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Research on Optimal Rescue Path Planning of Submersible Based on Submarine Terrain Modeling

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Abstract. In the process of deep-sea tourism exploration, due to the complex and ever-changing underwater environment, submarines may be affected by natural disasters, seawater pressure, and seabed topography, resulting in communication interruptions and mechanical failures during travel, causing harm to personnel in the submersible and causing huge losses to the tourism company. In order to address safety issues during deep-sea tourism exploration of submarines. This study takes the Inoian Sea as an example. Assuming that people encounter malfunctions during deep-sea tourism exploration while riding a submersible, immediate rescue is required. Firstly, we obtained high-resolution underwater terrain data from GEOCO 2023 and established a detailed three-dimensional underwater terrain model using Matalab software. During the search and rescue process, the sonar of the rescue vessel was used to search for the submersible, and the Markov Chain Monte Carlo (MCMC) method was used to predict the most likely position and probability distribution of the submersible. By combining the traveling salesman problem with genetic algorithm to process location and probability distribution data, the shortest path can be found. At the same time, we also established a dynamic model of the rescue process, allowing the rescue vessel to maximize the efficiency of maritime search and operation paths (such as spiral paths), and reflect the dynamic relationship between the rescue submersible and the damaged submersible.

Keywords: *Markov chain Monte Carlo, genetic algorithm (GA), traveling salesman problem (TSP), shortest path planning*.

1. Introduction

In the tourism project of the exploration of sunken ships in the Ionian Sea, small cruise submarines are mainly used to carry people into the sea, and the submarines are transported to specific places and released from the main ship without cables. So as to lead tourists to explore the shipwreck site at the bottom of Ionia. However, the submersible may be affected by submarine natural disasters, sea water pressure and submarine topography, resulting in communication interruption and mechanical failure. The Ionian Sea is one of the most earthquake prone areas in the world, most of which are more than 3000 meters deep, and the maximum depth in the east is 5267 meters. For the safety of tourists, safety procedures need to be developed to deal with communication interruption and mechanical failures. Since the submersible may stay on the seabed due to failure, and its position will also be affected by factors such as ocean current, seawater density and seabed topography, this research needs to develop a model to deal with the loss of communication with the main ship or possible mechanical failure, so as to complete the position prediction and rescue of the submarine.

In order to deal with the communication interruption with the main ship or possible mechanical failure, including the interruption of submarine propulsion, our work mainly includes the following points.

1) In order to solve the problem of the position of submarines in the deep sea, we obtained high-resolution seabed terrain data from GEBCO 2023 in the Inoian sea area and established a detailed 3D terrain model using MATLAB. At the same time, the Markov Chain Monte Carlo (MCMC) method was used to predict the most likely position and probability distribution of the submersible, providing important data support for subsequent rescue plans.

2) Based on the data in Model 1, use sonar to actively search for multiple suspected submersible location points, convert the returned location points into a Traveling Salesman Model Problem (TSP), and use genetic algorithm to optimize the TSP model to find the shortest path, so that unmanned diving rescue personnel can identify each suspicious target in the shortest time, eliminate location faults, and improve rescue efficiency.

3) A dynamic model of the rescue process has been established to enable rescue ships to maximize the efficiency of maritime search and operation paths (such as spiral paths), and to reflect the dynamic relationship between rescue submarines and crashed submarines. This model considers different rescue scenarios and predicts the success rate of rescue under different prediction accuracies.

4) A cost-benefit analysis model has been developed to analyze the costs, search efficiency, and cost-effectiveness of different search devices.

1.1. Research work

This research proposes an efficient search and rescue path planning method by analyzing the information data such as ocean current and seabed pressure, as well as the position, depth and possibility of disaster of submarines, combining the ocean dynamic model and Markov Chain Monte Carlo

(MCMC) method. This method uses active sonar to detect multiple targets, and uses the intelligent optimization algorithm of the traveling salesman problem to ensure that the search and rescue task is completed while minimizing the search path and distance. In the whole research, our main work is as follows.

1）data collection and analysis: obtain submarine topographic data with a resolution of 15" within the rectangular range of 36n20e~37n21e in the sea from the data file ionian.xlsx.

