

# An A\*-based bacterial foraging optimisation algorithm for global path planning of unmanned surface vehicles

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## 1. Introduction

The development and application of freshwater and marine areas is becoming increasingly extensive. Owing to the special working requirements of water, most water operations need to be accomplished by ships. Unmanned surface vehicles (USVs), with the advantages of flexible controllability, strong autonomy and field operation, have been widely applied in the civil and military fields, such as maritime cruise ships, emergency rescue activities, lake patrols and hydrological monitoring (Thomas et al., 2008; Liu et al., 2015; Nad et al., 2015; Nikola et al., 2015; Liu and Bucknall, 2016; Ma et al., 2016).

In order to guide a USV through a cluttered environment, planning a high-quality and collision-free path is a critical part during the USV's voyage (Perera et al., 2015). Particularly, path planning is an important technology in the application of the USV's intelligent control and an indispensable part of driverless technology, which not only determines the level of autonomy of the vehicle but also premises the reliability of a mission and the likelihood of success. Fundamentally, USV path planning is a branch of classical robot tracing, which mainly concerns two factors: the total path distance and safety (Zheng et al., 2014). In addition, the quality of the generated trajectory, such as smoothness and continuity, also needs to be taken into account (Smierzchalski, 1999).

Path planning technologies can be generally divided into two groups: the pre-generative approach (static planning) and the reactive approach (dynamic planning) (Liu and Bucknall, 2015). Shi et al. (2019) focused on the smoothness and seaworthiness properties of the path. A hybrid A\* algorithm with motion primitive constraints is proposed to generate an initial reference path. In order to optimise the path, a number of computational intelligent algorithms have been applied. A genetic algorithm (GA) is used to determine the optimised path for a USV under environmental loads in Kim et al. (2017). The optimised paths are determined by numerical simulations. An approach of fast path planning based on a Voronoi diagram and an improved GA has been proposed in Cao (2015). Furthermore, as a branch of intelligent

algorithms, the swarm intelligence algorithm plays an important role in research on USV global path planning. Song et al. (2015) proposed a method for USV global path planning based on particle swarm optimisation. By using typical obstacle modelling and the ant colony algorithm (ACO) for global path planning, the USV global path was achieved in Wang and Chi (2016). Song (2014) improved the ACO-based grid environment model for USV global path planning. Meanwhile, some works have been done to combine various intelligent swarm algorithms for USV global path planning. For example, in Hu et al. (2015), both GA and ACO are used to generate an initial pheromone distribution and carry out dynamic integration of genetic operators, which not only can improve the convergence rate of the algorithm, but also can solve the problem of precocious and poor global search ability.

The bacterial foraging optimisation (BFO) algorithm is a new bionic algorithm, which has become another hotspot in the field of heuristic computing. Owing to its advantages, such as parallel searching of the swarm intelligence algorithm and ease of jumping out from local minima, it has attracted more interest. At present, BFO has been successfully applied in many fields, such as image processing (Madhubanti and Chatterjee, 2008; Nandita et al., 2011; Rajinikanth and Couceiro, 2014), shop scheduling (Wu et al., 2007; Raj and Priya, 2013; Cheng et al., 2015; Li et al., 2015; Zhao et al., 2015), robotics (Jati et al., 2012; Mickael et al., 2012; Yang et al., 2012; Liang et al., 2013; Frantisek et al., 2014), etc.

### 1.1. Contributions of this paper

This paper proposes a more efficient grid partition-based hybrid BFO path planning method, named AS-BFO, by integrating the A\* algorithm to enhance the conventional BFO algorithm, thus solving the issue of the generation of a discontinuous path. The main contributions of this paper are listed below:

- (1) The bacterial foraging optimisation algorithm is improved and applied in USV global path planning under the grid environment.
- (2) The cost function of the A\* algorithm is integrated into the tumble motion, which solves the problem of repairing a discontinuous path.
- (3) The relative optimal parameter combination is obtained and it makes the AS-BFO algorithm run effectively in different working environments.

