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Intelligent Path Planning Algorithms in Autonomous Robot

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Abstract:

This paper presents a comprehensive review of various intelligent algorithms used for path planning in autonomous robots, focusing on multi-agent systems, mobile robots, and sustainable agricultural applications. Autonomous mobile robots rely on efficient path planning to navigate complex environments. This paper surveys path-planning techniques, comparing traditional algorithms with nature-inspired heuristics. Traditional algorithms, such as A and Dijkstra's algorithm, are contrasted with methods like Ant Colony Optimization (ACO), Firefly algorithms, and Genetic Algorithms (GA). The paper highlights the strengths and weaknesses of each approach and discusses hybrid methods that combine these techniques to leverage their respective advantages.

Keywords - **Path planning, autonomous robots, metaheuristic algorithms, multi-agent systems, intelligent algorithms.**

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I. INTRODUCTION

Path planning is a critical aspect of robotics and automation, where the goal is to determine an optimal route for a robot or agent to navigate from a starting point to a destination while avoiding obstacles[1]. The development of obstacles is becoming less of a problem with the development of autonomous robots and AIs. Path planning is a key challenge in robotics and automation where an optimal path needs to be designed from a start to end position, steering clear of obstacles[2]. Recently, the use of these algorithms has grown rapidly, and many researchers are looking at their usefulness in complex settings which go beyond conventional path planning approaches.

The combination of Firefly and Grey Wolf Optimization (GWO) has shown promising results in search optimization efficiency and path retrieval under dynamic conditions. Furthermore, developments like adaptive manoeuvre tuning with these algorithms are realistic as they are suited to varying densities of obstacles and complications within a given environment. This poises robotics to become versatile, but comprehension the strengths and flaws of every algorithm will be needed to create solution techniques that are effective when working in constraining rough terrain.

Additionally, the development of other meta-heuristic algorithms opened up further possibilities to improve path planning effectiveness. This is the case for the more recent studies which gave light to a new approach that involves hybrid Cuckoo Search (CS) and GWO to exploit the global optimum while overcoming local minima problems in dynamic scenarios, leading to more efficient route selections.

Mobile robots need efficient path planning to navigate from a starting point to a desired end point with no collisions. Path planning is important in many applications, such as autonomous cars, industrial robots, and search and rescue missions. This paper discusses the various path-planning algorithms, dividing into classic methods and heuristics into nature inspired and discussing their applicability to different environment and problems.

Motion planning, or path planning, or the navigation problem is a computational task aimed at computing a sequence of legal configurations to move an object or robot from an initial location to a specified goal[1]. It is a key element in any autonomous system that displays intelligent behavior[2]. The objective is to make robots, and autonomous agents shift themselves or other components of the world to a target goal by selecting a sequence of suitable actions. A simple motion planning problem is to calculate a continuous path that links a start configuration and a goal configuration without colliding with known obstacles[1]. Motion planning algorithms receive a description of tasks as input and output speed and turning commands transmitted to the robot's actuators[1]. The algorithms solve robots with multiple joints, complicated tasks, multiple constraints, and uncertainty[1]..

Algorithms with Static Environments

Classical path planning algorithms typically employ systematic search techniques that navigate the configuration space to determine the best path. Examples include:

Dijkstra's Algorithm: Finds the shortest distance from a given vertex to other vertices in a graph.

*A Algorithm:** A combination of Dijkstra's and Best-First Search, using heuristic functions to guide the search process more efficiently.

Algorithms for Obstacle Avoidance

One of the essential requirements for autonomous navigation is obstacle avoidance. In autonomous systems, fuzzy logic has been widely used to provide obstacle avoidance and adaptability in dynamic and uncertain environments[1]. For mobile robot navigation, Hilali et al. (2024) developed an optimized neuro-fuzzy controller that showed increased accuracy and computational efficiency[1]. To improve real-time obstacle detection and avoidance, the author also compared hybrid approaches, neuro-fuzzy architectures and Mamdani fuzzy systems[2].

