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Physarum polycephalum inspired routing for cave and catacomb navigation

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***Abstract*—The study of biological systems such as the slime mold *Physarum polycephalum*, known to optimize transport routes in search of food, inspires the development of advanced parallel routing algorithms. We introduce a parallel routing algorithm based on *Physarum polycephalum* for navigation in caves and catacombs. Designed to map complex subterranean environments, the algorithm takes advantage of the adaptive and exploratory properties of mold to determine optimal routes through natural mazes and subterranean structures. It stands out for its ability to adapt instantly to changes and its efficiency in continuous exploration without manual intervention. Experimental results indicate that the algorithm not only improves the efficiency of path generation but also demonstrates robustness to obstacles and topographic variations. These characteristics offer new tools for archaeological and geological exploration, advancing significantly towards the automation of subterranean exploration.**

***Index Terms*—Physarum polycephalum, routing algorithm, underground navigation, bio-inspired artificial intelligence, cave and catacomb exploration.**

I. Introduction

Nature and biology have undoubtedly been an inexhaustible source of inspiration for the development of algorithms and optimization techniques in various areas of science and engineering. In this article, we present a routing algorithm based on the slime mold Physarum polycephalum, a single-celled organism that has demonstrated exceptional abilities to find optimal routes in complex environments. This being has inspired the development of several algorithms not only for optimization and routing, but also for modeling and simulation of different types of biological and physical systems [1]–[3].

In the field of computation and artificial intelligence, the slime mold has been used for the development of routing algorithms and route optimization in various types of transportation networks and systems. In [4]–[6] have pioneered the application of this organism for solving routing problems in communication and transport networks. More recent works such as [7], [8] have demonstrated the effectiveness of algorithms based on Physarum polycephalum for the generation of efficient and robust routes in complex and changing environments. In this sense, the algorithm proposed in this work focuses on navigation in complex subterranean environments, such as caves and catacombs, where the topology of the terrain and the presence of obstacles represent a challenge for the generation of efficient and safe routes in thousand of points.

Routing algorithms have been used to find short routes, the best routes, or possible routes between two points. The algorithm proposed in this paper can be used as that kind of algorithm; moreover, since is inherently parallel, it can search in multiple points at the same time, generating more than one route to different destinations.

The algorithm proposed in this work is based on the adaptive and exploratory properties of slime mold to determine optimal routes in subterranean environments. The algorithm developed is quite robust and efficient in generating routes in complex environments, and has been shown to be able to adapt to different types of terrain and obstacles, to mention some of its characteristics. Experimental results indicate that the proposed algorithm improves efficiency in path generation and demonstrates robustness to obstacles and topographic variations, offering new tools for archaeological and geological exploration and advancing towards the automation of subway exploration.

This article is organized as follows: in Section II we discuss the organism Physarum polycephalum and its biological properties that make it useful for the development of routing algorithms. In Section III we present the proposed algorithm and describe its performance and main characteristics. In Section IV we present results of the algorithm in some cases. Finally, in Section V we present the conclusions and discuss possible future research directions.

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II. Physarum Polycephalum

Physarum polycephalum is an acellular myxomycete, this stems from the plasmoid stage of its life cycle, in which the plasmodium is a bright yellow, macroscopic multinucleated coenocyte formed into a network of intertwined tubes. This stage of the life cycle is the one used for the study of this organism [9]. Figure 1 displays a propagation to form the shape of a galaxy. This pattern is reached across several nutrients organized as a spiral.

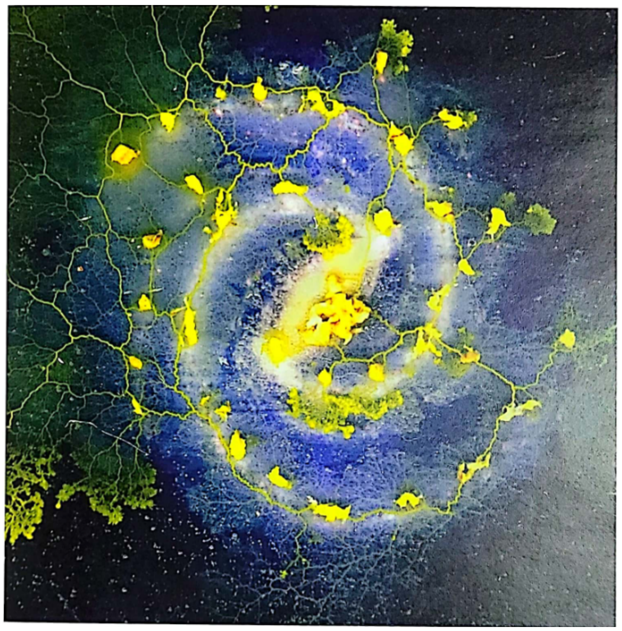

Fig. 1. Real Physarum propagating in an artist's impression of a galaxy obtained in [10].