2）Establish model 1, use the collected data to carry out 3D modeling for part of the bottom of inoian, and use MCMC method to simulate the possible location of the lost contact submersible, and obtain the probability distribution of the location.

3）Establish model 2. After determining the location distribution probability, the rescue ship carries out rescue operations. According to a series of points returned by the active search sonar where the suspected submersible is located, the GA algorithm is used to plan the shortest path, so that the unmanned submersible can be identified one by one in close range, so as to improve the rescue efficiency.

4）Establish model 3, the dynamic model of the search and rescue process, give the spiral path of the rescue ship to maximize the search efficiency on the sea, simulate the motion state of the rescue submersible and the wrecked submersible, and predict and show the success rate of rescue in different situations.

2. Materials and methods

A. Notions

The key mathematical notations used in this paper are listed in Table 1.

Table 1. Notations used in this paper

Notions	Utilization
x	longitude
y	latitude
t	The time from now
f	The Coriolis parameter
$q(x'\|x)$	The probability of transitioning from the current state x to a new state x '
β(x`|x)	The acceptance probability
P(x)	The probability density of the target distribution in state x
Ω	The rotational velocity of the Earth

B. The Establishment of Model 1

The Markov Chain Monte Carlo (MCMC) is a method used to sample from probability distributions (Brooks, 1998). «The future is independent of the past given the present», this sentence contains the basic idea of the Markov chain. We use the MCMC method to simulate the possible trajectory of the submersible on the Ionian seabed and estimate the position of the submersible. In the MCMC simulation, the submersible proposes a new position through a random process at each moment, and decides whether to accept the new position or not based on the acceptance probability [1]. The formula is shown in (1).

$$\beta(x' \mid x) = \min\left\{1, \frac{p(x')q(x \mid x')}{p(x)q(x' \mid x)}\right\} \quad (1)$$

where p(x) is the probability density of the target distributed under state x, and $q(x \mid x')$ is the probability of moving from state x to x'.

C. The Establishment of Model 2

The Traveling Salesman Problem (TSP) is a classic combinatorial optimization problem, and from the perspective of graph theory, the essence of the problem is to find a Hamiltonian loop with the smallest weight value in a completely undirected graph with weights. It's a bit like the «shortest path problem», and then we naturally think of using the Dijkstra algorithm to solve it [2][3].

In a graph with n nodes, the distance can be represented by a matrix D of one nn, where Dij is the distance from the i node to the j node. The goal is to minimize the path length.

$$\min \sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} D_{ij} x_{ij} \quad (2)$$

Where x_{ij} is a decision variable, if city i to city j is in the solution, then x_{ij} = 1, otherwise it is 0. In order to quickly find the missing submersible, we use Genetic Algorithm (GA) to solve the problem.

$$Fitness(x) = \frac{1}{dis\tan ce(x)} \quad (3)$$

Where distance(x) represents the total length of the path corresponding to chromosome x. The goal of this fitness function is to maximize the fitness value, i.e., to minimize the total distance.

D. The Establishment of Model 3

In addition, we need to get geostrophic currents to correct the behavior of the submersible, this is an approximate formula that describes the basic relationship of geostrophic currents (originally the basic formula for Coriolis winds).

$$\Delta V = \frac{-g}{f} \times \frac{\Delta h}{\Delta x} \quad (4)$$

Where ΔV is the geostrophic velocity, g is the acceleration due to gravity, f is the Coriolis parameter (related to latitude), Δh is the sea surface altitude difference (usually proportional to the underwater pressure difference), and Δx is the horizontal distance.

$$f = 2\Omega \sin(\varphi) \quad (5)$$

Ω is the angular velocity of the Earth, which is about 7.2921 X 10-5 radians per second, and φ is the latitude, with positive north latitude and negative southern latitude.

E. The Establishment of Model 4

We need to build a model for the selection of additional search equipment, determine what additional search equipment the main ship will carry and what rescue equipment may be needed, considering the cost factor. Analyze the relationship between the cost (purchase, maintenance, preparation, and use) of different devices and their search efficiency.

$$U(e) = \alpha * E(e) - \theta C(e) \quad (6)$$

e: Different search devices

E(e): Exploratory efficiency of the device

C(e): The total cost of the equipment

α and θ are the weight parameters that adjust the relative importance of search efficiency and cost in the utility function, and we can write a rough formula.

$$C(e) = Cp(e) + Cm(e) + Cr(e) + Cu(e) \quad (7)$$

They are the cost of purchase, the cost of maintenance, the cost of state of readiness, and the cost of use. Finally, we will select the optimal search equipment through a cost-benefit analysis.