The rest of the paper is organised as follows. Section 2 describes the basic steps of the BFO. Section 3 establishes an environmental model and introduces the AS-BFO for our problem. At the same time, a repellent signal is also released to warn other bacteria to keep a safe distance from itself. To gather information, corresponding methodologies (early detection architecture) are used, in which the information gathered through an intuitive and broad approach is assigned to previously defined subject areas. The parameter combination simulation and the optimal parameter combination are obtained, and the sensitivity analysis of AS-BFO parameters is carried out in Section 4. GA, ACO and AS-BFO are selected for comparison in different experimental environments. Section 5 concludes this work.

## 2. Description of BFO

BFO is a global random searching algorithm, whose operation aims to simulate the physiological behaviour of *Escherichia coli* bacterium in the process of foraging behaviour, the modelling iteration producing the optimal solution. The cost function of the A\* algorithm is integrated into the tumble motion, which solves the problem of repairing a discontinuous path. The BFO consists of three principal mechanisms to find the relative optimal solution: chemotaxis, reproduction and elimination–dispersal, each of which is detailed below (Passino, 2002; Kushwaha et al., 2012; Hossain and Ferdous, 2015; Zhao and Wang, 2015).

In biology, the movement of bacteria is called chemotactic behaviour, and there are two types of chemotaxis of bacteria: swim and tumble/rotate. The cost function of the A\* algorithm is integrated into the tumble motion, which solves the problem of repairing a discontinuous path. Swimming is the motion of bacteria forwards along the same direction as the last stage; rotation is the bacteria staying in the same position and rotating itself into a new direction. These two chemotactic operations guarantee that bacteria search the problem space as well as avoid obstacles in the searching process. The new position of the

bacteria after chemotaxis can be obtained by

$$\theta^i(j, k, l) = \theta^i(j + 1, k, l) + C(i) \frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}, \quad (1)$$

where  $\theta^i(j, k, l)$  represents the bacterium  $i$  in the  $j$ th chemotaxis,  $k$ th reproduction and  $l$ th elimination–dispersal step,  $C(i)$  denotes the size of chemotaxis during each swim or tumble, and  $\Delta(i)$  is the direction vector of the  $j$ th chemotactic step. Finally,  $\Delta(i)$  is a random direction vector with a range of  $[-1, 1]$ .

*Scanning is a validation activity. In the iPeM, validation is understood as a basic activity of product engineering and is the only activity that generates knowledge. Scanning is used to detect indicators for the future environment through comprehensive and undirected screening if no or only very vague information regarding changes in future development is available. To gather information, corresponding methodologies (early detection architecture) are used, in which the information gathered through an intuitive and broad approach is assigned to previously defined subject areas.*

During cell-to-cell communication, when each bacterium moves, it releases attractant to signal other bacteria to swarm towards it. At the same time, a repellent signal is also released to warn other bacteria to keep a safe distance from itself. Such a communication mechanism is also simulated by representing the combined cell-to-cell attraction and repulsion, which can be expressed by

$$\begin{aligned} J_{cc}(\theta^i(j, k, l), \theta(j, k, l)) &= \sum_{i=1}^S J_{cc}^i(\theta^i, \theta) \\ &= \sum_{i=1}^S \left[ -d_{\text{attract}} \exp \left( -\omega_{\text{attract}} \sum_{m=1}^D (\theta_m - \theta_m^i)^2 \right) \right] \\ &\quad + \sum_{i=1}^S \left[ h_{\text{repellant}} \exp \left( -\omega_{\text{repellant}} \sum_{m=1}^D (\theta_m - \theta_m^i)^2 \right) \right], \end{aligned} \quad (2)$$

where  $J_{cc}^i(\theta^i, \theta)$  denotes the object function value, which represents a time-varying objective function,  $S$  represents the total number of bacteria,  $D$  is the number of variables to be optimised, and  $d_{\text{attract}}$ ,  $\omega_{\text{attract}}$ ,  $h_{\text{repellant}}$  and  $\omega_{\text{repellant}}$  are coefficients representing the attractive depth, attractive width, repellent height and repellent width, respectively.

