Target Finding and Obstacle Avoidance Algorithm for Microrobot Swarms

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Abstract—Advances in the development of nanotechnology have led to microrobots applications in medical fields. Drug delivery is one of these applications in which microrobots deliver a pharmaceutical compound to targeted cells. Chemotherapy and its side effects can then be minimized. Two major constraints, however, must be considered: the robot’s onboard energy supply and the time needed for drug delivery, which are related to the travel distance of microrobots. Furthermore, a microrobot must avoid biological restricted areas which we treat as obstacles in the path. The main objectives of this work are to find optimal paths to targeted cells and avoid collision with obstacles in the paths. In this study, we control motion of microrobots based on the concept of swarm intelligence. Artificial Bee Colony, the swarm-based optimization method, is employed to implement the collision detection and the boundary distance detection modules. The offline path distance optimization approach is also employed to improve the path planning results. Numerical experiments have been conducted using various obstacle environments that confirm that the proposed approach is successful in avoiding obstacles and optimizing the distance traveled to reach the target.

Keywords - Target Finding and Obstacle Avoiding, Drug Delivery, Microrobotics, Artificial Bee Colony (ABC), Swarm Intelligence, Optimization.

I. INTRODUCTION

Advances in the field of nano- and micro-technology have led to the adoption of microrobots in medical applications, specifically in the field of nano-medicine [1-3]. Microrobots are machines or devices whose components are at or close to the micrometer scale. In a drug delivery process, microrobots may travel inside a blood vessel circuit with the goal of administering a pharmaceutical compound directly onto targeted cells, i.e., cancerous or infected cells. The direct delivery process improves the medical efficacy and minimizes risks introduced by chemotherapy [1]. In optimizing the paths, microrobots have to consider the shortest distance between two points while avoiding obstacles in the paths. Obstacles are biological restricted areas.

Many researchers have addressed the above-mentioned issues. To plan trajectories for a mobile robot in partially known environments, Stentz [4] proposed the “D*” algorithm. “D*” resembles the “A*” algorithm, except that it is dynamic in the sense that the arc cosine parameter can be changed during the search process. Tsuzuki et al. [5] applied the Simulated Annealing (SA) as the path-planning algorithm. The path can be represented linear, Bezier, or interpolated spline trajectories. The Genetic Algorithm (GA) for path planning based on area coverage has also been proposed by Tao and Zhang [6] who used the Online and Offline path planning to select the optimal path.

In recent years, algorithms based on swarm intelligence have been applied to solve the path finding problem. Brand et al. [7] worked with the Ant Colony Optimization (ACO) algorithm, which is inspired by the ant foraging behavior. The ACO can find the shortest and collision free route in a grid network for robot path planning. Obstacles with various shapes and sizes are considered to simulate a dynamic environment in this work. The Particle Swarm Optimization (PSO) algorithm, mimicking a bird flock or a fish school, has also been proposed for path planning by Qin et al. [8], Chen and Li [9], and Zhang and Li [10]. Moreover, to avoid obstacles, self-organized trajectory planning based on PSO has been introduced by Hla et al. [11] who simplified the problem by considering only circular shaped obstacles.

To improve the efficiency of microrobots’ path finding, the quorum sensing technique, which is the ability of bacteria swarms to communicate and coordinate via molecule signaling, has been introduced by Chandrasekaran and Hougen [12].

In this study, we extend the previous work [8,10,11] and find the optimal path with an obstacle avoidance mechanism that considers the travelling distance of the microrobots. The Artificial Bee Colony (ABC) algorithm [13], based on the honeybee foraging behavior, has been employed for path planning. Techniques for collision detection and the boundary distance detection and their avoidance will be described. Finally, the offline path distance optimization approach will be presented.

The paper is organized as follows. Section II describes the framework for microrobotics in drug delivery including the problem statement, microrobots model, microrobots movement, obstacle avoiding techniques, offline path distance optimization, and microrobots control mechanism using ABC algorithm. Section III presents numerical experiments and
discusses simulation results. Section IV summarizes conclusions of the work.

II. FRAMEWORK FOR MICrorOBOTICS IN DRUG DELIVERY

A. Problem Statement

Two major constraints on the microrobots ability for a drug delivery process are considered in this work:

- The robot’s onboard energy supply is limited. Once the available energy has been consumed, the robot can become inactive and thus not deliver the drug to the target.
- Avoidance of the biological restricted areas is mandatory.

In the work described here, the microrobots are assumed to move in a two dimensional rectangular search space under the following assumptions:

- The starting and target positions with respect to a given referenced coordinate system are known.
- Microrobots are not allowed to move outside the blood vessel boundary.
- Microrobots may occupy the same location with respect to the reference coordinate system.
- Microrobots do not have power outage.
- The obstacles in the search space are stationary, and can be described as polygons with boundaries represented by linear equations.

