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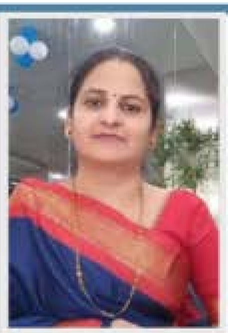

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Energy Efficient Random Search in Euclidean Space using Lévy Flight

Nara Narwandaru[1], *Jordan* Vincent[1], and *Bambang* Soelistijanto[1*]

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Abstract. Agents operating in unknown environments commonly rely on fundamental random search strategies to locate targets without prior knowledge of their surroundings. This research is motivated by the need to identify the most efficient movement strategy in autonomous robotics applications. Previous works often focus on specific aspects, lacking a comparative analysis of the random walk movements. Here, we investigate the comparative performance of agents utilizing random walk movements such as Random Waypoint, Brownian Motion, and Lévy Flight. The simulations were performed using the Opportunistic Network Environment (ONE) simulator. Each movement was tested under similar conditions, where targets were spread using a spatial Poisson random distribution and a spatial clustered distribution. We evaluated their performance based on the coverage over time for each movement under various target distributions and analyzed the best parameter for Lévy Flight on the defined target distributions. Results offer practical insights for agent designs during random search and validate whether Lévy Flight demonstrates superior performance as suggested in previous studies.

1 Introduction

Searching is a fundamental action used by organisms to investigate their environment and locate their targets. Many operations adapt this biological movement to reach their objective, which various fields often rely on. This strategy has been implemented on many scales, starting from autonomous home cleaners, search and rescue missions, and was even employed during the Second World War to detect submarines [1, 2]. At a glance, this operation might seem simple, as the searching agents may only need to know what to look for. But in spite of that, we also have to consider the environment in which the agents are conducting on. In many real-world scenarios, these environments are highly uncertain, where agents must operate without prior knowledge of the target locations [2, 3]. This uncertainty is further challenged in real-life practice due to cost constraints, power limitations, or operational requirements. Typically, some agents only possess basic sensors for obstacle detection and target identification, without an advanced navigation system to guide the movement decisions.

Under these constraints, agents must rely on basic movement strategies that function effectively without detailed input or prior environment knowledge. Traditional search

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algorithms require detailed information about the environment and the target location, making them unsuitable for such uncertain scenarios. This limitation necessitates the use of random search strategies, which can achieve effective area coverage without prior knowledge of the space. Some basic movement strategies are random search strategies, such as Random Waypoint movement, where the destinations are chosen uniformly within the search area; Brownian Motion that follows short-range correlated steps resembling natural diffusion; and Lévy Flight, which is a mix of frequent short movements and occasional long jumps [1].

The effectiveness of random search strategies is affected by the distribution of the targets within the search environment. In some real-world scenarios, targets are seldom arranged uniformly; instead, they exhibit varying spatial patterns that can influence search efficiency. In this study, we focus on two distinct distribution patterns that represent the opposite of the distribution pattern: spatial Poisson distributions, where targets are randomly and independently dispersed throughout the environment [3], representing scenarios such as scattered disaster debris and clustered distributions, where targets are grouped, mimicking situations like resource patches in ecological systems or groups of survivors in rescue missions. Each distribution pattern presents distinct challenges: The Poisson distribution requires broad area coverage to detect isolated targets, while clustered distributions require coverage around the targets. Therefore, it is important to understand how different random walk strategies perform under these varying target distributions to help identify the most effective movement strategies. Using the ONE simulator [4], this study compares and evaluate the performance of each random search movement given the target distribution to find an optimal strategy for each distribution.

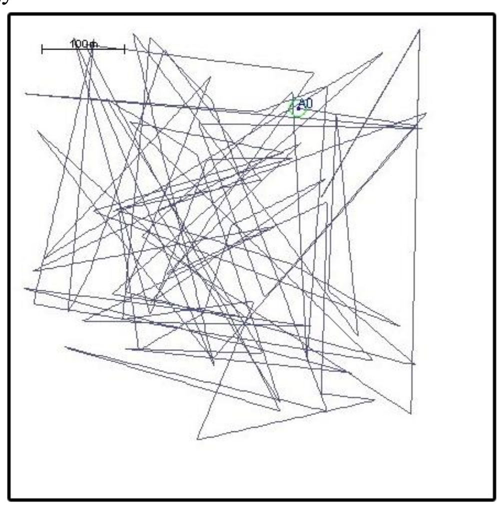

Fig. 1. Random waypoint.