## 2.1. Reproduction

After the chemotaxis, the health status of each bacterium is determined by the sum of the step fitness, i.e.  $\sum_{j=1}^{N_c} J(i, j, k, l)$ , where  $N_c$  is the maximum step in a chemotaxis process. Based on their health status (fitness values), all bacteria are sorted.<sup>1</sup>

## 2.2. Elimination–dispersal

In order to avoid the bacteria becoming stuck around the initial positions or local optima, the elimination–dispersal process is introduced in the BFO. In the elimination–dispersal process, some bacteria are selected, based on a probability  $P_{ed}$ , to be moved to another position within the environment.

## 3. AS-BFO for USV global path planning

The proposed AS-BFO method is detailed in this section. In particular, given a known map with a number of obstacles, the proposed algorithm first grid partitions the given map into an  $n \times n$  grid environment. The parameters of AS-BFO are tightly coupled. The selection of the parameters directly affects the performance of the algorithm. Then, the conventional BFO algorithm is applied to find the optimal path. During the chemotaxis operations of the BFO, each step will be monitored to check whether or not

<sup>1</sup> In the reproduction step, the half of the bacteria with higher fitness values survive and the others are eliminated. And then each surviving bacterium splits into two identical ones. The reproduction process keeps the population of bacteria constant.

the tumbled node is continuous with the previous node as well as the following node. The parameters of AS-BFO are tightly coupled. The selection of the parameters directly affects the performance of the algorithm. If any discontinuous path is identified, the A\* algorithm is employed to repair the discontinuous part. This process will be applied until an optimal solution is found. The final optimal solution will be the best path for the given map. The flowchart of the proposed method is shown in Figure 1, and the key components are detailed below.

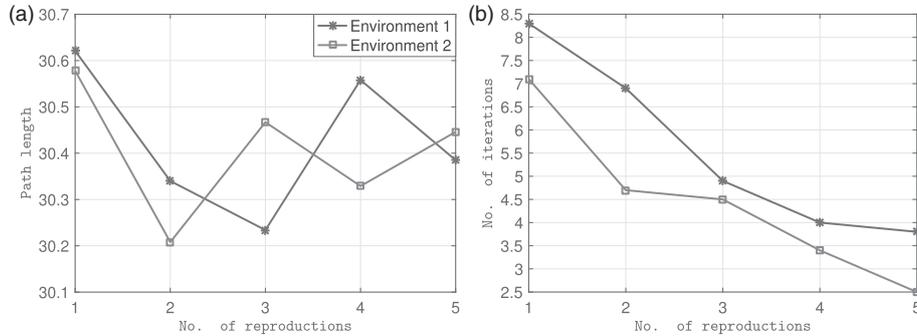


Figure 1. Flowchart of AS-BFO

The grid method is an effective modelling method. The method is easy to construct, modify and simulate the geographical environment. The grid map not only can simulate relatively accurate environmental information for the USV, but also can provide simulation environments of different sizes and complexity for algorithm experiments. This provides a good basis for analysing the performance of the algorithm.<sup>2</sup> Electronic charts can provide map information for USVs, but such maps are less flexible than grid maps. The parameters of AS-BFO are tightly coupled. These two chemotactic operations guarantee that bacteria search the problem space as well as avoid obstacles in the searching process. The selection of the parameters directly affects the performance of the algorithm. A cellular grid map is also applied to the study of global path planning. However, in cellular grid maps, the minimum steering angle can only reach  $60^\circ$ , so the grid map has an advantage in steering angle. USVs usually work in vast stretches of water.

The work environment can be considered as a two-dimensional space with static obstacles. Therefore, the working environment of a USV can be gridded. In the general analysis, if obstacles occupy less than one grid, it will be considered as one whole grid (Yang et al., 2012). Thus, it will establish a one-to-one correspondence between the grid number and the two-dimensional coordinates. These two chemotactic operations guarantee that bacteria search the problem space as well as avoid obstacles in the searching process. The data structure of the algorithm is a nine-square graph centred on the current node, with a total of eight adjacent nodes. The following node must be chosen from these eight neighbours. In the  $n \times n$  grid environment.

