

Naturally Inspired Optimization Algorithms as Applied to Mobile Robotic Path Planning

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Abstract—Global path planning as applied to mobile robotics can be approached in a similar fashion as classic optimization problems involving combinational constraints (e.g. the Traveling Salesman Problem). A single, exact optimal solution for the shortest path may not exist, and obtaining near-optimal solutions selected and ranked by criteria, or deemed “good-enough”, can satisfy the problem. An overview is provided on a select subset of naturally inspired iterative search algorithms; Simulated Annealing (SA), Genetic Algorithm (GA), and Ant Colony Optimization (ACO) have all been studied and applied to the task of mobile robotic path planning. These three techniques or algorithms (respectively) represent a broader range of naturally inspired physical processes, evolutionary or biological processes, and animal kingdom behavioral examples. It has been demonstrated that these algorithms have been utilized on their own, or as part of a collaborative hybridization of iterative algorithms and heuristic modifiers, to effectively balance the constraints, strengths and weaknesses in a given path planning approach. A brief contextual summary of current literature provides insights regarding implementation of this category of algorithms, and suggests approaches for future experimentation and research in this topic area.

I. INTRODUCTION

A. Solutions and Constraints – The Pareto Optimal Set

In solving an optimization problem where more than one objective or constraint is given (multi-objective optimization e.g. minimize distance + A + B + ...) multiple solutions can exist that will satisfy the problem, in a way that a particular solution may optimize one objective at the cost of moving another objective away from optimal (a so-called tradeoff). These solutions are referred to as a Pareto optimal set or front. Each solution in the Pareto optimal set can potentially be accepted as a valid answer to the problem, however, for a particular problem or group of problems, there may also be a non-numerical or heuristic preference of one solution over another. Given two travel paths that are equidistant from the start to the target, there can be additional problem or workspace information available for consideration when selecting a suitable solution. Examples of these qualitative types of factors as applied to robotic path planning include fewer robot direction changes, preference for movement through the least number of grid nodes, executing more turns

to the left than right, or preference for a path that is more easily mapped to an arc segment or set of arcs. A comprehensive robotic path planning strategy weighs and utilizes tradeoffs between various optimal solutions.

A mathematical or quantitative optimization representation of a robotic path planning problem may be difficult to fully or accurately express. The problem can quickly become over constrained, and is not necessarily intuitive by inspection. It is possible that the problem can take a form where only some of the constraints can be satisfied, also known as a constraint satisfaction problem (CSP), and the solution objective would be satisfying the maximum number of constraints (but not all of them). An algorithmic approach toward optimization, with or without heuristic components, can be successfully utilized to deal with these challenges. This may lead to acceptance or even preference for path planning solutions which move away from Pareto optimality and efficiency, and into a CSP form. A graphic example of solution points in a constrained workspace as described above can be seen in Fig 1. Ultimately, an algorithmic derived “good enough” path through the workspace can be reached by iteratively collecting and utilizing the solution space knowledge [1], [2].

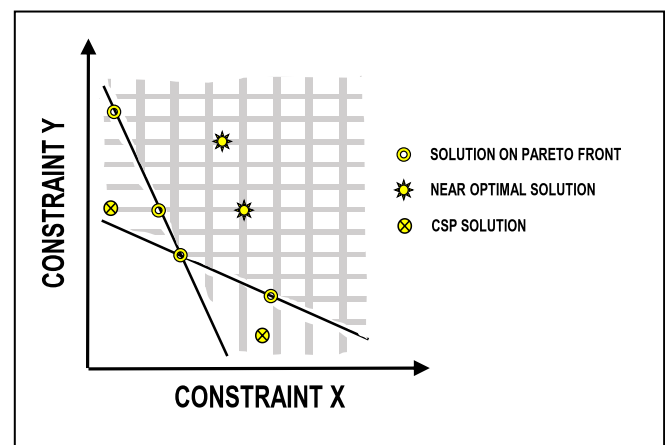


Figure 1. Examples of solution points in a constrained workspace.

