfaction problems:

The distributed constraint satisfaction approach is a system that involves multiple agents. The authors refer to the

Distributed Constraint Satisfaction approach [Yokoo et al, 1998, 2000] and they provide a detailed comparison on how ERA differs from this approach. A table providing a comparison of these two approaches, on several scales of the N -queens problem, is presented. Here, it is shown that ERA outperforms several variations of the distributed constraint satisfaction problems, in terms of the number of steps to reach a solution state for the N-queens problem. The following table that is included by the authors summarizes this result.

N	Asynchronous Backtracking	Asynchronous Backtracking with Min-conflicts Heuristic	Asynchronous Weak-commitment search	ERA
100	510	504	51	22
1000	-	324	30	18
2000	-	-	-	30

Table 1.0

Detailed Descriptions provided by the authors on their approach

Definitions and Derivations: The authors provide a detailed description of their formulation that include definitions of new terms that are being used, such as the better move, least move and random move to name a few. Pseudo codes that represent significant sections of their formulation are included. Derivations to prove the correctness of their algorithm, and derivations to the time complexity of operations that are central to the system are also presented.

Empirical Analysis: Analyses on the performance of this approach on two benchmark problems i.e. the N-queens problem and the Graph Coloring problem, is reported. The authors compare the various modes by which the algorithm can function, under different parameter settings. They evaluate the performance of their heuristic by reporting execution runtimes. Such experiments have been performed for different ranges of N in the N-queens problem (N = 100 to N = 7000). A similar analysis is presented in the case of graph coloring problems. These experiments have been performed on instances of graph coloring problems that are taken from the Donald Knuth's Stanford Graph Base. The authors state that tests are performed by executing their algorithm on a single machine and that this is a simulation of a distributed approach on a sequential execution.

Reported Results: The authors claim that the algorithm takes only three steps to reach a state where 80% of the variables satisfy constraints, for most instances of the graph coloring problem and N-queens problem. The authors also state that, results relating to the efficiency in obtaining a final solution-state on some cases of the graph coloring problem, is relatively low due to the structure of the problem.

Directions on Further Research

The authors claim that research ahead will be oriented towards incorporating explicit communication and co-operation mechanisms, and discovering new properties of this approach, in order to solve new types of Constraint Satisfaction Problems.

Citations

- Jiming Liu, Xiaolong Jin (2002), Distributed Problem Solving Without Communication – An Examination of Computationally Hard Satisfiability Problems

- Hui Zou, Berthe Choueiry (2003), Multi-Agent Based Search versus Local Search and Backtrack Search for solving Tight CSPs: A Practical Case Study

- Xiaolong Jin, Jiming Liu (2003), Efficiency of emergent constraint satisfaction in small-world and random agent networks
- Yi Tang, Jiming Liu and Xiaolong Jin (2003), Agent Compromises in Distributed Problem Solving

- J Liu, X Jin, Y Tang (2004), Multi-Agent Collaborative Service and Distributed Problem Solving

- Jing Liu, Weicai Zhong, Licheng Jiao (2006), A Multi Agent Evolutionary Algorithm for Constraint Satisfaction Problems

[Liu et al, 2002]

Research Motivation and Background

The authors address the problem of solving Satisfiability problems with their previously reported formulation - ERA. It appears that this is the first formulation to use a self organizing multi agent system to solve Satisfiability problems. The authors refer to their previous publication that introduces the concept of ERA [Liu et al, 2002]. The previous paper does not provide results on satisfiability problems. The authors claim that their approach produces results that are comparable to popular approaches that address this class of problems. It should be noted that this is a revised edition of similar work that has been presented at the IDEAl, third international conference in 2002 at Manchester, UK.

The Authors Description of the Approach (MASSAT)

After a section that introduces the reader to a few basic concepts on multi agent systems and satisfiability problems, the authors describe in detail, features of their proposed approach. They provide definitions of terms that are used in the context of the algorithm. A pseudo code on the generic ERA algorithm is provided.

