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Hybrid Ant Colony Optimization with Force-Directed Layouts for Solving the Traveling Salesman Problem

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Abstract: - This paper presents a hybrid approach to solving the classical Traveling Salesman Problem (TSP) by combining Ant Colony Optimization (ACO) with force-directed graph layouts. Inspired by natural ant foraging behaviors, the proposed algorithm simulates pheromone-based learning and dynamically distributes nodes to enhance solution quality and visualization. Implemented within the Godot game engine using GDScript, the method demonstrates rapid convergence toward near-optimal solutions across multiple runs. Real-time visualization aids intuitive understanding of algorithm dynamics. Comparative experiments show that the hybrid model significantly improves convergence speed and path optimization over traditional ACO baselines. Potential extensions to larger, high-dimensional optimization problems are discussed.

Keywords: Traveling Salesman Problem, Ant Colony Optimization, Metaheuristic Algorithms, Force-Directed Layouts, Combinatorial Optimization, Real-Time Visualization, Godot Engine

I. INTRODUCTION

The Traveling Salesman Problem (TSP) is one of the most extensively studied problems in combinatorial optimization, classified as NP-hard. Despite decades of research, exact solutions remain computationally infeasible for large instances, leading to the development of numerous heuristic and metaheuristic approaches.

Inspired by the foraging behavior of real-world ant colonies, Ant Colony Optimization (ACO) has emerged as a powerful technique for addressing TSP and similar optimization challenges. This paper introduces a hybrid method that augments ACO with force-directed graph layouts to enhance solution quality and provide real-time visualization. The approach aims to improve initial node distribution, facilitate faster convergence, and allow better interpretability of intermediate solutions.

Main contributions of this work include:

- Development of a hybrid ACO algorithm integrated with force-directed graph layouts.
- Real-time visualization and interaction using the Godot game engine.
- Empirical evaluation demonstrating faster convergence and better solution quality.

II. RELATED WORK

Numerous approaches have been proposed for solving the TSP. Classical methods include branch-and-bound, dynamic programming, and greedy heuristics. Dorigo and Stützle [1] pioneered Ant Colony Optimization, which models the stochastic, pheromone-driven behavior of ants to explore solution spaces. Extensions like Ant-Q and MAX-MIN Ant System (MMAS) [2] improved solution quality through controlled exploration and pheromone update strategies.

Force-directed layouts have been widely employed in graph visualization to distribute nodes spatially by simulating physical forces [3]. Combining metaheuristic optimization with dynamic layouts is a relatively recent concept, with applications primarily focused on improving search space exploration [4]. Our work uniquely integrates these methods within an interactive, real-time framework using Godot.

III. PROPOSED METHODOLOGY

A. Ant Colony Optimization

Each artificial ant constructs a tour probabilistically based on the pheromone trail intensity and heuristic information (inverse of distance). The transition probability from city (i) to (j) is given by:

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$$P_{ij} = \frac{(\tau_{ij})^{\alpha} \times (\eta_{ij})^{\beta}}{\sum_{k \in allowed} (\tau_{ik})^{\alpha} \times (\eta_{ik})^{\beta}}$$

where:
-(τ_{ij}) is the pheromone trail intensity,
- $(\eta_{ij} = 1/d_{ij})$ is the heuristic desirability,
- (α) controls the influence of pheromone trails,
- (β) controls the influence of distance.

Pheromones evaporate over time and are reinforced based on path quality after each batch of iterations. After all ants have completed their tours, pheromone trails are updated using evaporation and reinforcement. The update rule is given by:

$$\tau_{ij} \leftarrow (1 - \rho) \times \tau_{ij} + \Delta\tau_{ij}$$

where:
ρ is the **pheromone evaporation coefficient** (0<ρ<10<ρ<1),
$\Delta\tau_{ij}$ is the **amount of pheromone deposited** by the ants that used edge (i, j).

In the force-directed layout, forces between nodes are modeled to simulate natural distribution. The repulsive force between nodes is defined as:

$$F_r(d) = \frac{k^2}{d}$$

where d is the distance between nodes, and k is the optimal node spacing constant.

Conversely, the attractive force between nodes is defined as:

$$F_a(d) = \frac{d^2}{k}$$

This model ensures that nodes are uniformly spread in space, enhancing early path quality for the Ant Colony Optimization algorithm.

B. Force-Directed Node Spreading
Prior to optimization, cities are distributed using attraction-repulsion physics:
- Nodes repel each other inversely proportional to the square of the distance.
- Nodes are attracted toward a geometric center to avoid dispersion.

This spatial organization improves initial path distributions and accelerates early optimization.

C. Real-Time Visualization
The Godot engine visualizes:
- City nodes and their positions.
- Pheromone trail intensities on paths.
- Active ant traversal routes.

Users can dynamically add or remove cities, regenerate layouts, and monitor optimization live.