B. Application of Naturally Inspired Algorithms

Global level approaches for mobile robotic path planning include treating the problem as a single objective (minimize distance), or as a multi-objective optimization (e.g. minimize distance + move only at right angles). On the surface, it appears that for global path planning, the objective is strictly singular - minimizing distance between the target and goal, and then allowing local sensing and motion control schemes deal with workspace objects, traps and platform dynamics. However, the genetic algorithm and techniques described by Hu [3], [4] demonstrated the utilization of unique domain knowledge modified algorithm operators to avoid or plan around the obstacles, suggesting that the solution was multi-objective (minimize distance + avoid obstacles) and did not solely rely on a conventionally derived objective function to obtain a path solution.

Further, iterative algorithms inspired by natural processes and behaviors, as when applied to solve robotic path planning optimization problems, leverage the inherent flexibility and structure of our natural environment and systems. They also yield to the creativity and innovation of the practitioner, to apply, modify and combine the algorithms in a manner necessary to reach the desired level of optimization.

II. GLOBAL PATH PLANNING FOR MOBILE ROBOTICS

A. Grid Based Path Planning

The fundamental concept of grid based path planning can be viewed as a permutation optimization problem (seeking optimal solutions in a discrete search space) and solved in a similar manner to the open traveling salesman problem (TSP) [5]. In the open TSP, the traveler moves once to each point or city specified to create a path with the objective function being to minimize the total distance traveled. The complexity of the objective function compounds if additional constraints or specific behaviors are required of the traveler.

B. Problem Representation and Decomposition

Expanding further on the parallels between the optimization of a mobile robotic global path and the TSP, the path search space can be represented or superimposed with a two dimensional Euclidean grid system. The size, shape, number of divisions, and movement style (node or edge) within the grid may vary, and may be selected or specified in a manner to influence the speed, fidelity and complexity of the movement within the workspace.

Several workspace variations may impact the algorithmic approach and formulation of the global path optimization cost function design. For example, particular knowledge of the search space or environment may be given a priori, the search space size or shape may be static or dynamic, and the search space may or may not have pathway obstacles. All of these particular characteristics should be considered in the

global path planning strategy, and also need to be considered or factored into the localized movement of the mobile robotic platform. An example of a 10 by 10 grid system workspace with obstacles added is shown in Fig. 2.

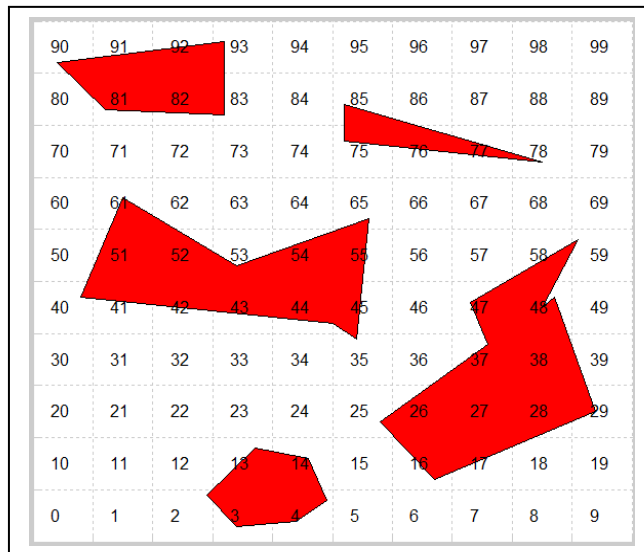


Figure 2. Grid based workspace with known obstacles.