3. Results and discussion

A. The Solution of Model 1

In this model, we used MATLAB to implement The Markov Chain Monte Carlo (MCMC) algorithm, the code I will put in the appendix of the article. Through a series of mathematical calculations, including interpolation, random perturbation processing, probability calculations, and basic physical motion calculations, the trajectory of the submersible on the seafloor is simulated and visualized with data.

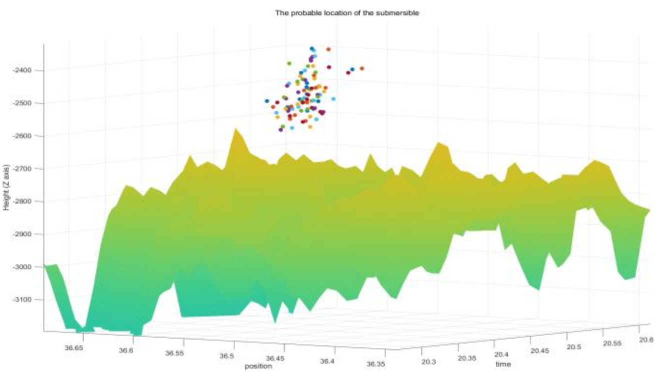

Figure 1. Position prediction of submersible after losing power

Each solid point in the scatter plot represents the result of a simulation, or the predicted position of the submersible at different points in time. The different colors of the dots represent different predictions or different phases of time. Three-dimensional surfaces represent related geographic information.

B. The Solution of Model 2

In the Traveling Salesman Model Problem (TSP) model, we use MATLAB to implement the GA algorithm and set parameters.

Size:100
Crossover probability:0.95
Probability of variation:0.1
Maximum number of iterations:2000
Run the code and here are the results.

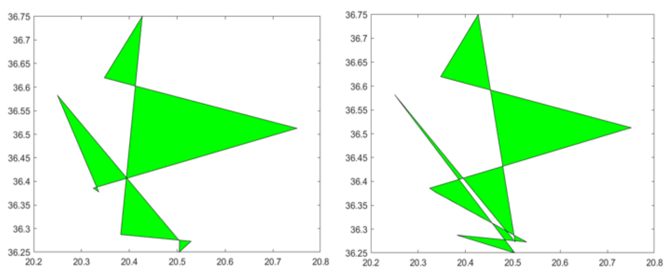

Figure 2. The first and last generation search paths

Finally, we run the code and get the final result of 291.29KM, which means that the shortest path is 291.29KM. it is much shorter than the 1013.45KM of the original result. This means less time spent searching and rescue, and at the same time, a higher chance of success.

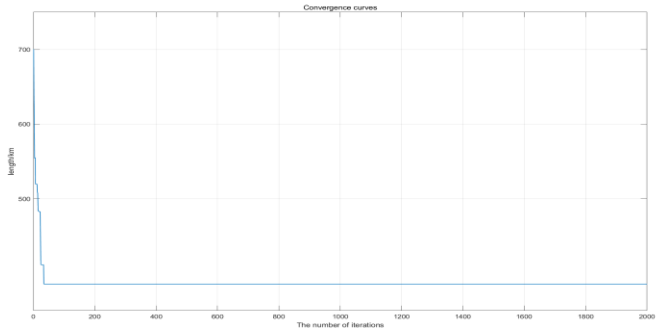

Figure 3. Convergence curves

After the submersible malfunctioned, we cannot immediately carry out rescue, so the above model needs to be used to predict the possible location of the submersible and then search and rescue. The rescue process is roughly divided into three steps, first of all, the main ship needs to release the active sonar search system, which is assisted by the corresponding equipment to complete the range search of the area where the submersible can appear the most, of course, this is the step required after the GPS positioning fails. Second, we verify the position of the submersible through small unmanned underwater vehicles, which should be scattered throughout the sea surface as needed, and set up corresponding supply stations, when the main ship receives the sonar signal, the unmanned underwater vehicle will go to the location point for search and rescue [4].