Physarum polycephalum is a widely explored organism for the study of biology and physics, since it has unique properties that make it a very special complex organism. This slime mould is able to solve mazes, find the shortest route between two or multiple points, and make complex decisions based on the information it receives from its environment. In addition, the slime mould is able to learn and remember information, and to adapt to its environment gradually.

III. Implementation

The proposed algorithm in this paper is inspired on Jones agent model [11]. The algorithm is a cellular automaton that simulates the behavior of Physarum polycephalum in a maze, so we need to define some concepts. Let $\mathbb{Z}$ be the set of integers, and let us define the length of a tuple x as $|x|$. For all tuples x and y where $|x| = |y|$, let us denote $x \oplus y$ as the results from the component-wise sum of x and y, that is, $(x \oplus y)_i = x_i + y_i$ for all $i \in \mathbb{Z}$.

A cellular automaton is defined as a tuple $(\mathbb{Z}^n, S, N, f)$ where n is the dimension such that $n \in \mathbb{Z}^+$, S is a finite non-empty state set, N is a non-empty finite set of neighborhoods belonging to $\mathbb{Z}^n$, and f is a local transition function, that is, $f : S^N \to S$ where S^N represents the set of all possible neighborhood configurations in N.

Thus, the algorithm proposed in this work it is define as a cellular automaton $(\mathbb{Z}^2, S, N, f)$ where $n = 2$, $S = \{0,1,2,3,4,5,6,7,8\}$, $N = \{0,1,2,3,4,5,6,7,8\}^9$, and $f : \{0,1,2,3,4,5,6,7,8\}^9 \to \{0,1,2,3,4,5,6,7,8\}$, $P = (C(x,y:t), N(x,y:t), M(x,y:t))$ represent the combined state, neighborhood, and memory of the cell at position (x,y) at time t. The transition function f is defined as follows:

$$f(P) = \begin{cases} 7 & \text{if } C(x,y:t) = 0 \\ & \vee \exists N \in \{3,4,6\} \\ & \vee M(x,y:t) = 0 \\ 6 & \text{if } C(x,y:t) = 1 \\ & \vee \exists N \in \{5,6\} \\ 5 & \text{if } C(x,y:t) = 4 \\ & \vee \exists N \in \{3,5,6\} \\ & \vee M(x,y:t) = 0 \\ & \vee N \notin \{0,7\} \\ 0 & \text{if } C(x,y:t) = 5 \\ & \vee M(x,y:t) \notin \{5,8\} \\ & \vee N \notin \{1,3,4,6\} \\ 8 & \text{if } C(x,y:t) = 5 \\ & \text{and the above condition is not met} \\ 4 & \text{if } C(x,y:t) = 7 \\ & \vee \exists N \in \{3,4,6\} \\ 5 & \text{if } C(x,y:t) = 8 \\ C(x,y:t) & \text{otherwise} \end{cases}$$

Where the states of the cellular automaton are defined as follows:

TABLE I
States of the Cellular Automaton

Color	State	Description
Blue	0	Free field
Light blue	1	Nutrient not found
Red	2	Repellent
Black	3	Initial point
Yellow	4	Contracting gel
Dark green	5	Composite gel
Cream	6	Nutrient found
Dark gray	7	Physarum expansion
Green	8	Uncompounded gel

In the aforementioned source, the basic Physarum polycephalum algorithm, originally designed to operate with a von Neumann neighborhood, is detailed. However, in the version proposed here, we chose to modify the neighborhood to a Moore neighborhood, thus facilitating access to a larger number of neighbors for comparison and allowing us to obtain a clearer perspective on the optimal direction for agent displacement.

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IV. Results

In all of the proposed examples, the input of the algorithm was the initial state, which corresponds to the coordinates of the cells that were chosen to be defined as the starting point and the end point, as well as the distribution of the state representing the repellent, in which the plasmodium cannot cross and which helps to generate a defined space. An example is shown in Fig.2

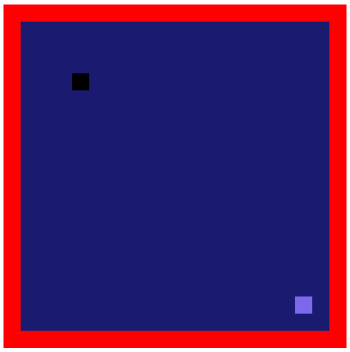

Fig. 2. Example of an initial state, black cell represents initial point and blue cell, the nutrient that will serve as a destination. Red cells (repellent) has the function of a container, where the Physarum polycephalum cannot escape.