C. Solutions

The inherent benefit to using an iterative solution based algorithm is the freedom from being forced or constrained to solve for an “exact” answer or solution. Here we recognize that an exact solution may or may not exist, but articulate that a “good enough” solution will satisfy the problem. The level of optimality of the “good enough” solution needs to be determined by the practitioner. In the case of most optimization problems, there is a desire to balance and generate a solution set that satisfies all of the given constraints. This can and often does lead to multiple solutions that are considered “fit” to solve the problem. Because of this, a ranking or fitness criteria needs to be defined for the optimization, to be used in halting the iterative selection process. Typically, either the minimum fitness of the objective function or a time / loop constraint on the iterations is used to terminate the algorithm process. Because the solution may be driven to a local minima, most algorithm schemes incorporate some form of tunable or adjustable parameters used to force the solution into a different area of search space, seeking to avoid local minimization and reach global minimization. The definition and parameterization of the initial cost function, fitness ranking of solutions, and stop search criteria are typically heuristic and are subject to the specifics of the path planning strategy and workspace being optimized.

III. NATURALLY INSPIRED ITERATIVE ALGORITHMS (NIIA)

The discussion of naturally inspired iterative algorithms begins with a definition of what “naturally inspired” means for our application. These algorithms all have design elements or characteristics that are patterned after processes found in the natural or biological domain. A generalized algorithmic description outlining the iterative search for solutions is shown in Fig. 3.

1. Initialize the solution variables and related parameters
2. Evaluate current versus new solutions
3. If new is not better than current:
 - a. Generate new candidate solutions inspired by natural process or behavior
 - b. Compare / Rank new solutions
4. Replace current solution with new candidate solution
5. Do evaluate step until global optimization goal is satisfied

Figure 3. Generalized description of a naturally inspired iterative search algorithm.

We will introduce the underlying concepts of three naturally inspired iterative algorithms (NIIA), but refrain from specific path planning implementation details in the scope of this paper. These algorithms have all been widely studied and applied to mobile robotic path planning [6].

A. Simulated Annealing

The simulated annealing (SA) search algorithm is inspired by the metallurgical process called annealing. Annealing is the process of heating and cooling a metal to alter the properties of its internal structure. As the heated metal begins to cool, changes to the internal structures become fixed. In general, the simulated annealing algorithm uses a “temperature” variable that is initialized at a high level, and gradually allowed to go lower or “cool” over time. When the temperature is high, the algorithm explores a larger area of the search space, and can freely move between poor and better optimization solutions. As the algorithm execution time accumulates, subsequent iterations are said to “cool down”, meaning that only tradeoffs resulting in better solutions are accepted. This gradual probabilistic acceptance technique is the mechanism which allows the algorithm to avoid local minima or maxima solutions, and continue to iteratively explore the search space toward a global minima or maxima solution more effectively. Miao and Tian [7] have explored using SA for path planning with the added complexity of moving obstacles. An example of SA search and convergence is shown in Fig. 4.

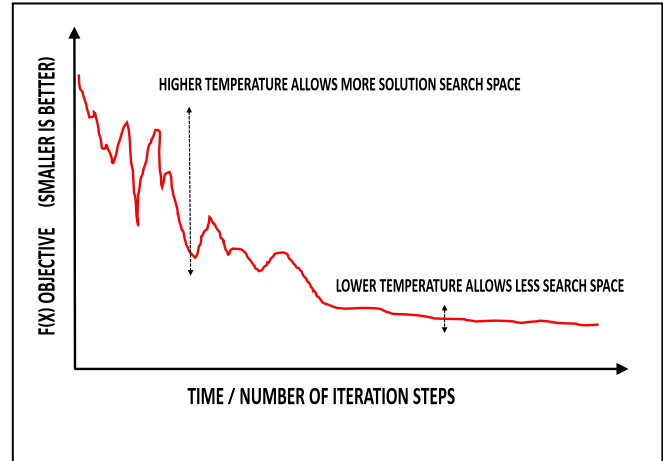


Figure 4. Example of Simulated Annealing search and solution convergence.

B. Genetic Algorithm

The Genetic Algorithm (GA) is a subset of a larger class of iterative search algorithms which are inspired by the concept of evolution. As the name implies, GA is inspired by the natural process of selecting characteristics from a population of donors and transferring those traits, (particularly if deemed desirable), to subsequent populations. Here the population represents a pool of potential solutions, and the chromosome represents a single solution in the set. There are several methods used to represent the individual genes inside the chromosome, which correspond with individual problem constraints and/or desired outcomes in the solution. This encoding or mapping is typically in a binary format or, integer format, but may be tailored to fit the optimization problem. Additionally, the chromosome format may be of fixed or variable length, and can be used to represent the number of path nodes in the solution or other characteristic.