When the predicted position changes over time, the search range of the main ship is also corrected.

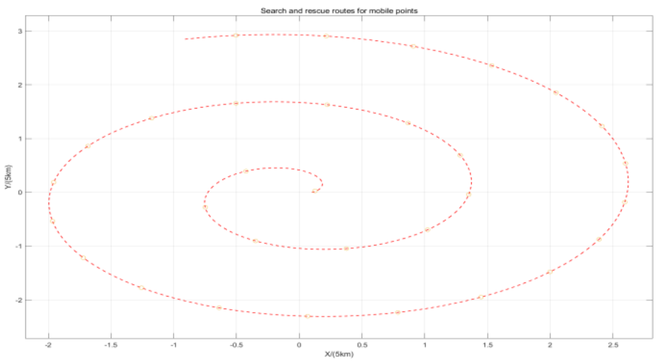

Figure 4. Search and rescue routes at stationary points

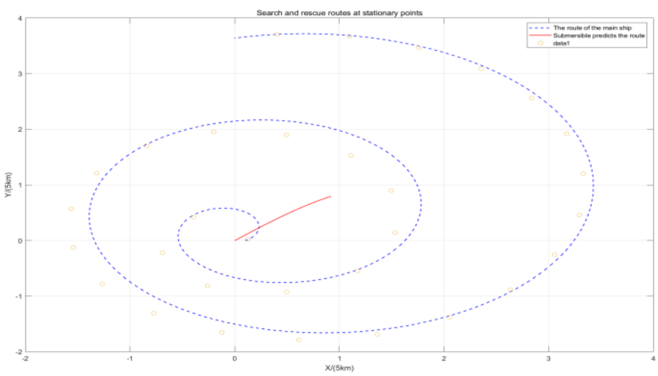

Figure 5. Search and rescue routes for mobile points

C. The Solution of Model 3

A dynamic model is established in MATLAB, which indicates that the prediction error is within the acceptable range and beyond the acceptable range.

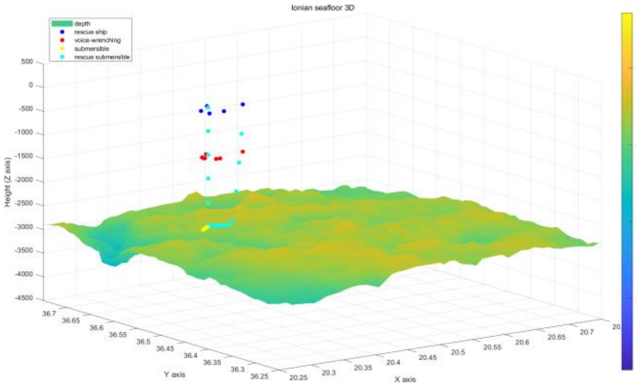

Figure 6. The forecast error is within acceptable limits

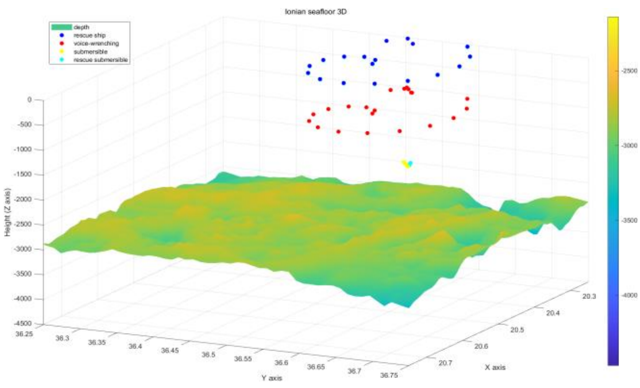

Figure 7. The prediction error is beyond the acceptable range

D. About the Extension of Model

As I said in the review, this rescue solution is highly adaptable and can deal with different terrain and emergencies, and only needs to obtain seabed data from the sea area to be studied and model the 3D surface, such as the Caribbean Sea.