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- The cost function of the A\* algorithm is integrated into the tumble motion, which solves the problem of repairing a discontinuous path.
- The relative optimal parameter combination is obtained and it makes the AS-BFO algorithm run effectively in different working environments.

where  $\text{mod}(\cdot)$  is the remainder operation and  $\text{ceil}(\cdot)$  rounds an element to the nearest integer towards positive infinity. As mentioned above, the goal of path planning is to find an ordered grid with the shortest distance among feasible ordered grids.

<sup>2</sup> The electronic chart is a digital chart that is a type of map model for USV global path planning.

### 3.1. Coding method

The population described in this paper consists of a limited number of bacteria. Each bacterium is connected by a series of nodes. One bacterium represents a feasible path. It should be noted that, owing to the randomly generated paths being composed of different numbers of nodes, the lengths of the paths are not uniform. Therefore, variable length bacteria are used to represent individuals. Figure 2 shows a path and its corresponding bacterium.

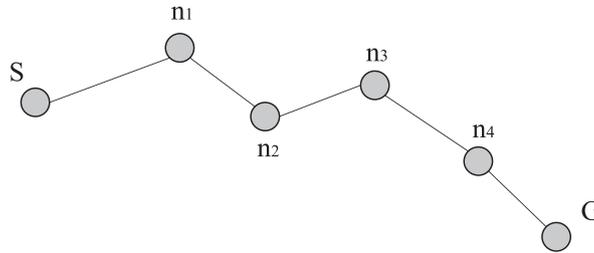


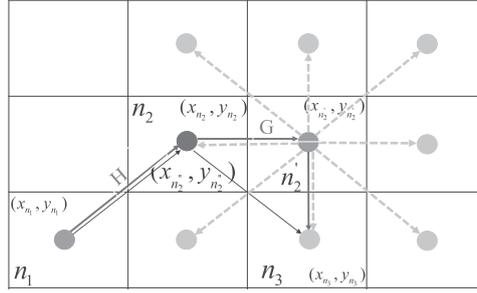
Figure 2. A feasible path

This paper defines the chemotaxis operation of BFO in the grid environment. Chemotaxis in traditional BFO means that any nodes will tumble and swim in any direction. However, some tumbling motions can result in discontinuous paths in the grid environment. Therefore, AS-BFO improves the chemotaxis operator. Firstly, it judges whether the tumbled nodes are continuous with the previous and the following nodes. Then, the discontinuous paths are repaired using the A\* algorithm.

*Monitoring is a targeted search for in-depth information on the development of previously identified indicators for the future environment that are potentially relevant for the company's own process and system development. By systematic and continuous observation of selected indicators during development, monitoring enables the early, cross-generational recognition of changes in future development and thus supports the definition and introduction of suitable actions.*

Currently, monitoring is mainly used to update company strategies. However, it is useful to make it available for the cross-generational product development approach to make the process agile and adaptive. Boundary conditions, objectives and requirements are often uncertain and vague in the early stages. The closer the product comes to market launch, the clearer but also more restrictive these become. Monitoring should be used to identify and take account of changes as early as possible. This should involve a two-way networking of the information flow with feedback between the boundary conditions and premises derived from the foresight and the solutions being developed for the various product generations to check their validity. This requires the definition of indicators that enable targeted and comprehensible monitoring of individual aspects for all generations in different stages of a product. These are defined within the activity scanning and could be, for example, changed trends or adapted laws that significantly influence a specific product characteristic. If a change with an impact on the underlying environment, technology or product scenarios is identified at a certain time, it is necessary to assess whether this has a relevant impact on the properties and design of the product generations currently under development. If this is the case, its extent must be assessed and the various options for action must be weighed up for a decision. A decision could also be to launch the next generation as planned as changes would take too much time to implement but consider the new information to adapt further generations that are already in development. When the chemotaxis operator is performed, the following situations are possible. Firstly, after the node is tumbled, the tumbled node is continuous with its previous and following nodes, as shown in Figure 3. These can be trends, prognoses or laws, for example, which must be linked to the product properties. Trend radars, the development of certain competitors' products, technological developments and social debates on specific topics are possible points of reference. The initial search is undirected but may be based on the underlying scenarios. In strategic foresight, there exist approaches and methods. If  $n_2$  is a tumble node, it can be randomly tumbled to the adjacent free grids. Taking Figure 3 as an