The use of the Moore neighborhood instead of the von Neumann neighborhood introduces certain challenges not present in the original algorithm. One of these challenges arises at corners (NW, NE, SW, SE), where the repeller could allow the agent to escape, contrary to what is desired. To address this drawback, a solution was implemented that consists of placing an imaginary repeller in the corner when two adjoining corners present repellents at a 90° angle to each other. This adjustment allows for the creation of a wider range of shapes, as illustrated in Figs. 3, 4, and 5. In this images the total number of cells is 50×50.

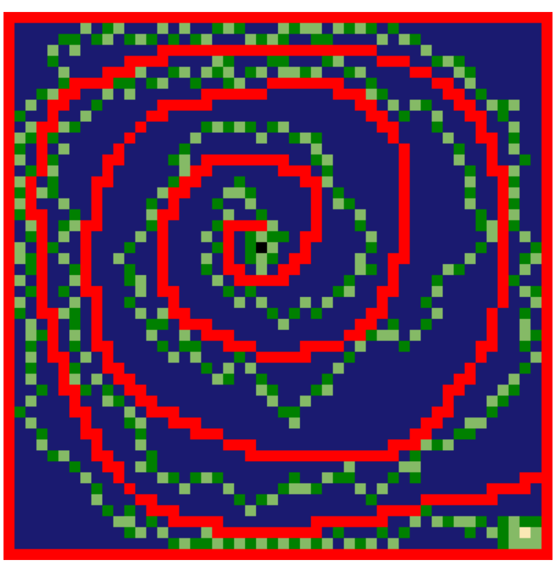

Fig. 3. Physarum polycephalum solving a spiral maze.

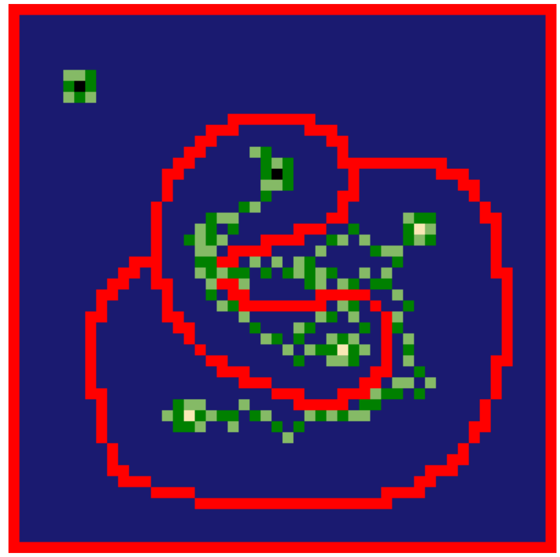

Fig. 4. Physarum polycephalum solving a circular maze.

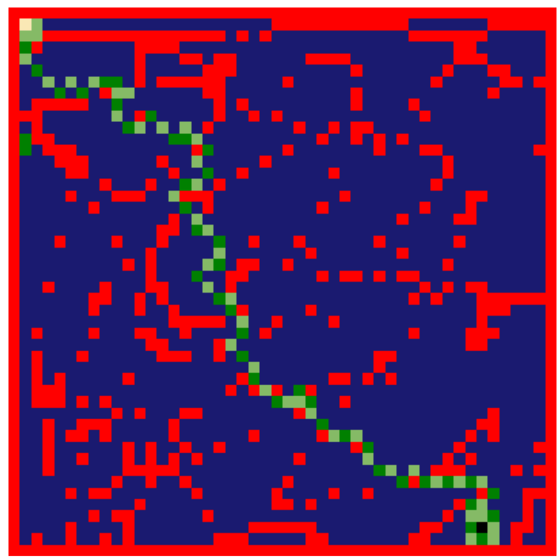

Fig. 5. Physarum polycephalum solving a random maze.