Key to the genetic algorithm is the application of operators to mimic the natural selection process. Some of the more common selection operators used are elitism, tournament, and roulette wheel techniques. The crossover operator deals with how much or where in the chromosome the evolutionary process will affect. Crossover may take place at a single point in the chromosome, two-points, or some other divisional scheme. Last, the algorithm allows for probabilistic mutation and deletion of genes in a solution, and some forms of the algorithm have been modified further with specialized operators which have been heuristically selected for a specific application or function (e.g. local minima trap avoidance). A recent example of autonomous mobile robotic path planning by Samadi and Othman [8] details GA implementation and evaluation of results. Fig. 5 shows a typical iteration through the GA process.

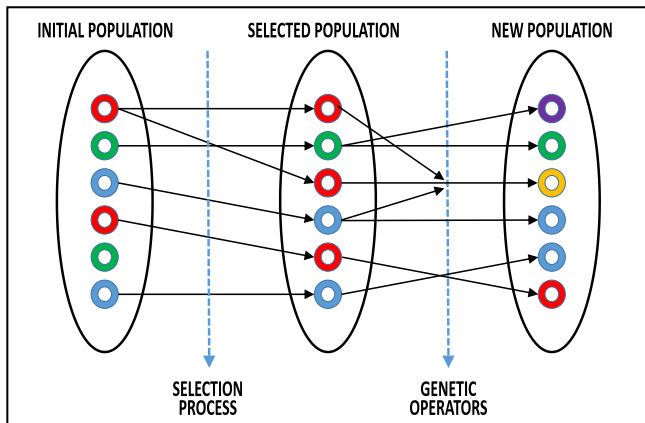


Figure 5. Example of Genetic Algorithm iteration flow.

C. Ant Colony Optimization

The ant colony algorithm (ACO) is inspired by the behavior of ants searching for food, and characteristically creating paths once a food source is located. At first, the ants search for food in a random manner. When a food source is found, the ant returns to the colony, marking the path with pheromones that show the path has a connection to the food source. As other ants encounter a pheromone marked path, there is a certain probability that they will follow the path. If the ant follows the original marked path and finds food it will mark the path with more pheromones, strengthening the probability of that particular path being used by other ants. When the food source is depleted, the pheromones slowly decline, and the ants will return to a random search. Brand et al. [9], describe a representative ACO based robotic path planning implementation and simulation.

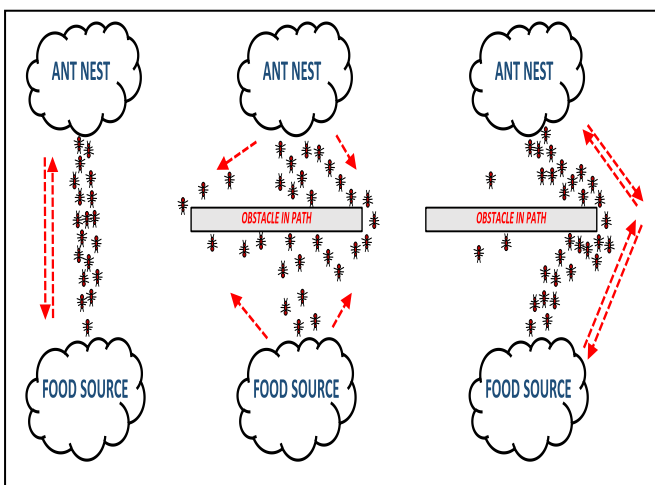


Figure 6. Ant Colony Optimization – convergence toward shortest path.