2 Methods

2.1 Random search strategies

2.1.1 Random waypoint

Random Waypoint (RWP), as presented in Figure 1, is a simple mobility model where a node randomly chooses its next destination and makes a straight-line flight towards that destination [5]. This movement is commonly used in computer networking for mobile network research studies [5]. Its simplicity of choosing random points, however, results in questionable performance as a model for human mobility.

2.1.2 Brownian motion

Brownian Motion (BM), as depicted in Figure 2, is a subtype of random walk that characterizes the diffusion of tiny particles and can even be seen in some animal movement [5]. Such movement can be seen as sugar dissolves in still water and great white sharks hunting near abundant sources of prey [5, 6]. The movement’s steps tend to be of similar magnitude, being drawn from an exponential distribution [6]. Its normal diffusion is indicated by the proportionality of mean squared displacement (MSD), measuring the average displacement from its origin over time [5]. While the true origin of Brownian Motion has remained unexplained, previous microscopic observation demonstrates that the motion over longer durations becomes truly random, obeying a Gaussian distribution [7].

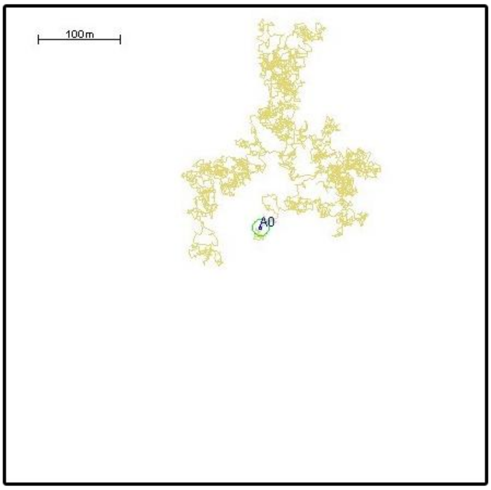

Fig. 2. Brownian motion.

2.1.3 Lévy flight

Lévy Flight (LF), as illustrated in Figure 3, is a class of random walk where each movement is drawn following a probability distribution with a power-law tail, known as the Pareto-Lévy distribution [6]. This movement can be observed in albatrosses flying over different areas in search of prey, great white sharks hunting sparsely distributed prey, movements of other foraging animals, and is similar to the human mobility model [1, 5, 6]. The movement is characterized by a series of short flights that are connected to occasional long flights [1]. Lévy Flights comprise instantaneous flight lengths; it does not consider a finite velocity walk with displacement determined after a time, as seen in Lévy Walk [6]. A study suggests that Lévy movement is an optimal way to find dispersed objects; some even argue that it is more efficient than Brownian Motion [6, 8].

In addition to other studies, LF has been extensively applied in optimization algorithms, such as harmony search [9], improved wild horse optimization [10], and numerous other metaheuristic approaches as discussed in comprehensive LF-based surveys [11]. These optimization applications utilize LF probabilistic characteristics to enhance solution space exploration in computational problems. However, this study focuses on LF as a movement strategy.

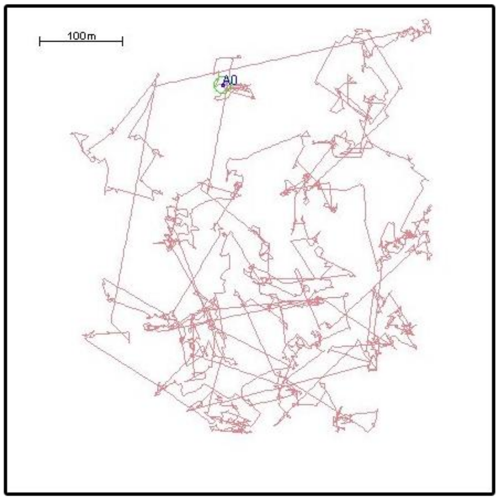

Fig. 3. Lévy flight.

2.2 Target distribution models

2.2.1 Spatial poisson random distribution

In the Poisson Distribution, as shown in Figure 4, targets are randomly and independently placed with constant intensity throughout the entire search environment [3]. This approach has fundamental properties: independence (target locations do not influence each other), stationarity (constant intensity across the environment), and spatial randomness (no clustering or patterns).