IF-THEN principles are used in a Mamdani fuzzy system, a type of fuzzy inference system that mimics human decision-making. It is used to model and simulate systems with imprecise or unclear inputs. In order to demonstrate the usefulness of fuzzy systems in cluttered environments, Kumar et al. (2024) used a Takagi-Sugeno fuzzy logic model in indoor mobile robots. In autonomous systems, fuzzy logic has been widely used to provide obstacle avoidance and adaptability in dynamic and uncertain environments[1]. For mobile robot navigation, Hilali et al. (2024) developed an optimized neuro-fuzzy controller that showed increased accuracy and computational efficiency[1].

Algorithms which are Biologically Inspired or Nature Inspired

Biologically inspired algorithms are based on the emulation of human and animal neural and behavioural mechanisms observed in realistic experiments to enhance robotic navigation. Boahen et al. (2024) on neuromorphic sensory systems that can help robots adapt better to changes in the surrounding environment by colloquially mimicking biological signal processing systems. Lochner et al. (2024) proposed insect-inspired reinforcement learning models that demonstrate improved navigation in novel environments.

Furthermore, Alzaydi et al. (2024) incorporated fuzzy logic into biologically inspired neural networks, demonstrating better learning efficiency and rapidity in decision making. While these models exhibit excellent generalization, their dependence on significant computing power restricts their deployment in on-board low-power robotic equipment in real-time scenarios.

Recent studies explore:

- **Neuromorphic Sensory Systems:** Mimic biological signal processing for adaptive responses.
- **Insect-Inspired Reinforcement Learning:** Enhance navigation in novel environments.
- **Fuzzy Logic in Neural Networks:** Improve learning efficiency and decision-making speed.

Algorithms Based on Maze-Based Path Planning Techniques

In robotics tasks, particularly automated ones in industrial environment, maze-based algorithms have been a key player in structured path planning. Dao et al. (2024) proposed a PID control-based algorithm for an energy-efficient approach of navigating a maze. Zulfiqar et al. (2023) implemented an IR sensor-based Left-Hand-Wall Algorithm with an emphasis on path optimization in non-looped maze environments. Zulfiqar et al. (2023) proposed a decision-making framework based on ultrasonic sensors, which provided high recall and accuracy when solving a maze.

These studies demonstrate the strength of maze-based navigation, however, generalization to dynamic environments and integration with multi-agent systems is still an open research question. The literature review conducted shows that fuzzy logic, biological inspired models and maze-based algorithms have different advantages:

- **PID control-based algorithms** for efficient maze navigation.
- **IR sensor-based Left-Hand-Wall algorithms** for non-looped maze environments.
- **Ultrasonic sensor-based frameworks** for high-accuracy maze solving.

Algorithms which Predict the Movements of Obstacles

Motion prediction of moving obstacles is essential for safe and effective navigation in autonomous systems. Several algorithms have been proposed to solve this problem, taking advantage of predictive modelling and artificial intelligence methods. The Kalman Filter (KF) is one of the most popular techniques, which makes motion prediction in real-time by computing the position and velocity of dynamic obstacles from previous observations. Extended Kalman Filters (EKF) and Unscented Kalman Filters (UKF) increase prediction accuracy even further by integrating non-linear motion models.

The second method utilizes machine learning algorithms, specifically Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks, that learn from historic movement patterns to forecast future obstacle paths. These have proven to be highly accurate for dynamic scenarios like pedestrian and car motion prediction.

Probabilistic approaches, such as the Particle Filter (PF) and Bayesian Networks, are also utilized to approximate the probability distribution of obstacle locations over time, enabling autonomous systems to modify their navigation routes in response. Such approaches are most beneficial in cases where sensor measurements are noisy or uncertain.

Hybrid approaches combining reinforcement learning (RL) with predictive models have shown exceptional performance in complex dynamic environments. These methods leverage the learning capabilities of RL algorithms while incorporating predictive elements to anticipate future obstacle movements.