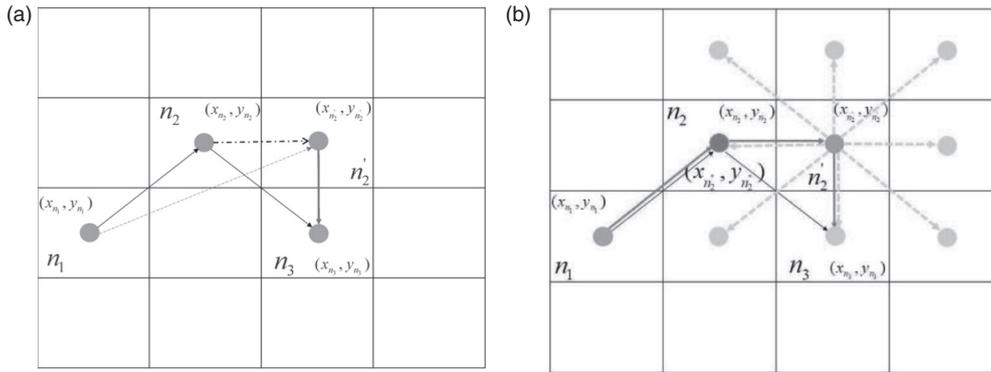
example,  $n_2$  tumbles to  $n'_2$ . Then, according to Equation (4), it is judged whether  $n_1$  and  $n'_2$ ,  $n'_2$  and  $n_3$  are, respectively, continuous. If  $\Delta = 1$ , then  $n_1$  and  $n'_2$ ,  $n'_2$  and  $n_3$  are continuous; otherwise, they are not:



**Figure 3. Schematic diagram of continuous nodes**

Here  $(x_{tumbled}, y_{tumbled})$  are the horizontal and vertical coordinates of the tumbled node ( $n'_2$ ) and  $(x, y)$  are the horizontal and vertical coordinates of the previous or the following node ( $n_1, n_3$ ). The path after the tumble motion is marked by the red line.

Secondly, it is discontinuous with the previous or the following node, when the node is tumbled. As shown in Figure 4(a),  $n_2$  is used as the tumble node. So  $n_2$  is tumbled to  $n'_2$ , and then it is judged whether  $n_1$  and  $n'_2$ ,  $n'_2$  and  $n_3$  are, respectively, continuous. It can be observed that  $n'_2$  and  $n_3$  are continuous; however,  $n'_2$  and  $n_1$  are not continuous. At this time, the evaluation function of the A\* algorithm is applied to the tumble motion, and the problem of repairing the discontinuous path has been solved. Figure 4(b) shows that there are many repaired nodes around  $n'_2(x, y)$ , and the yellow nodes are repaired nodes.



**Figure 4. Schematic diagram of discontinuous nodes. (a) Intermittent path, (b) Patching path**

A repaired node will be selected depending on Equations (5)–(7):

$$F_{\min} = G + H, \quad (3)$$

$$G = \sqrt{(x'_{tumbled} - x''_{tumbled})^2 + (y'_{tumbled} - y''_{tumbled})^2}, \quad (4)$$

$$H = \sqrt{(x - x''_{tumbled})^2 + (y - y''_{tumbled})^2}. \quad (5)$$

Here  $(x, y)$  represents the coordinates of the previous node,  $(x'_{tumbled}, y'_{tumbled})$  denotes the coordinates of a node after it has been tumbled, and  $(x''_{tumbled}, y''_{tumbled})$  indicates the coordinates of the repaired nodes. As shown in Figure 4(b), we use  $(x''_{n'_2}, y''_{n'_2})$  as the coordinates of the repaired node. When the discontinuous path is repaired, it is represented by the red line. Although the path increases slightly, this method solves the problem that the path is discontinuous after the node is tumbled.