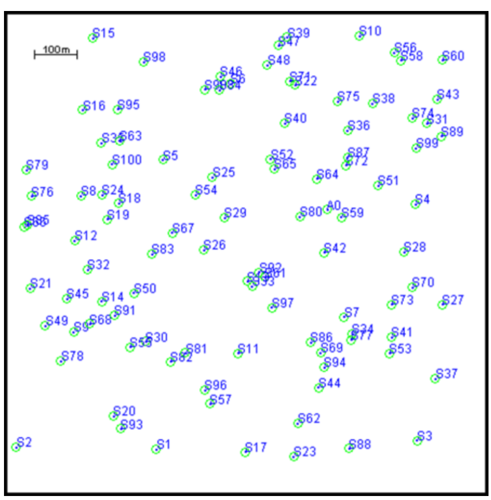

Fig. 4. Poisson distributed targets.

2.2.2 Spatial clustered distribution

This model, as seen in Figure 5, implements the Thomas Clustered Point Process, which follows a three-stage process. First, cluster centers or Point of Interest (POI) are randomly distributed throughout the search environment. The number of clusters is determined by the configuration parameter; we put 10 target clusters for our simulations. Second, cluster center selection for each target placement follows Pareto distribution weighting, creating certain clusters that receive more targets than others. Third, the distance of each target from the cluster center is determined using the Rayleigh distribution, which generates patterns with high concentration around cluster centers.

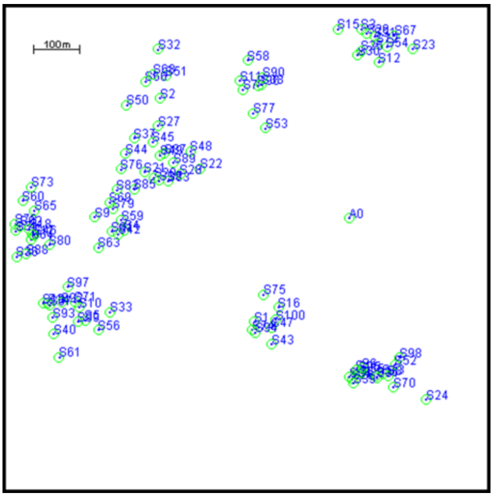

Fig. 5. Clustered distributed targets.

2.3 Simulation process

Experimental simulations were conducted using the Opportunistic Network Environment (ONE) simulator with parameters listed in Table 1[1]. Three random search strategies were tested under identical environmental conditions: Random Waypoint, Brownian Motion (diffusion coefficient = 1000.0, time step = 0.1), and Lévy Flight with a scale factor of 1.0 and varying alpha values. The simulations were run in one simulation week within a known area boundary and an unobstructed Euclidean plane, with scenarios limited to single-agent.

2.3.1 Evaluation process

Target discovery data was recorded every 3600 seconds throughout each simulation, capturing timestamp, cumulative discovered nodes, and coverage percentages. The simulation results were processed in three stages. First, extracting each simulation run's performance metrics, including minimum, average, and maximum coverage percentages, as well as the time required to reach 25%, 50%, 75%, and 90% coverage thresholds. Next, results from multiple simulation runs were aggregated and averaged to ensure statistical reliability. Lastly, comparative visualizations were generated to analyze performance differences between movement strategies.

2.3.2 Optimal lévy flight parameter exploration

Eight α values (0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0) were systematically tested for Lévy Flight. Based on average coverage performance, the optimal α will be selected.

[1] Simulation code available at: https://github.com/ZeroFairy/onesim-random-search

Table 1. The simulation parameter values.

Parameter	Value
Area size	1000 x 1000
Movement Seed	Random
Movement model	StationaryClustered, StationaryGaussian
Speed (m/s)	0.5
Number of total nodes	101
Number of searching nodes	1
Number of target nodes	100
Simulation time (s)	604800
Transmission range (m)	10

2.3.3 *Coverage performance analysis*

Performance comparison between Random Waypoint, Brownian Motion, and the optimal Lévy Flight strategies. Evaluation focused on coverage effectiveness metrics and temporal efficiency, providing a comprehensive assessment of search performance under identical environmental and target distribution conditions.