Experimental Results and Comparisons with other Approaches

The authors evaluate the performance of the MASSAT on instances of Satisfiability problems taken from SATLIB. The authors claim that they use two commonly used benchmark problems packages from SATLIB namely uf100 or Uniform Random 3-SAT, and flat-50 or Flat Graph Coloring. They claim that both these packages are cases of 3-SAT problems.

The authors compare the number of ‘flips’ of other approaches with the number of ‘movements’ on MASSAT. They provide a rationale behind making this comparison. The authors conclude from their experiments that ERA can be applied to SAT problems and that their approach is comparable and more stable with respect to other approaches.

Citations

- Tibor Bosse, Mark Hoogendoorn and Catholijn Jonker (2005), The Distributed Weighing Problem: A Lesson in Co-operation Without Communication

[Liu et al, 2006]

Research Motivation and Background

The authors introduce a new approach to solve CSPs in a multi agent environment. The authors state that constraint satisfaction problems are classifiable into two categories i.e. permutation constraint satisfaction problems and non-permutation constraint satisfaction problems. They state that, the properties of CSPs from this classification, is used to design the behaviors of the agents in their approach. They also claim to use a new encoding method called the minimum conflict encoding, to overcome disadvantages of general encoding methods. They show that their results are better than previous standard approaches to solve CSPs. A reference to [Liu et al, 2001], has been made where the comparison with the ERA approach was needed to be made.

A description of the authors approach

The authors provide a description of their approach by explaining various properties of their algorithm including the details on behaviors of agents. They provide pseudo codes on competitive behavior and self-learning behavior. They also provide a pseudo code for their main algorithm. In addition, a space complexity analysis of the algorithm has also been included.

Experimental Comparisons and Conclusions

The authors first report their results on an initial set of experiments that are performed on non-permutation CSPs. They report their results on 250 benchmark binary constraint satisfaction problems and 79 graph coloring problems form the DIMACS challenge. They compare the results of this with 6 other approaches namely, H-GA.1, H-GA.3, SAW, Glass-Box, SSC and ERA. They claim that their approach outperforms all these approaches. Secondly, in order to test the performance of their approach for permutation CSPs, they provide results on the N-queens problem and the Job shop scheduling problem. They claim that their results on the job-shop-scheduling problem, is an indicator of MAEA being suitable for practical applications. The authors provide a parameter analysis of the MAEA approach and conclude from their results that their approach is robust and easy to use.

Citations

L Jiao, Jing Liu and W Zhong (2006), An organizational coevolutionary algorithm for classification

[Modi et al, 2003]

Research Motivation and Background

The author mentions that “Existing methods for DCOP are not able to provide theoretical guarantees on global solution quality while operating both efficiently and asynchronously”. The authors mention that Distributed Constraint Optimization or DCOP is able to model a large class of multi agent collaboration problems where a solution can be found within given quality parameters. The authors refer to the book: Distributed Constraint Satisfaction: Foundation of Co-Operation in Multi Agent Systems [Yokoo, 2001] and Hirayama et al [2000]. The authors mention that previous approaches that involve extending the Asynchronous Backtracking Search to solve the over-constrained CSP’s, have been applied to only limited types of constraint satisfaction problems.
The authors introduce their new method named ADOPT, that addresses the DCOP. The problem being addressed is stated to be a generalization of the Distributed Constraint Satisfaction Problem (DCSP).

Authors Description of the Approach

The authors provide details of the algorithm being presented and they also include a few definitions that relate to the approach. Descriptions of Algorithm correctness and an analyses on its complexity have been provided. A pseudo code on the procedure to receive messages has been provided and a pseudo code on the procedure of updating backtrack thresholds has also been provided.

Experimental Evaluation Reported and Conclusions

The authors perform experiments on three algorithms:

- Synchronous Branch and Bound
- Synchronous Iterative Deepening
- Adopt

The authors comparisons show that Adopt performs better than the other two algorithms. The authors conclude that a certain class of optimization problems have been solved efficiently and optimally by Adopt and it obtains significant orders of magnitude speed up over distributed branch and bound search.