Thanks to the resolution of corner leakage by our algorithm, it is possible to generate more diverse mappings of caves and catacombs. This approach significantly improves our understanding of the topography of the explored area. In addition, the diversity in mapping facilitates the identification of the number and variety of available paths, which has been implemented by an image mapping algorithm that assists in the graphical representation of such topography, as shown in Fig. 6. The space explored by the algorithm is $10^3 \times 10^3$ cells and has a total of 146,135 red cells or repellent cells. The full simulation is available in the next video https://youtu.be/fhtMwIJaK9A.

Also the algorithm has been tested in a real environment, where it has been able to generate optimal routes in the Paris catacomb, as shown in Fig 7. The space explored by the

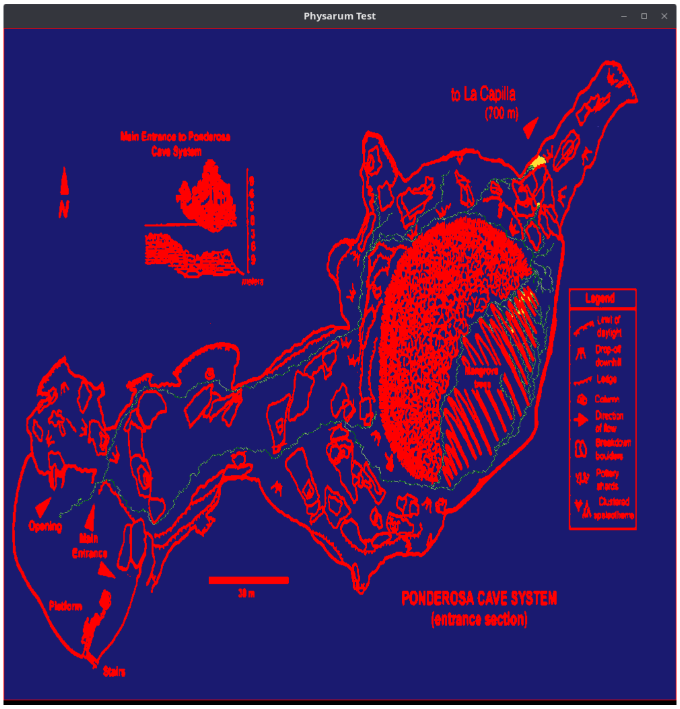

Fig. 6. Cave system mapping using Physarum polycephalum to determines roads. The initial condition begin with 853861 in state 1, 3 in state 1, 146135 in state 2 and the rest of sates with 0 elements. The simulation runs on 3,221 generations to yield a route, evolving in a space of $10^3 \times 10^3$ cells. Original map from CaveAtlas website, Copyright CaveAtlas.com 1995 (www.caveatlas.com/systems/system.asp?ID=201&co=MX#)

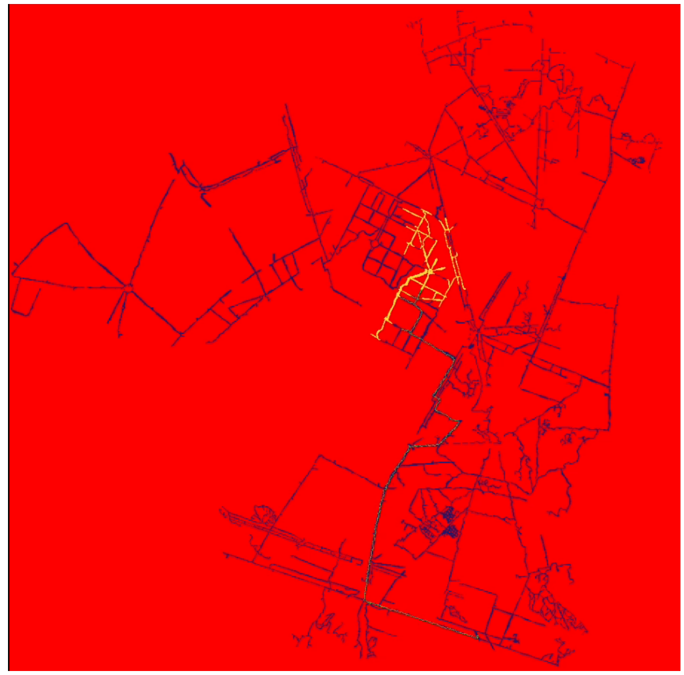

Fig. 7. Catacomb mapping using Physarum polycephalum to determines roads. It runs on a large map starting with 32891 in state 0, 967105 in state 2, 1 in state 1, 2 in state 3, and the rest of states in 0. The simulation needs 5,264 generations to yield a route, running in a space of $10^3 \times 10^3$ cells. Original map of the Paris catacombs and underground quarries, great southern network, version III, 2007. Copyright CUBE 2001-2007 (www.explographies.com).

algorithm is $10^3 \times 10^3$ cells.