3 Results and discussions

3.1 Finding optimal lévy flight α parameter

The analysis of eight α values ranging from 0.25 to 2.0 was implemented into the two types of target distribution models, revealing the optimal performance of Lévy Flight at α = 0.5. As shown in Figure 6, the Spatial Poisson Distribution achieved the highest average coverage percentage of 75.31% at α = 0.5. While in Figure 7, the Spatial Clustered Distribution, α = 0.5, also achieved the highest average coverage percentage at 76.51%. Both Figure 6 and Figure 7 show that the average coverage decreases as the α value increases. Maximum coverage also shows a similar degradation pattern. This confirms that α = 0.5 provides the optimal value of search in this environment for Lévy Flight.

Looking at Figure 6 and Figure 7, we can observe that α values beyond 1 decrease the speed of coverage in the experiments, while lower values perform better. The results empirically demonstrate how α affects the Lévy Flight's long-distance flight chance. We find that lower values are more optimal, specific to the experiments' target distributions. This is likely the result of targets having relatively large distances for Poisson distributed targets, given 100 targets within a 1000 x 1000 area, as seen in Figure 4. Hence, the agent was able to do long flights more often to find the targets spread, instead of having a more frequent short flights around a specific area. For the spatially clustered distribution, lower α values help the searching agent to find inter-cluster POIs faster. However, this requires the agent additional time to locate the intra-cluster targets while travelling between clusters. We note that this parameter optimization may differ in a multi-agent setup, as other agents would sparsely move through space, potentially requiring fewer long flights with higher α values for an optimal Lévy Flight strategy.

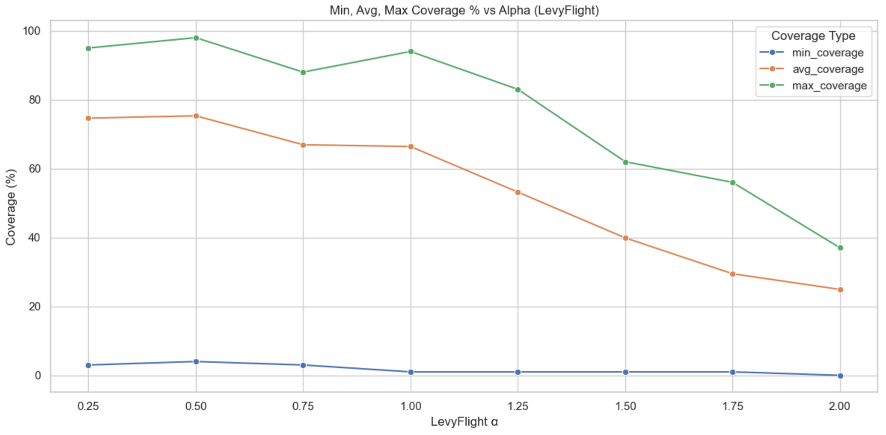

Fig. 6. Lévy flight α values comparison on spatial poisson distributed targets.

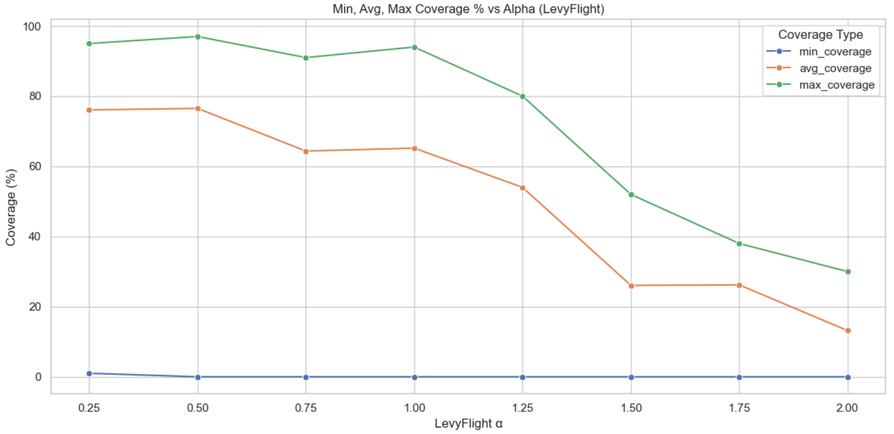

Fig. 7. Lévy flight α values comparison on spatial clustered distributed targets.