Directions for Further Research

The authors state that future work can be oriented towards addressing non-binary constraints, and allowing multiple variables per agent.
The authors state that distributed methods for discovering efficient DFS variable orderings, will also be developed.

Citations:

- Modi, Shen, Tambe, Yokoo (2006), ADOPT: Asynchronous Distributed Constraint Optimization with Quality Guarantees

[Schoofs et al, 2000]

Research Motivation and Background

Ant Colonies are systems that were previously used to solve optimization problems. The authors address the issue of whether the ant system can be applied to solve constraint satisfaction problems as well. They refer to the work of [Dorigo et al, 1999], where the approach to use ant colonies in discrete optimization is presented. They claim that ant colony systems can be used to solve CSPs, by providing a comparison of their method with other standard approaches in evolutionary computation, in terms of performance. They claim that their approach outperforms all other approaches that are considered for comparisons here.

Description on Approach Being Presented

The authors provide a description of the general ant system and its algorithm. The authors provide a description of the parameters in the algorithm and include detail on parameter tuning. They also determine the best parameters for solving randomly generated CSPs.

Experimental Results and Conclusions

The authors provide a comparison-table on the performance of their approach with seven other stochastic approaches. They include performances of the Random-hill-climber, Population-based incremental learning, Mutual information maximizing input clustering,
Genetic algorithm with bit-based simulated crossover, Genetic algorithm with adaptive mutation rate, Univariate marginal distribution algorithm and the Bivariate marginal distribution algorithm. The authors claim that their algorithm outperforms all other stochastic approaches that they have tested, both in speed and convergence percentage.

Future Work

The authors mention that stochastic approaches to solve constraint satisfaction problems including their own are not able to decide on whether a given problem has a solution or not. The authors mention how this could be avoided in the future. They mention that an adjustment on the penalty function could resolve this drawback. They state that the effect of dynamic search landscapes on ant algorithms in under investigation. They claim that this could avoid premature convergence.

Citations

- Yun-Chia Liang, Smith (2004), Ant Colony Optimization Algorithm for the redundancy allocation problem.

[Schoofs et al, 2002]

Research Motivation and Background

The authors present an approach to solve binary constraint satisfaction problems using the Particle Swarm. The authors claim that their algorithm is an adaptation of the approach presented in Kennedy et al [1997]. The particle swarm system is usually used to solve optimization problems. The authors here report an approach that uses the same system to solve constraint satisfaction problems. It appears that these authors are the first ones to report a Particle Swarm algorithm to solve CSPs in general. They also refer to
[Solnon, 2001], for reporting performance comparisons.

Description Provided by the Authors on their Approach

The authors explain some of the terms and definitions that apply to their approach. They provide details on parameter tuning. The authors also provide a pseudo code for particle swarm algorithm to solve CSPs and later report 4 modifications that they have made on the particle swarm, to suit the requirements of constraint satisfaction problems.

Experiments and Empirical Results

First, the authors report the results of experiments to determine a ‘quasi-optimal setting’. The authors state that for every combination of parameter values, the authors perform 10 experiments on different instances of the same problem class.
Secondly, the authors report experimental results that explains, the nature in which the search process get affected by the parameters.

Thirdly, the authors compare their approach with three other approaches that are mentioned as follows:

- Ant Colonies as reported by Solnon [2001]
- The Stochastic Hill Climber
- Generational Genetic Algorithm

The authors claim that they compare these approaches by using two metrics: the number of conflict checks until termination, and the success rate.
The authors claim that their approach does not perform better than the other two approaches. The authors also conclude that the Ant Colonies approach has the best success rate as compared to the other two.

Main Conclusions made by Authors

The authors finally conclude that their approach is suitable to solve randomly generated constraint satisfaction problems, however, they also state that this approach is not better than the generational genetic algorithm or the stochastic hill climber.