TABLE I
CLASSIFICATION OF AI-BASED PATH-PLANNING APPROACHES

AI-Based Approach	Algorithm(s)	Description

Machine Learning-Based Approaches	Reinforcement Learning (DQL, SARSA, PPO), Supervised Learning-Based Path Planning	Uses data-driven models to improve path planning based on previous experience.
Neural Network-Based Approaches	Artificial Neural Networks (ANN), Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN)	Learns complex patterns and optimizes pathfinding in uncertain environments.
Evolutionary Algorithm-Based	Genetic Algorithm (GA), Differential Evolution (DE), Artificial Bee Colony (ABC)	Uses biological evolution principles to optimize paths over generations.
Swarm Intelligence-Based	Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Cuckoo Search (CS), Firefly Algorithm (FA)	Mimics collective behavior in nature to explore optimal paths.
Fuzzy Logic-Based	Fuzzy Logic Controllers, Adaptive Neuro-Fuzzy Inference Systems (ANFIS)	Handles uncertainty and imprecision in decision-making for navigation.
Hybrid AI Approaches	Hybrid Firefly-Cuckoo Algorithm, GA-ANN Hybrid, RL-ACO Hybrid	Combines multiple AI techniques for enhanced efficiency and adaptability.
Deep Learning-Based	Deep Reinforcement Learning (DQL), Transformer-Based Navigation Models, Generative Adversarial Networks (GANs)	Uses deep neural networks to model and predict complex navigation scenarios.
Model-Based AI Planning	Markov Decision Process (MDP), Partially Observable MDP (POMDP), Model Predictive Control (MPC)	Uses probabilistic and predictive models to optimize real-time decision-making.

II. METHODOLOGY

The methodology is designed to conduct a complete and unbiased analysis of the applications of fuzzy logic, biologically inspired algorithms, and maze-based path planning methods in autonomous navigation[1]. The process of data collection entailed choosing peer-reviewed journal and conference articles with an emphasis on these three methodologies. Articles were selected according to their contributions to autonomous navigation, real-world applicability, and methodological soundness[1][2].

The literature was compared using a comparative framework that evaluated important performance indicators like navigation accuracy, computational efficiency, adaptability, and robustness. For the purpose of an unbiased assessment, the survey divided studies into three main categories: fuzzy logic for obstacles avoidance, biologically inspired algorithms for adaptive learning, and maze-based navigation for structured path planning.

Every paper was analysed based on its experimental design, algorithm efficiency, and practical application. Comparative measures were used to evaluate the performance of various algorithms, and research with evidence of real-world implementations was prioritized. Furthermore, articles combining hybrid methods, for example, reinforcement learning with fuzzy logic or biologically inspired neural processes, were considered based on their potential to improve navigation.

The rationale behind this approach is its capacity to give a systematic and balanced assessment of the research landscape. Segregating studies into specific categories ensures a concentrated examination of the merits and demerits of various navigation methods. The comparative paradigm not only underscores important performance metrics but also specifies research gaps that need to be addressed. Furthermore, giving importance to real-world applications guarantees that the results are practically applicable and relevant to contemporary autonomous systems.

In addition, the research included an examination of experimentation configurations across various studies. There were simulations in controlled environments in some of the papers, while others tested their assertions with actual implementations, including warehouse automation and UAV navigation. This methodology allows both theory and practice to be accounted for, making the results more reliable and applicable based on conclusions drawn from the survey.

III. CONCLUSION

The results of this survey suggest that fuzzy logic, biological inspiration algorithms, and maze-based approaches greatly improve autonomous navigation systems[1]. Fuzzy logic offers a sound paradigm for managing uncertainties in dynamic settings, enhancing adaptive decision-making and obstacle avoidance[1][2]. Biologically motivated models improve navigation performance by taking advantage of neural and behavioural processes in nature, resulting in more adaptive and intelligent robots.

Maze-based path planning methods also improve structured navigation in pre-defined settings like industrial automation and warehouse management, providing efficient and scalable solutions. Despite such progress, various challenges persist. Computational complexity and real-time processing constraints prevent fuzzy logic and biologically inspired models from being fully applied in large-scale autonomous systems. Maze-based methods, efficient as they are in structured spaces, are at a loss with generalization to dynamic and unforeseen conditions.

Future studies must aim at creating hybrid models that combine fuzzy logic, reinforcement learning, and biologically inspired algorithms for optimal efficiency, flexibility, and computational practicability. The integration of machine learning techniques with traditional path planning algorithms shows promise for overcoming current limitations.

In summary, the integration of these navigation methods offers a promising avenue for improving autonomous systems. Ongoing research in hybrid models, real-world testing, and computational optimization will be instrumental in overcoming present constraints and realizing the full potential of intelligent path planning algorithms in autonomous robotics. The development of more sophisticated algorithms that can handle multi-objective optimization while maintaining real-time performance remains a critical area for future research.

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