This paper introduces a novel methodology for analyzing the spatial distribution and co-presence of objects within home interiors utilizing graphs. This approach entails constructing a graph where nodes represent individual objects, such as furniture or decor, and edges denote these objects' co-presence or

relational adjacency within a given space, such as a specific function of an entire home. The weight of each edge corresponds to the frequency or significance of the co-presence of the connected objects. This method facilitates an analysis of object-to-object relationships and their centrality within the domestic environment. A quantified domestic activities trend is enabled where traditionally invested based on the attributes of the physical environment, such as size, connectivity, and layout of the homes. In this graph, unique object pairs are extracted to ensure no repetition of objects within a single graph representation. Finally, the tumbled node is discontinuous with the previous node and the following node after the node is tumbled. Then, the repaired point can be found by Equations (5)–(7) so that the path is continuous. Note that we need to use the evaluation function of the A\* algorithm twice in this condition. The method to deal with discontinuity with the previous and the following nodes is the same as the above method. Therefore, an effective method to repair discontinuous paths is proposed, which ensures that each tumble can be performed efficiently.

### 3.1.1. Reproduction

When the chemotaxis operation is completed, the path length represented by each bacterium is sorted. The half of the bacteria with longer paths are eliminated, and the half of the bacteria with shorter paths are reproduced. Thus, bacteria number is kept unchanged.

### 3.1.2. Elimination–dispersal

When the reproduction operation is completed, a random probability  $P_r$  is generated and compared with the fixed migration probability  $P_{ed}$ . If  $P_r < P_{ed}$ , the bacterium is dispersed. This operation can reduce the possibility of bacteria falling into a local optimal solution. It can also be a good solution for maintaining diversity.

## 3.2. Algorithm description

In this algorithm, the path optimisation problem is encoded. One feasible path represents one bacterium. The initial population is usually randomly generated without infeasible paths, which can reduce the blindness of initial population generation. Among the three main operators in the algorithm, the chemotaxis operator can improve the local search accuracy of bacteria, the reproduction operator can increase the convergence performance of bacteria, and the elimination–dispersal operator can increase the diversity of solutions. The parameters of AS-BFO are tightly coupled. The selection of the parameters directly affects the performance of the algorithm. At present, there is no perfect theoretical basis to determine the optimal combination parameters. The traditional method is repeated trials to obtain the relative optimal combination of parameters.

## 4. Analysis of results

It is very important for the application of AS-BFO in practical problems to study the parameters of population size, chemotaxis number, replications number and elimination–dispersal number. However, the setting of the parameters mainly depends on the statistical data and simulation experiment. This paper studies the path planning in two different environments, in which the islands represent the obstacles.

### 4.1. Experiment 1

Different parameter settings may lead to different performances. In this experiment, different parameters are applied in the proposed method, in order to compare the performances generated by different parameter settings.

#### 4.1.1. Population number

In this experiment, the chemotaxis number  $N_c = 5$ , reproduction number  $N_{re} = 2$  and elimination–dispersal number  $N_{ed} = 2$  are fixed, and the population number  $P$  is selected to be 10, 20, 30, 40, 50, 60, 70 and 80, respectively. The results show that the greater the number of bacteria, the faster the convergence rate.

#### 4.1.2. Chemotaxis number

The chemotaxis operator is an important operator of AS-BFO, and the chemotaxis number directly affects the local optimisation ability of the algorithm. In this simulation experiment,  $P = 50$ ,  $N_{re} = 2$  and  $N_{ed} = 2$  are fixed, and the chemotaxis number is set to  $N_c = 1, 2, 3, 4, 5, 6, 7$  and  $8$ . For environment 1, when  $N_c = 7$ , the path is the shortest. When  $N_c = 8$ , the number of iterations is the least. For environment 2, when  $N_c = 8$ , the path is the shortest. When  $N_c = 6$ , the number of iterations is the least.

#### 4.1.3. Reproduction number

The reproduction operator reduces population diversity and increases the convergence rate of the algorithm. In the simulation experiment,  $P = 50$ ,  $N_c = 5$  and  $N_{ed} = 2$  are fixed, and the reproduction number is set to  $N_{re} = 1, 2, 3, 4$  and  $5$ . For environment 1, when  $N_{re} = 5$ , the path is the shortest. When  $N_{re} = 4$ , the number of iterations is the least. For environment 2, when  $N_{re} = 2$ , the path is the shortest. When  $N_{re} = 5$ , the number of iterations is the least.