IV. COLLABORATIVE COMBINATIONS OF ITERATIVE ALGORITHMS

It is worth noting that each algorithm has strengths and weaknesses, and collaborative use of iterative search or optimization algorithms often appears to offer more potential than a singular methodology or approach. [10] These mixtures of algorithms are sometimes referred to as collaborative combinational algorithms, hybrid algorithms or fusion algorithms [11], [12]. Desirable optimization elements or features of particular algorithms optimization steps are added or combined to form hybrid algorithms that resemble the functionality or behavior of one or some of the originals to warrant a new nomenclature or designation. Examples of this technique, using the Genetic Algorithm (GA) as the base algorithm, and including elements or features found in other iterative search algorithms, yields combination notations such as GA+SA, GA+SA+ACO, and so on.

V. PERFORMANCE OF ITERATIVE ALGORITHMS

The performance of naturally inspired algorithms utilized for path planning optimization has been researched and discussed widely. An important trait that is shared among iterative algorithms is their inherent parallelism. An iterative optimization algorithm is ideally suited for parallel distribution through hardware implementation [13], [14], [15], and/or can be designed in a manner capable of executing parallel processing traits from a software design perspective [16], [17]. Another common element or characteristic is some form of probabilistic perturbation in the search or solution selection technique. Performance comparisons between algorithms are typically focused on solution optimality, speed of convergence, or effectiveness in addressing qualitative aspects of the path or workspace environment.

Although these techniques can be very effective, the practical application of the algorithms can suffer because of the basic form or problem setup being defined too generally, leaving the problem representation subject to wide heuristic input and adjustment to fit the desired problem description. This can potentially lead to ambiguity regarding the performance or direct comparison of algorithms, particularly if original source pseudo-code or programming is not open to review or evaluation. However, as more research and experimentation is done in a specific topic area (e.g. mobile robotic path planning) or treatment of a particular constraint (e.g. obstacles in the workspace) becomes repeated in the literature, directions and approaches can be followed, repeated and expanded by researchers.

VI. COMPARISON OF RELATED WORK / LITERATURE SURVEY

Evaluating the common themes and nuances of recent research involving the use of naturally inspired iterative algorithms for path planning, some patterns can be observed, and suggest the trajectory of future research and experimentation in this area. The first segment of research in this area focused primarily on using a single optimization algorithm [3], [7], [8], [9], and the adaptation or modification of the algorithm to provide enhanced performance when applied to path planning [4], [18], and [19]. Other segments of research deal with problem representation, such as modifying the GA chromosome based on the search environment parameters, or modification to the operators in the GA to compensate for obstacles in the path. Subsequent publications provided performance comparisons between individual algorithms, suggesting solution or performance synergies through a combination of search techniques [20], [21], [22].

There has also been a steady recognition of the inherent parallelism of the naturally inspired iterative search algorithms, and to this end, exploration into FPGA hardware implementations [23], [24], and parallel searching techniques have been published [25], [26]. These studies also address on-line processing versus, off-line processing computational constraints such as time to convergence [27].

Based on the current state of the art, one path for future research is likely to occur in the area of hardware implementation (due to lower processing and memory costs), and algorithm enhancements or software operating system developments which allow for improvements in real-time solution performance. There is also continued work on developing hybrid algorithms, and new forms or variations of naturally inspired algorithms continue to appear in literature. These forward looking trends include further work on probabilistic operators, parallel implementations and learned search space environment architectures. Another trend observed is the exploration of applying naturally inspired algorithms to the task of cooperative or multi-agent robot coordination and path planning. Last, authors put forth that based on currently available literature and search analytics, the topic of naturally inspired optimization algorithms in the robotic domain remains quite active and offers continued opportunities for future research [28], [29] and [30].

VII. CONCLUSION

For mobile robotic platforms, path planning using naturally inspired iterative search algorithms has been effectively demonstrated. These algorithms are ideal for multi-objective optimization problems where non-exact, near optimal (good-enough) solutions for motion pathways in the workspace are acceptable. We have briefly introduced three of these algorithms (SA, GA and ACO), and illustrated some of the application synergies that may be exploited through

combinatorial or modification techniques. Last, an overview of recent literature provided temporal context and follow on topics for future experimentation and research.

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