3.2 Coverage performance analysis

The results show a performance difference among the three strategies across both target distribution models. Under the Spatial Poisson Distribution shown in Figure 8, Lévy Flight with α = 0.5 achieved the highest average coverage of 76.51%, followed by Random Waypoint (76.08%) and Brownian Motion (57.63%). Similarly, on the Spatial Clustered Distribution shown in Figure 9, Lévy Flight with α = 0.5 also achieved the highest average coverage of 75.31%, followed by coverage of Random Waypoint with 68.92% and Brownian Motion at 54.46%. The maximum coverage analysis in both target distribution models also shows Lévy Flight achieving the highest coverage, followed by Random Waypoint and Brownian Motion.

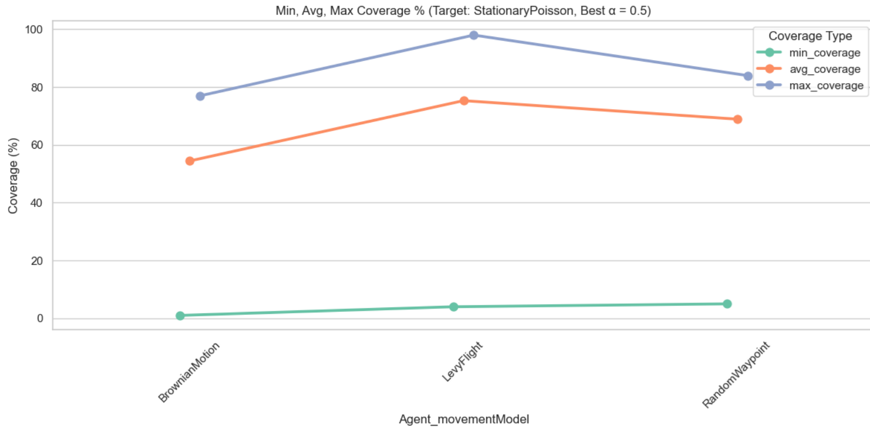

Fig. 8. Minimum, average, and maximum coverage performance on spatial poisson distributed targets.

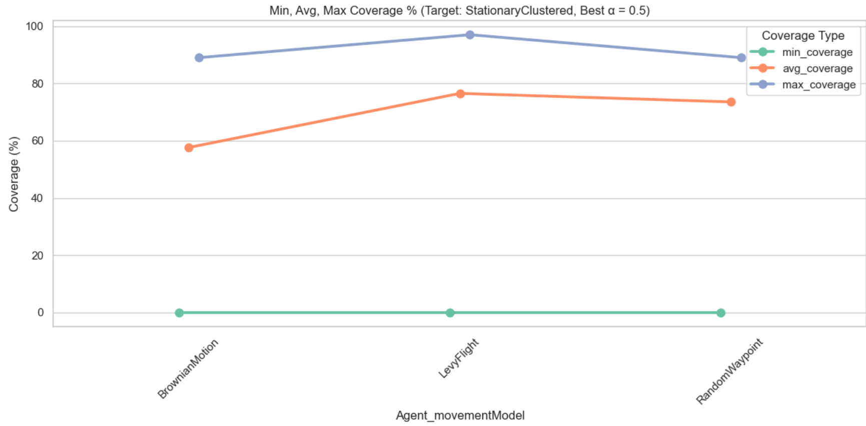

Fig. 9. Minimum, average, and maximum coverage performance on spatial clustered distributed targets.

3.3 Time-to-coverage analysis

The analysis reveals distinct performance patterns among three random search strategies, shown in Figure 10 and Figure 11. Under both target distributions, Random Waypoint achieved the fastest time to reach coverage 25% and 50%, while Brownian Motion had the longest completion time across all thresholds. Lévy Flight with α = 0.5 demonstrated intermediate performance at lower coverage levels and managed to reach a 90% coverage rate within the simulation time. Notably, in this run, both Random Waypoint and Brownian Motion failed to reach 90% thresholds within the simulation time. These results indicate that Random Waypoint provides superior performance in initial start, while Lévy Flight offers better performance over time. Random Waypoint and Lévy Flight, however, perform almost similarly on Clustered Distributed Targets.