[Solnon, 2000]

Introduction and Research Motivation

The author addresses the issue of solving permutation constraint satisfaction problems by using the ant colonies. The author refers to the Ant Colony Optimization metaheuristic [Dorigo et al 1999a, Dorigo et al, 1999b] and states that the work being presented is based on the ant colony optimization metaheuristic. This formulation can be placed in the broad class of stochastic and incomplete algorithms. The author introduces the concept of the Ant-p solver by describing how artificial ants walk along the edges of the permutation graph in a stochastic and incomplete way. As it has been stated in this paper, artificial ants communicate in a local and indirect way by laying an artificial 'pheromone' on the edges of the graph that is being searched for the solution to the permutation constraint satisfaction problem.

Description of the approach

The author provides a detailed description on the working of the algorithm by describing important features and functions of the Ant-p solver. Definitions of new terms are provided by the author and a pseudo-code of the ant-p solver and path function are also included.

Empirical Results

The author provides an empirical evaluation of the approach being presented by comparing test results with another approach known as the ILog solver, a tree search based solver. The author reports the experimental evaluation of both these approaches by testing both of them on an HP 715/100 station. The author reports comparisons on the N-queens problem, the car sequencing problem and the all interval series problem. The results on these experiments have been presented on comparison tables. The author specifies instances where the Ant-p solver reports better efficiency as well as instances where the efficiency is reported to be less.

Conclusions

The author does not make concluding statements regarding the efficiency of the approach, however, the author does mention that the approach being presented is proven to be a permutation-constraint-satisfaction problem solver, that can be enhanced with additional work and modifications.

References on Related work

The author has referred to other approaches that are used to solve the same class of problems. Remarks and comparisons have been made by the author on other approaches, even though, without empirical evidence. The author has referred to GENET and two of its extensions i.e. SWAPGENET and E-GENET. A reference on the GAcSP, genetic algorithm has been made.

Future Research Prospects

The author mentions that the current approach may be improved by introducing repair based techniques. The algorithm could also show good results if it could be parallelized.

Citations

- Solnon (2002), Ants Can Solve Constraint Satisfaction Poblems

- Dorigo (2004), BOOK: Ant Colony Optimization

[Solnon, 2002]

Research Motivation

The author provides a generic tool to solve constraint satisfaction problems by using ant colonies. The author states that her algorithm should be able to solve all constraint satisfaction problems. A reference on the authors previous paper [Solnon, 2000], is made. This paper introduces approaches to boost the algorithm by using Local search and a Preprocessing Step.

Background and Description of approach

The author provides a description of her approach. She provides a theoretical background on phase transitions and details of the ant solver such as the pheromone trail updates, construction of assignments by ants and parameter settings. A description on the preprocessing step and the local search, is provided.

Experimental Reports and Conclusions

The author first provides the results of an experimental study on the preprocessing step.
She later provides comparisons on different variations of the ant solver. She compares the ant solver, ant solver with min conflicts heuristic local search (AS MCHLS) and the ant solver with min conflicts heuristic local search and preprocessing step (AS MCHLSP) and presents the results of the experimental comparisons on a table. In addition to this, the author later compares all these approaches with the random walk local search on various parametric values of constraint satisfaction problems. Based on the experiments, the author concludes that ants alone can solve constraint satisfaction problems although they are slow. When ACO is combined with the LS procedure, the performance is boosted. In addition to this, it has also been concluded that the preprocessing step improves the success rate and running time.

Directions on Future Research

The author claims that further research would involve integrating Ant solver with GSAT or Tabu search.
The author claims that 'dedicated graphs' will be integrated with Ant solver to deal with global constraints.

Citations

- Dorigo (2004), BOOK: Ant Colony Optimization
- B. Scheuermann, M. Guntsch, M. Middendorf, O Diessel, H. ElGindy, H. Schmeck (2004), FPGA implementation of population based Ant Colony Optimization
- Hemert V, Solnon C (2004), A Study into Ant Colony Optimisation, Evolutionary Computation and Constraint Programming on Binary Constraint Satisfaction Problems.