First, we set up 100 linear interval points to create a grid, randomly generate the positions of the main ship and submersible, and then calculate the distance from each submersible to each ship through a weighted distance matrix. The Hungarian algorithm (a complex optimization algorithm used to solve the optimal matching problem) is implemented to find the optimal pairing of submersibles and vessels. The maximum rescue distance is updated according to the optimal pairing.

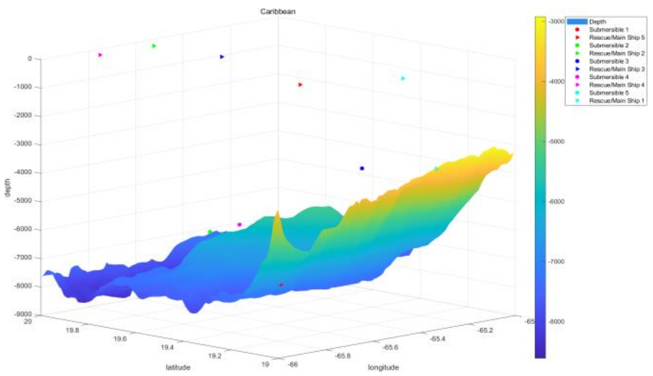

Figure 8. Expansion forecast

E. Sensitivity Analysis

In order to identify and capture the sensitivity of the optimal path planning in the process of identifying and capturing the submersible using the traveling salesman model and the genetic hybrid algorithm, this section analyzes the sensitivity of the model by increasing the number of possible locations of the submersible in the sea, that is, changing the population size parameter of the genetic algorithm. The changed parameter data are shown in the table below.

Table 2. Reference data table

model algorithm	population size	crossover probability	probability	iterations
TSP+GA	150	0.95	0.1	2000
TSP+GA	200	0.95	0.1	2000
TSP+GA	250	0.95	0.1	2000
TSP+GA	300	0.95	0.1	2000

The reason for only considering the increase rather than the decrease is to reflect that in the worst case, i.e. identifying and fishing the location of the submersible and exploring the possible location points are too many.

Therefore, re-simulate the calculation results to obtain four groups of curves, as shown in the following figure.

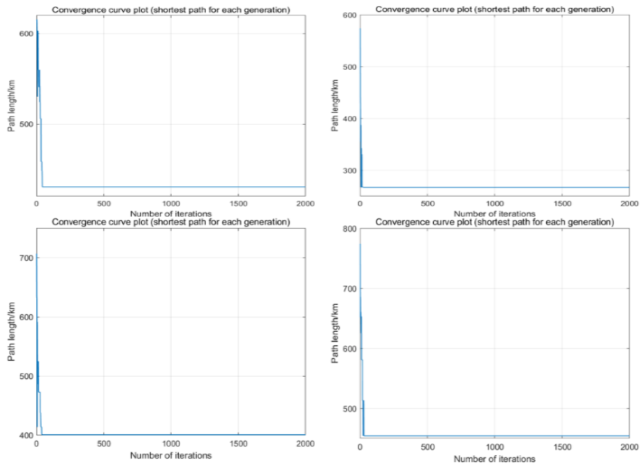

Figure 9. Convergence curve (shortest path)

Finally, total energy consumption usually refers to the total amount of electrical energy consumed by the system to complete a certain amount of computing tasks or a certain period of time, usually in kWh. In a connected car environment, low energy consumption means that the system can use batteries or other energy sources more efficiently, reducing operating costs. Following Table 2 compares the energy consumption in identical processing situation.

4. Conclusions

This study provides a comprehensive solution from submarine fault to location, identification and rescue. By using the high-resolution submarine terrain data provided by GEBCO 2023, a detailed three-dimensional terrain model of the Ionian Sea has been established. Then, the Markov chain Monte Carlo method is used to simulate the probability distribution of the possible position of the lost submersible to provide specific guidance for rescue operations.

When faced with multiple possible underwater vehicle locating points, the problem is transformed into a traveling salesman problem, which can be optimized by genetic algorithm to find the shortest identification path. In addition, combined with the dynamic model of the search and rescue process, including the search path of the rescue ship/main ship on the sea surface (such as the spiral path) and the dynamic relationship between the rescue submersible and the wrecked submersible. The model considers various possible rescue scenarios, predicts the success rate of rescue in different situations, and provides theoretical guidance and strategic choices for actual rescue operations. The successful implementation of this step can reduce the search and rescue time and improve the search and rescue efficiency.