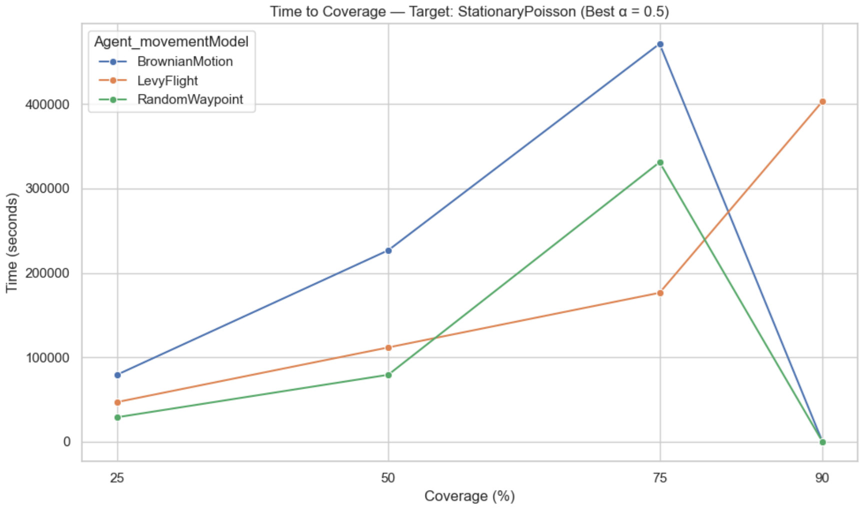

Fig. 10. Average time to coverage of BM, optimal LF, and RWP on poisson distributed targets.

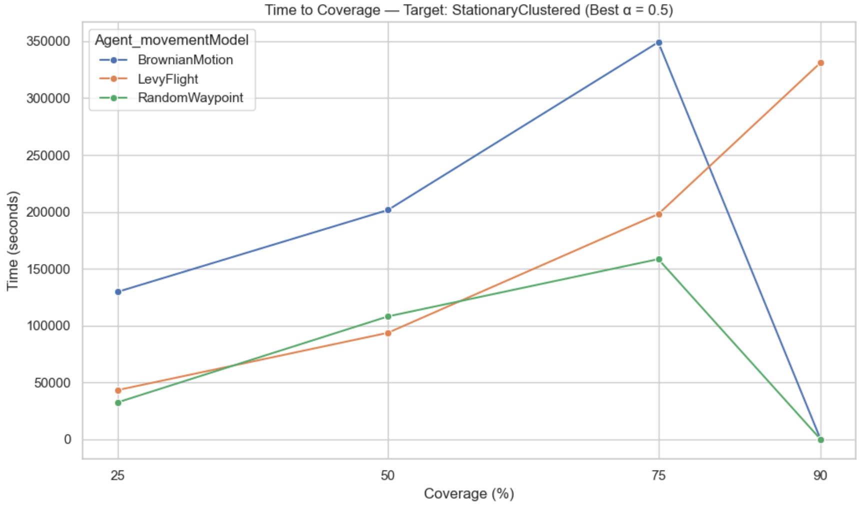

Fig. 11. Average time to coverage of BM, optimal LF, and RWP on clustered distributed targets.

4 Conclusions

This study presents a comparative analysis between three random search strategies in an unknown environment using the ONE simulator. The results show that Lévy Flight with an optimal α value of 0.5 performs the most efficient time-to-coverage and is consistent across both target distribution models. Lévy Flight achieves the highest average coverage rate of 76.51% for the Poisson target distribution and 75.31% for the clustered target distribution. This result alone outperforms Random Waypoint (respectively achieving 76.08% and 68.92%) and surpasses Brownian Motion (respectively achieving 57.63% and 54.46%).

Lévy Flight's intermediate performance during the early stages, followed by higher coverage over longer periods, supports previous studies' conjectures about the efficiency of this movement. Lévy Flight reaches 90% coverage within the simulation timeframe, while Random Waypoint faster reached lower thresholds of 25% and 50% coverage, highlighting its superior long-term search effectiveness. The optimal diffusibility of Lévy Flight may differ given distinct simulation periods and distribution targets; thus, it is wise to adapt the α parameter for the goal environment.

In practice, our findings could be implemented in scenarios involving autonomous robotic applications, search and rescue operations, environmental monitoring, and resource exploration, where the agents operate without prior knowledge of target locations. The coverage performance of Lévy Flight suggests potential energy savings in search operations by more quickly achieving target detection with reduced operational time.

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