[Tang et al, 2003]

Research Outline

The authors address the problem of the inefficiency caused by the 'random move' in their original ERA algorithm [Liu et al, 2002]. The authors present an improvisation over the original ERA heuristic. The authors state that the random move is supposed to avoid the problem of local minima traps. The authors claim that this problem of local minima traps, is tackled by a new feature that is being introduced in this paper.

They introduce the concept of 'agent compromises' by incorporating a new move named as the 'make-compromise' move. They claim that this feature has addressed the structure of the graph coloring problem. They have reported the results of experiments conducted on benchmark instances of the graph coloring problem. They state that the approach being presented in this paper, outperforms the original ERA formulation[Liu et al, 2001].

Empirical Study

First, they perform experiments on the original ERA heuristic on an instance of the graph coloring problem from Donald Knuth's Stanford Graph Base. This instance has been referred to by the filename myciel7.col. This is an example of a graph with 191 vertices, 2360 edges and there is a limit of 8 colors within which it needs to be colored. The authors compare the results of the original ERA algorithm on different parameter values. The parameter being varied is the probability of the random move behavior. They report that each case has been executed 100 times, before the average number of steps is calculated for every case. Based on these results on the original ERA heuristic, the authors state that the random move operation is inefficient.

The second experiment that the authors report is a test on the 'make-compromise' move. This is the new feature that is intended to be added to the original formulation. They perform experiments on the same problem i.e. myciel7.col. These trials are performed on different parameter settings and it has been reported that their new feature does prove to be more efficient. They claim that the number of movements involved in obtaining the solution is reduced by 26% on an average. The variation lies between 14% to 44% according to their report.

Finally, the authors present the results of a third experiment to analyze the overall performance of the new approach. They now test their heuristic on 7 more instances of Graph Coloring Problem's taken from the Donald Knuth's Stanford Graph Base. A table is included that provides a description of the results obtained in this experiment. It indicates a reduction in the number of movements that were required to obtain solutions to these benchmark problems.

Citations

As of April 2006, citations have not been made on this paper.

[Yokoo, 1992]

Research Motivation and Background

The authors address the problem of solving constraint satisfaction problems in distributed multi agent environments. They appear to be the first group to identify this problem that is also called the Distributed Constraint Satisfaction Problem (DCSP). They state that this approach is useful in formalizing Cooperative Distributed Problem Solving techniques.

They present an approach that is called the asynchronous backtracking search. The authors have referenced 'An Overview of DAI: Viewing Distributed AI as distributed search' [Lesser, 1990].

Description of the new approach

The authors claim that "the asynchronous backtracking removes drawbacks from the synchronous backtracking by allowing agents to run synchronously and concurrently".

They provide details on how agents communicate with each other with messages. They provide a pseudo-code that describes how messages are received. They describe their approach in detail by explaining how their approach avoids infinite processing loops and how it handles asynchronous changes. An explanation on how the algorithm is sound and complete is also provided.

Experiments and observations

The authors report the results of experiments that compare the performance of the centralized backtracking, synchronous backtracking and the asynchronous backtracking approaches. They state that these approaches were tested on the n-queens problem. They mention that a queen can be assigned to an agent in this algorithm. The authors conclude from their experiments that if local problems are loosely-coupled, asynchronous backtracking outperforms centralized backtracking even if communications are relatively low.

Conclusions

The authors conclude from their study, that solving DCSPs is worthwhile when the problems solved by the individual agents are loosely-coupled.

Directions on further Research

The authors claim that their ongoing research efforts involve using heuristics to improve the performance of the asynchronous backtracking algorithm.