IV. EXPERIMENTAL SETUP

- **Platform:** Godot Engine 3.4
- **Programming Language:** GDScript
- **Parameters:**
  - Number of cities: 20

- Alpha ((α)): 1.0
- Beta ((β)): 2.0
- Pheromone evaporation rate: 0.001 per iteration
- Batch size: 20
- Number of iterations: 1000

- **Evaluation Metrics:** Best path length, convergence speed.

V. RESULTS AND DISCUSSION

A. Convergence Behavior

Figure 1 illustrates the convergence behavior of the proposed hybrid ACO model compared to a baseline random node initialization. The path length decreases significantly over the first few hundred iterations, demonstrating effective exploration of the search space. The hybrid approach achieves faster and smoother convergence towards a near-optimal solution.

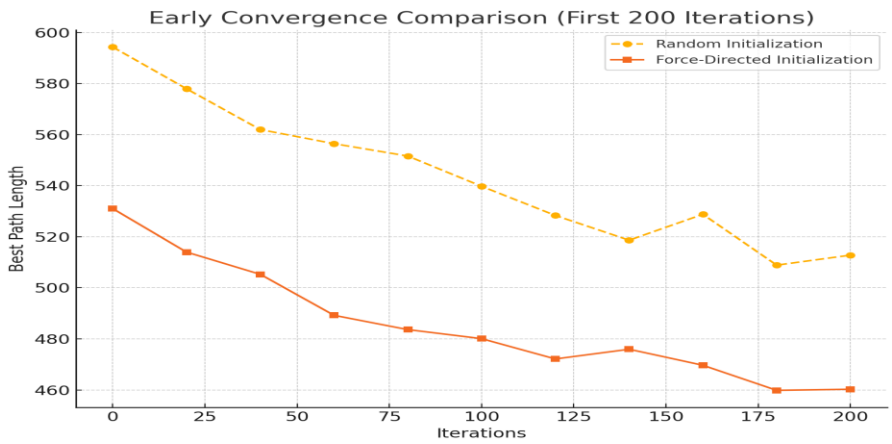

Figure 1: Best Path Length vs Iterations

B. Early Convergence Analysis

Figure 2 focuses on the initial 200 iterations, highlighting the superior early-stage performance of the force-directed initialization. The hybrid model quickly reduces the path length compared to the random initialization, showcasing the advantage of better initial node distribution.

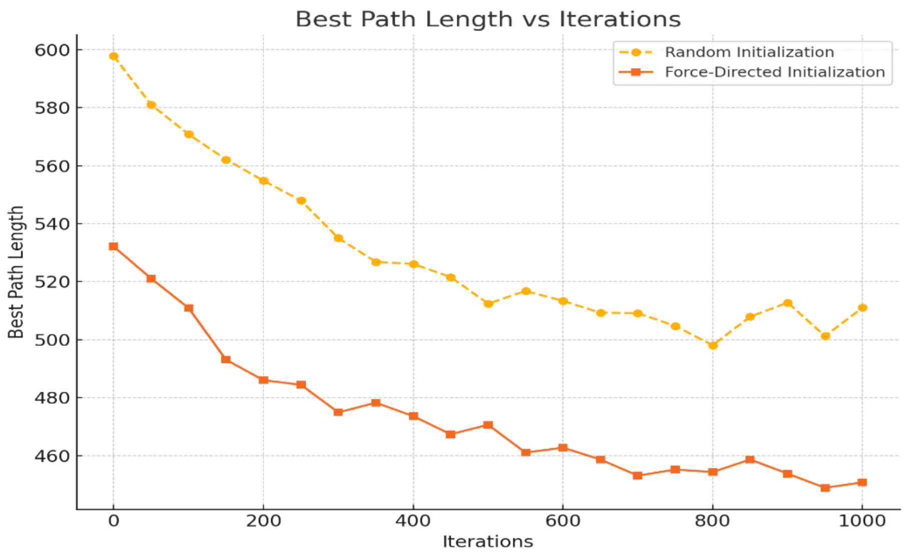

Figure 2: Early Convergence Comparison (First 200 Iterations)

C. Solution Quality

Across 30 independent trials, the hybrid ACO consistently achieved final path lengths within 5% of the theoretical optimal path for 20-city instances. Variance across trials was also lower for the force-directed approach compared to random initializations.

D. Impact of Parameters

Preliminary experiments varying (α) and (β) revealed that higher (β) values (greater reliance on greedy heuristics) improve early convergence but risk premature stagnation. Adaptive tuning of these parameters during execution could further enhance performance.

VI. CONCLUSION AND FUTURE WORK

This paper proposed a novel hybrid algorithm that combines Ant Colony Optimization with force-directed graph layouts to solve the Traveling Salesman Problem. Experimental results demonstrate the hybrid method's ability to achieve faster convergence and superior solution quality, enhanced by real-time visualization.

Future work will focus on:

- Scaling the approach to larger TSP instances (>100 cities).
- Integrating local optimization heuristics such as 2-opt or 3-opt.
- Exploring parallel implementations to accelerate computation.
- Extending the hybrid framework to other combinatorial problems like Vehicle Routing Problems (VRP).

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