Figs 8, 9 and 10 present stacked line plots designed to comprehensively illustrate the temporal evolution of the states in Figures 3, 6 and 7, respectively. These plots allow a clear comparison of state transitions over time, highlighting trends, specific key variations, and the number of cells in each scenario. X axis represents generations and the Y axis represents the number of cells for each generation.

It should be noted that since the algorithm is bio-inspired, the function that simulates plasmodium behavior is assigned in a pseudo-random manner to an adjacent neighbor, with a probability of $1/8$. This feature allows the expansion of the algorithm to take a circular form rather than a square or linear expansion. However, by modifying the likelihood function, it is possible to achieve a more irregular rather than merely circular expansion.

As mentioned above, the use of our algorithm prevents the Physarum plasmodium from escaping around corners as it normally would due to the use of Moore's neighborhood. This makes it a good choice for routing and space exploration because the generated routes are not generated in the places where they should not be access. This makes the algorithm practical for routing in two-dimensional spaces of different dimensions, and, thanks to the parallel nature of the algorithm, it is possible to cover these spaces with only a few iterations. In addition, different routes to different destination points

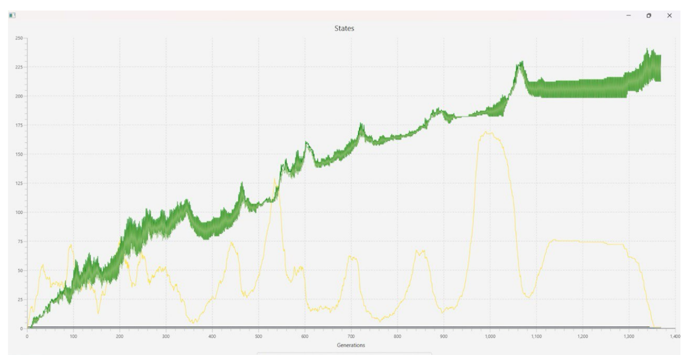

Fig. 8. Stacked line graph of the spiral maze simulation from Fig. 3, showing that states 7 and 8 remain dominant throughout the generations. The fluctuating peaks and troughs of state 4 suggest that the irregular spiral structure, with its varying corridor sizes, periodically allows for more or less presence of state 4.

can be obtained from a single initial point, because when running in parallel through the entire two-dimensional space and with the rules obtained, the generation of multiple routes to different destinations does not require additional calculation, since everything is calculated in the same iteration.

Unlike algorithms such as, for example, A*, it is not necessary to provide some kind of heuristic or external information, which means that its implementation as an automaton is only by applying the rules proposed in the algorithm, thus facilitating the generation of routes by providing a starting

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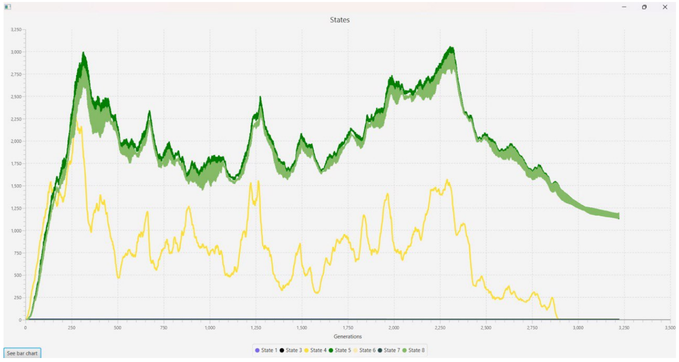

Fig. 9. Stacked line graph of the Cave System Simulation of Fig. 6, showing that states 7 and 8 become more abundant than state 4 over generations, indicating an open space map.

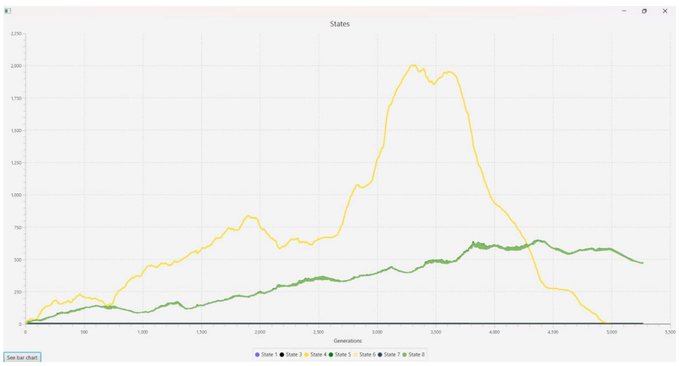

Fig. 10. Stacked line graph of the Paris Catacomb Simulation of Fig. 7, showing that state 4 becomes more abundant before starts contracting than states 7 and 8 over generations, indicating a map with narrow corridors.

point and a destination point or points (Fig.11).