Citations:

- Makoto Yokoo, Edmund H. Durfee, Toru Ishida, Kazuhiro Kuwabara(1998), Distributed Constraint Satisfaction Problem: Formalization and Algorithms

- Makoto Yokoo, Katsutoshi Hirayama(2000), Algorithms for Distributed Constraint Satisfaction Problems: A review

- Makoto Yokoo (1995), Asynchronous Weak-Commitment Search for Solving Distributed Constraint Satisfaction Problems

- Makoto Yokoo, Katsutoshi Hirayama (1998), Distributed Constraint Satisfaction Algorithm for Complex Local Problems

- Katsutoshi Hirayama, Makoto Yokoo, (2000), An Approach to Over-Constrained Distributed Constraint Satisfaction Problems: Distributed Hierarchical Constraint Satisfaction

[Yokoo, 1995]

Research Motivation and Background

The author reports an improved method to solve Distributed Constraint Satisfaction Problems. The author refers to the Asynchronous-Backtracking algorithm reported in Yokoo et al [1992] and the Weak-commitment Search algorithm reported in Yokoo et al[1995]. The author claims that the Weak-Commitment search algorithm has inspired this new approach.

The Authors Description of the New Approach

The author states that “the algorithm can revise a bad decision without an exhaustive search by changing the priority order of the agents dynamically.” He mentions that agents can act asynchronously and concurrently based on their local knowledge without any global control, while guaranteeing the completeness of the algorithm. He provides an explanation on how his new approach is different from their previous Asynchronous Backtracking and it appears that a theoretical basis has been provided to explain, why is the new approach better. The author revisits the asynchronous-backtracking algorithm and the weak-commitment search algorithm, and describes them in a few words. Following this, he provides details on the new approach and illustrates an example of the algorithm execution. A pseudo code on the procedure of receiving messages is provided, and an explanation on the completeness of the algorithm is also given by the author.

Experiments and Inferences:

The author conducts experiments to compare the min-conflicts heuristic, asynchronous-backtracking algorithm with the asynchronous weak-commitment search. He provides details on how he measures the performances of these algorithms. He applies these algorithms on the distributed n-Queens problem and provide results on a table reporting the performances for values of n ranging from 10 to 1000. Following this, the author conducts experiments on the graph coloring problem. In order to test the algorithm on a real-life problem, the author reports the results of experiments on the distributed resource allocation problem. Based on the experiments, the author claims that his new approach can solve problems that other algorithms cannot solve and based on the results provided in tables, it appears as if the number of cycles required to solve a problem is less in the new approach as compared to the other two approaches, in all cases. The author claims that asynchronous weak-commitment search is “far more efficient” than the asynchronous backtracking algorithm for solving CSPs.

Conclusions

Based on his study, the author concludes that a flexible agent organization, where hierarchical order is changed dynamically performs better than an organization where the agent organization is static and rigid.

Directions on Further Research

The author claims that their future work includes, showing the effectiveness of the asynchronous weak-commitment search in more practical application problems, and examining ways to introduce other heuristics (e.g forward checking) into the new approach, and developing iterative improvement algorithms for DCSPs.

Citations:

- Makoto Yokoo, Edmund H. Durfee, Toru Ishida, Kazuhiro Kuwabara(1998), Distributed Constraint Satisfaction Problem: Formalization and Algorithms

- Makoto Yokoo, Katsutoshi Hirayama(2000), Algorithms for Distributed Constraint Satisfaction Problems: A review

- Makoto Yokoo, Katsutoshi Hirayama (1998), Distributed Constraint Satisfaction Algorithm for Complex Local Problems

- Katsutoshi Hirayama, Makoto Yokoo, (2000), An Approach to Over-Constrained Distributed Constraint Satisfaction Problems: Distributed Hierarchical Constraint Satisfaction

- Aaron Armstrong and Edmund Durfee, (1997), Dynamic Prioritization of Complex Local Agents in Distributed Constraint Satisfaction Problems

[Yokoo, 1998]

Research Motivation and Background

The author claims that previous approaches to solving distributed constraint satisfaction problems cannot efficiently or in a scalable way, allow more than one local variable per agent. The author refers to the previous work on asynchronous weak-commitment search [Yokoo, 1995] and the new approach is based on this approach, as stated by the author. The author addresses how the approach can take the advantage of multiple local variables. The authors makes a reference to the approach presented in [Armstrong et al, 1997], to compare that with the new approach being presented in this paper.