#### 4.1.4. Elimination–dispersal number

The elimination–dispersal operator is designed to improve global optimisation and maintain the diversity of solutions. As the outermost nesting of the algorithm, the elimination–dispersal number directly affects the algorithm running time. In the simulation experiment,  $P = 50$ ,  $N_c = 5$  and  $N_{re} = 2$  are fixed, and reproduction number varies as  $N_{ed} = 1, 2, 3, 4$  and  $5$ . For environment 1, when  $N_{ed} = 3$ , the path is the shortest. When  $N_{ed} = 5$ , the number of iterations is the least. For environment 2, when  $N_{ed} = 4$ , the path is the shortest. When  $N_{ed} = 4$ , the number of iterations is the least. There are four uncertain parameters, population number  $P$ , chemotaxis number  $N_c$ , reproduction number  $N_{re}$  and elimination–dispersal number  $N_{ed}$ , involved in the proposed model. Table 1 shows the sampling ranges of each parameter during the sampling processes of the Morris method. As demonstrated above, different values

**Table 1. Sampling range of each parameter**

Parameter	Range
Population number ( $P$ )	$P \sim (10, 100)$
Chemotaxis number ( $N_c$ )	$N_c \sim (2, 12)$
Reproduction number ( $N_{re}$ )	$N_{re} \sim (1, 8)$
Elimination–dispersal number ( $N_{ed}$ )	$N_{ed} \sim (1, 10)$

of parameters lead to completely different results. The most influential parameters are identified by sensitivity analysis (SA), as well as to understand their impact on the model output. For this reason, the Morris method (Cadero et al., 2018) is applied to develop the parameter sensitivity analysis. Briefly, the Morris method involves the generation of uncertain parameter samples via a trajectory-based sampling process. The method calculates and evaluates the standard deviation  $\sigma_i$  of the elementary effects  $\mu_i$ , where  $i$  is the  $i$ th date sample, over  $r$  repetitions to assess the factors' importance. A high value of  $\mu_i$  indicates a high linear effect for a given factor, while a high value of  $\sigma_i$  represents either nonlinear or non-additive factor behaviour. The importance of input factors of the model can often be assessed by plotting the factors  $(\mu^*, \sigma)$ , where  $\mu^*$  is the mean of  $\mu_i$  in two-dimensional space. The factors closest to the origin are less influential.

Preliminary conversations with stakeholders in Trondheim highlighted that the context of work migrants in the building and construction industry is not completely understood or clearly communicated, which makes it difficult to propose new strategies to combat modern slavery and inadequate work and housing conditions. The comprehensive representation of stakeholders was unclear, and there is no regional policy for providing inclusive housing for work migrants, even though the city has established inclusive housing strategies specifically for refugees. Our aspiration was that design could help illustrate the full picture, identify new areas of intervention, and see new possible connections that can propose a new future of how to regard housing for work migrants in the city.

## 4.2. Parameter sensitivity analysis

In this experiment, the Morris method runs a model with five factors along four trajectories, and a total of 20 samples have been extracted, as listed in Table 2. Each generated data sample is applied as the input to the proposed method 10 times to get an average optimal path length. According to the Morris method, the corresponding standard deviation  $\sigma$  and its elementary effects  $\mu$  for each trajectory can be calculated, shows the sensitivity of each parameter in the environmental map of different sizes. In addition, the  $(\mu^*, \sigma)$  is also plotted in a two-dimensional plot, for parameter importance analysis. It is clear that parameter 3 ( $N_{re}$ ) and parameter 4 ( $N_{ed}$ ) are away from the origin, which indicates that those parameters are the most important. Within several stages of the framework, the interpretation of multiple data streams in mixed formats is pivotal. The effectiveness of this will rely on the ability to interpret the data streams, which will rely on the expertise at hand, the computational resource available, data storage facilities, the data stream quality, applicability, and suitability to the problem amongst other factors. This also plays into the balancing of a mixed-method approach. As illustrated in Section 4, the quantification of human preferences could potentially remove the nuances, and the incorporation of qualitative feedback in a computational space is challenging.