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Сүңгуір қайықтардың рельефін модельдеу негізінде су астындағы кемелерді құтқарудың оңтайлы жолын жоспарлау бойынша зерттеулер

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Аңдатпа. Терең теңіз туризмін барлау процесінде күрделі және үнемі өзгеріп отыратын су асты ортасына байланысты суасты қайықтарына табиғи апаттар, теңіз суының қысымы және теңіз түбінің рельефі әсер етуі мүмкін, нәтижесінде саяхат кезінде байланыс үзіліп, механикалық ақаулар туындап, персоналға зиян келтіруі мүмкін. суға батып, туристік компанияға үлкен шығын әкелді. Терең теңіз туризмі кезінде суасты қайықтарын барлау кезінде қауіпсіздік мәселелерін шешу үшін. Бұл зерттеу мысал ретінде Иной теңізін алады. Адамдар суға батып бара жатқанда теңіздегі туризмді барлау кезінде ақауларға тап болады деп есептесек, шұғыл құтқару қажет. Біріншіден, біз GEOCO 2023-тен жоғары ажыратымдылықтағы су асты рельефі деректерін алдық және Matalab бағдарламалық құралын пайдалана отырып, егжей-тегжейлі үш өлшемді су асты рельефінің моделін құрдық. Іздестіру-құтқару процесінде су астындағы кемені іздестіру үшін құтқару кемесінің сонары пайдаланылды, ал су астындағы кеменің ең ықтимал орналасуы мен ықтималды таралуын болжау үшін Markov Chain Monte Carlo (MCMC) әдісі қолданылды. Орналасқан жер мен ықтималдықты тарату деректерін өңдеу үшін саяхатшы сатушы мәселесін генетикалық алгоритммен біріктіру арқылы ең қысқа жолды табуға болады. Сонымен бірге біз құтқару процесінің динамикалық моделін құрдық, бұл құтқару кемесіне теңіздегі іздестіру және пайдалану жолдарының (мысалы, спиральды жолдар) тиімділігін арттыруға мүмкіндік береді және құтқару суасты және зақымдалған суасты құралы арасындағы динамикалық қатынасты көрсетеді.

Негізгі сөздер: *Марков тізбегі Монте-Карло, генетикалық алгоритм (GA), саяхатшы сатушы мәселесі (TSP), ең қысқа жолды жоспарлау.*

Исследование оптимального планирования пути спасения подводных лодок на основе моделирования подводной местности

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Аннотация. В процессе освоения глубоководного туризма из-за сложной и постоянно меняющейся подводной среды подводные лодки могут подвергаться воздействию стихийных бедствий, давления морской воды и топографии морского дна, что приводит к перебоям связи и механическим сбоям во время плавания, причиняя вред личному составу. в подводном аппарате и причинил огромные убытки туристической компании. В целях решения вопросов безопасности при глубоководном туристическом освоении подводных лодок. В данном исследовании в качестве примера взято Инойское море. Если предположить, что люди сталкиваются с неисправностями во время глубоководных туристических исследований во время поездки на подводном аппарате, требуется немедленная помощь. Во-первых, мы получили данные о подводной местности в высоком разрешении от GEOCO 2023 и создали подробную трехмерную модель подводной местности с помощью программного обеспечения Matalab. В ходе поисково-спасательных работ для поиска подводного аппарата использовался гидролокатор спасательного судна, а для прогнозирования наиболее вероятного положения и распределения вероятностей подводного аппарата использовался метод Марковской цепи Монте-Карло (MCMC). Объединив задачу коммивояжера с генетическим алгоритмом для обработки данных о местоположении и распределении вероятностей, можно найти кратчайший путь. В то же время мы также создали динамическую модель процесса спасения, позволяющую спасательному судну максимизировать эффективность путей морского поиска и операций (например, спиральных путей) и отражать динамическую взаимосвязь между спасательным подводным аппаратом и поврежденным подводным аппаратом.

Ключевые слова: *Цепь Маркова Монте-Карло, генетический алгоритм (GA), задача коммивояжера (TSP), планирование кратчайшего пути*.

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