Authors Description of the Algorithm

The author provides a description of the asynchronous weak-commitment search with the single local variable and the asynchronous weak-commitment search with multiple local variables. A pseudo code is provided for describing the procedure of receiving 'ok?' messages, in the case of the asynchronous weak-commitment search with multiple local variables. For illustration, the author provides an example of algorithm execution.

Experimental Evaluations

The author performs experiments to compare the performance of his approach with two other approaches namely,

- The asynchronous weak commitment search with agent prioritization using the decaying nogoods heuristic as reported in Armstrong et al. [1997]
- Single variable asynchronous weak commitment search

According to the author, the distributed graph coloring algorithm is used to perform the evaluations on the algorithms. The author provides details on how the performance of these algorithms are measured to compare for performance.

Conclusions from Experiments

The author claims that the number of interactions in this approach can be decreased and that a bad local solution can be modified without forcing other agents to exhaustively search for their local solutions. From the results of the experiments, author concludes that the approach presented in the paper proves to be more successful than the simple extension of the asynchronous weak-commitment search, and the algorithm that employs prioritization among agents.

Citations:

- Makoto Yokoo, Katsutoshi Hirayama(2000), Algorithms for Distributed Constraint Satisfaction Problems: A review

- Modi, Shen, Tambe, Yokoo (2006), ADOPT: Asynchronous Distributed Constraint Optimization with Quality Guarantees

- Jiming Liu, Han Jing, Y.Y Tang (2001), Multi-agent Oriented Constraint Satisfaction

- Katsutoshi Hirayama, Makoto Yokoo, (2000), An Approach to Over-Constrained Distributed Constraint Satisfaction Problems: Distributed Hierarchical Constraint Satisfaction

[Zou et al, 2003]

Research Description and Background

The authors provide a report on an empirical study that they claim to have made on the multi agent approach to solve constraint satisfaction problems(also known as ERA) reported in Liu et al[2002]. They compare this approach with 2 other approaches on a problem type that has not been addressed in Liu et al [2002]. They examine the performance of ERA on both these cases, by comparing it with two other approaches and report their findings and conclusions.

An overview of the test problems of study

- The authors state that their experiments have been made on the problem of assigning Graduate Teaching Assistants (GTAs) to academic courses. They state that, this constraint satisfaction problem is most of the times over-constrained i.e. it is not solvable. They also describe this as a non-binary CSP. The authors state that some of the instances that have been studied by them are solvable, while some are not.

- Experimental results on the N-queens problem (N=100), that is addressed in Liu et al[2002] have also been reported in order to be on a common level with Liu et al[2002].

Experiments Conducted and Results

The authors experimentally compare the ERA method with:

- Systematic backtracking search with dynamic variable ordering [Glaubius and Choueiry, 2002]

- Hill climbing local search [Zou, 2003]

From the results of various experiments, the authors conclude ERA performs better than the other two approaches in the case of tight CSP's that are solvable. In addition, they point out that ERA performs poorly when the CSP is over-constrained, as compared to the other two approaches. They state that this problem is a result of a 'deadlock phenomenon' that they claim to have observed in their experiments. They provide a diagram illustrating their observation. They also furnish other experimental reports with graphs and tables that display parameter values against which they base their conclusions. They state that their results are an indication of a fact that ERA may not be useful in solving real world problems.

In addition to the new findings that the authors report, they appear to also experimentally confirm the results of experiments on the N-queens problem that were reported in Liu et al[2002]. It appears that their results tally with Liu et al [2002].

Directions for Future Research

The authors propose new strategies and make suggestions for future research to address the problems that they claim to have found with the ERA formulation:

- They propose the idea of introducing conflict resolution strategies to overcome deadlocks.
- They suggest search hybridization techniques with Local Search.

The authors state that their studies can be expanded to include other methods to solve CSPs and to empirically evaluate the behavior of various algorithms in randomly generated problems.

Citations

Hui Zou (2003), Iterative Improvement Techniques for Solving Tight Constraint Satisfaction Problems