**Table 2. Extracted samples**

Factor	Trajectory 1 ( $P, N_c, N_{re}, N_{ed}$ )	Trajectory 2 ( $P, N_c, N_{re}, N_{ed}$ )	Trajectory 3 ( $P, N_c, N_{re}, N_{ed}$ )	Trajectory 4 ( $P, N_c, N_{re}, N_{ed}$ )
1	(63,2,3,7)	(100,2,8,3)	(10,5,6,10)	(30,2,1,10)
2	(63,5,3,7)	(100,9,8,3)	(10,2,6,10)	(30,5,1,10)
3	(30,5,3,7)	(100,9,8,7)	(10,2,6,1)	(63,5,1,10)
4	(30,5,3,1)	(10,9,8,7)	(30,2,6,1)	(63,5,6,10)
5	(30,5,1,1)	(10,9,6,7)	(30,2,8,1)	(63,5,6,3)

The performance of the proposed method is evaluated and validated in this section. Generally speaking, GA and ACO are adopted to against the proposed approach. Likewise, we first obtain the relative optimal parameters of ACO and GA through repeated experiments in the S3 environment, and then apply the parameters to other environments. In order to evaluate the performance of each method under different environments, the simulated environments, are grid partitioned into five different size, denoted as: S1,  $10 \times 10$ ; S2,  $15 \times 15$ ; S3,  $20 \times 20$ ; S4,  $25 \times 25$ ; and S5,  $30 \times 30$ . Each size is considered as an individual scenario. In each environment, the ratio of the obstacle area to the entire map area is approximately equal. The experimental results of three approaches under five different sizes are listed shows the relative optimal paths of the two environments in the five size maps.

From Table 1, we can see that the AS-BFO has a better average path length using a very small iteration number. Moreover, the maximum path length obtained by AS-BFO is less than ACO and GA in the 20 repeated experiments. In S1, S2 and S3, AS-BFO's AIN has a great advantage. However, the advantages in MaxPL, MinPL and APL are not obvious. In S4, the advantage of AS-BFO's AIN is still obvious. It is worth noting that AS-BFO's MaxPL is 24.39 (32.04) smaller than ACO and 6.83 (5.07) smaller than GA. AS-BFO's MinPL is 6 (14.49) smaller than ACO and 1.76 (0.59) smaller than GA. In S5, the advantages of MinPL's AIN are equally obvious. AS-BFO's MaxPL is 76.67 (53.01) smaller than ACO and 17.66 (12) smaller than GA. The MinPL of AS-BFO is 40.39 (57.93) smaller than ACO and 3.76 (2.58) smaller than GA. Analysis shows that the larger the map size  $L$ , the greater the advantage of AS-BFO. Therefore, AS-BFO is superior to GA and ACO in searching efficiency and obtaining an optimal solution.

## 5. Conclusions

This paper proposes a more efficient path planning method based on the AS-BFO algorithm. The effects of bacteria number, chemotaxis number, reproduction number and elimination–dispersal number on the global path planning are analysed. Through experimental analysis, bacteria number is inversely proportional to the path length. The greater the chemotaxis number, the stronger is the local optimisation

ability of the algorithm. Correspondingly, the path length and iteration number will decrease. However, the greater the reproduction number, the smaller the diversity of the population and the faster the convergence of the algorithm. The experiments indicate that the increase of elimination–dispersal number will decrease both the path length and iteration number within a certain range. It can be found from the comparison of algorithms that AS-BFO performs better than comparative algorithms in terms of average iteration number, average path, maximum path and minimum path. A parameter sensitivity analysis shows that the effects between the various parameters and the effect of each parameter on the output are different in different environmental maps.

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## Appendix A

AS-BFO's MaxPL is 76.67 (53.01) smaller than ACO and 17.66 (12) smaller than GA. The MinPL of AS-BFO is 40.39 (57.93) smaller than ACO and 3.76 (2.58) smaller than GA. Analysis shows that the larger the map size  $L$ , the greater the advantage of AS-BFO. Therefore, AS-BFO is superior to GA and ACO in searching efficiency and obtaining an optimal solution.