V. Future work and Conclusions

The proposed algorithm exploits this slime's adaptive and exploratory properties to determine the optimal routes through these environments. Key points include the algorithm's ability to adapt to changes and its effectiveness in continuous exploration without manual intervention. Experimental results show that the algorithm is robust to obstacles and topographic variations, offering new tools for archaeological and geological exploration and contributing significantly to the automation of subsurface exploration.

Future research should focus on several key areas. The first step is to optimize the algorithm to increase its efficiency and scalability. Implementing advanced optimization techniques such as genetic algorithms or particle swarm optimization can help fine-tune the parameters of the Physarum-inspired model and increase the speed and accuracy of route generation, especially in more extensive and more complex environments.

Furthermore, it is essential to integrate the algorithm with advanced sensor technologies such as LiDAR, sonar and infrared imaging to improve the algorithm's ability to navigate in realistic subsurface environments. This integration will

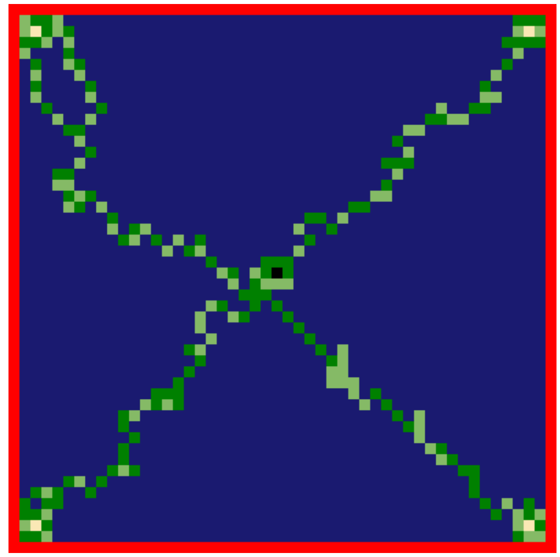

Fig. 11. Due the algorithm is inherently parallel, multiple routes can be obtained from single initial point to multiple destination points.

enhance real-time mapping capabilities and more accurate detection of obstacles and topographic features.

Research should also explore the possibility of extending the algorithm's application to different environments, such as forests, deserts, and urban underground systems. This would validate the algorithm's versatility and adaptability in various environments and increase its practicality. Another exciting research direction is developing a hybrid model that combines the Physarum-inspired algorithm with other bio-inspired and conventional algorithms such as ant colony optimization, Dijkstra's algorithm or A* search. Such a hybrid model could leverage the strengths of different approaches to create a more comprehensive and versatile navigation algorithm.

Improving the visualization and user interface is another step that would improve the algorithm's usability and accessibility for practical applications. The development of advanced visualization tools and user interfaces will allow users to interact more easily with and interpret the generated maps.

Field tests in real underground environments are necessary to validate the algorithm's performance. Such tests will provide empirical evidence of the algorithm's effectiveness and help identify potential areas of improvement based on real-world challenges.

Another important direction is to ensure the algorithm's safety and robustness under adverse conditions. Simulations of various adverse conditions, such as signal loss, physical obstacles, and dynamic environmental changes, will help test the algorithm's resilience and improve its robustness. The research should also explore multi-agent systems where multiple instances of the algorithm could work together to explore and map large underground areas. This would increase the coverage and efficiency of mapping large and complex cave systems.

Further research can thus significantly advance underground

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navigation and mapping and offer practical solutions for various fields, such as archaeology, geology, and exploration.

In this work, we have presented a routing algorithm based on Physarum polycephalum for navigation in caves and catacombs. The algorithm is implemented in real time and is designed to map complex subterranean environments. The algorithm takes advantage of the adaptive and explorative properties of the mold to determine optimal routes through natural mazes and subterranean structures. It stands out for its ability to adapt instantly to changes and its efficiency in continuous exploration without manual intervention. Experimental results indicate that the algorithm not only improves the efficiency of path generation, but also demonstrates robustness to obstacles and topographic variations. These characteristics offer new tools for archaeological and geological exploration, advancing significantly towards the automation of subway exploration.

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