The objective function used in optimizing the path travelling distance as a fitness value is given below:

$$\begin{align*}
\text{Minimize} \ D &= \frac{1}{N} \sum \left( \sum_{s=1}^{S} \sqrt{(x_{i,s} - x_{i,s-1})^2 + (y_{i,s} - y_{i,s-1})^2} \right) \\
&+ \sqrt{(x_t - x_{i,s})^2 + (y_t - y_{i,s})^2} \\
\text{Subject to} \quad \sqrt{(x_t - x_{i,s})^2 + (y_t - y_{i,s})^2} &= 0 \text{ for } i = 1, 2, 3, \ldots N \\
&\text{when } s = S \\
x_{i,b} &< x_{i,s} < x_{i,u} \quad \text{for } i = 1, 2, 3, \ldots N \\
&\text{and} \quad s = 1, 2, 3, \ldots S \\
y_{i,b} &< y_{i,s} < y_{i,u} \quad \text{for } i = 1, 2, 3, \ldots N \\
&\text{and} \quad s = 1, 2, 3, \ldots S \\
d_{i,o,s} &\geq \varepsilon \quad \text{for } i = 1, 2, 3, \ldots N \\
&\text{and} \quad o = 1, 2, 3, \ldots M \text{ for all } s \\
\end{align*}$$

Where

- \( D \) = Sum of distance from starting point to target point for all robots
- \( N \) = Number of robots
- \( S \) = Number of robot’s steps
- \( M \) = Number of obstacles
- \( x_{i,s} \) = \( x \)-coordinate of robot \( i \) at step \( s \)
- \( y_{i,s} \) = \( y \)-coordinate of robot \( i \) at step \( s \)
- \( x_t \) = \( x \)-coordinate of target
- \( y_t \) = \( y \)-coordinate of target

- \( x_{i,b} \) = Lower bound for \( x \)-coordinate in the search space
- \( x_{i,u} \) = Upper bound for \( x \)-coordinate in the search space
- \( y_{i,b} \) = Lower bound for \( y \)-coordinate in the search space
- \( y_{i,u} \) = Upper bound for \( y \)-coordinate in the search space
- \( d_{i,o,s} \) = Distance between robot \( i \) and obstacle \( o \) at step \( s \)
- \( \varepsilon \) = Threshold distance value

B. Microrobots Model

In a microrobot model designed for drug delivery, factors to be considered include the following: how the microrobot is powered, how the microrobot finds the target cells, what are the communication methods, and how microrobots can be removed when the job is finished. This section briefly reviews the technology that can potentially address these questions.

The research reported in [2, 14-16] has suggested the possible sources of energy for microrobots. The adenosine triphosphate (ATP) synthase enzyme, which is applied in rotary bio-molecular motor-powered nano-devices, is one example. Other examples include the remote inductive power presented by Takeuchi and Shimoyama [15], and the use of CMOS for active telemetry and power supply for implanted devices introduced by Sauer et al. [16].

Moreover, chemical and biochemical sensors [2, 3, 6] are required to sense the environment and detect the targets. The microrobots can recognize target cells and obstacles based on these sensors. The sensors will detect changes in volume, concentration, displacement and velocity, pressure, or temperature of cells in order to identify the targets.

RFID (radio frequency identification device) technology [17] has opened up new expectations in the fabrication of nano-devices implanted in the human body. The technology can be used to locate and track objects or even to remotely control human biological functions. RFID is thus often mentioned in microrobots communication methods.

Finally, in order to excrete the microrobots when their task is completed, the microrobots must be created with disposable materials. An alternative is to create a microrobot that can anchor itself to a blood vessel for easy surgical removal [2, 6, 18].

C. Microrobots Movement

The movement of microrobots from one point to another inside the blood vessels can be modeled as shown below.

Let

\( (x_{i,s}, y_{i,s}) \) be the position of robot \( i \) at time step \( s \),

\( \theta_i \) be the angle of rotation of robot \( i \) to align itself towards the target position,

\( v_{i,s} \) be the velocity of a robot \( i \) at time step \( s \), and

\( \Delta t \) be the time step. Then

$$\begin{align*}
x_{i,s} &= x_{i,s-1} + v_{i,s-1} \cos \theta_i \Delta t \\
y_{i,s} &= y_{i,s-1} + v_{i,s-1} \sin \theta_i \Delta t
\end{align*}$$

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D. Obstacle Avoiding Techniques

In real applications, microrobots should be able to detect obstacles along their paths using their chemical and/or biochemical sensors. However, under the simulated environment, there exists the need to design a computational mechanism that allows obstacles to be recognized. In this paper two computational methods are proposed: the collision detection and the boundary distance detection.

1) Collision Detection

To detect a collision between a microrobot and an obstacle, the point of intersection of a robot trajectory with an object boundary is identified. In Fig. 2, the intersected coordinate point \((x_{\text{cross}}, y_{\text{cross}})\) from a microrobot trajectory line and a boundary line of the obstacle is calculated. If this point is located between the lower bound and the upper bound on both of these two lines, the collision is detected. Point \((x_{\text{cross}}, y_{\text{cross}})\) can be calculated as shown below:

\[
x_{\text{cross}} = \frac{-(c_o - c_r)}{m_o - m_r} \quad (4)
\]

\[
y_{\text{cross}} = m_o x_{\text{cross}} + c_o \quad (5)
\]

The robot and the obstacle will collide if the following criterions are satisfied.

\[
(x_{o f 1} \leq x_{\text{cross}} \leq x_{o f 2}) \land (x_{i-1} \leq x_{\text{cross}} \leq x_i)
\]

and

\[
(y_{o f 2} \leq y_{\text{cross}} \leq y_{o f 1}) \land (y_{i-1} \leq y_{\text{cross}} \leq y_i)
\]

2) Boundary Distance Detection

A microrobot is required to have a minimum distance from boundaries of an obstacle. The distance, \(d_{io}\) between a microrobot position and boundary line of an obstacle is given by equation (6).

\[
d_{io} = \frac{|m_{o ub} x_i + c_{o ub} - y_i|}{\sqrt{m_{o ub}^2 + (-1)^2}} \quad (6)
\]

The robot’s current position must satisfy the following criterion:

\[
y_i \geq m_{o ub} x_i + c_{o ub} \land y_i \leq m_{o ub} x_i + c_{o ub}
\]

E. Offline Path Distance Optimization

This section describes a simple algorithm used to optimize the path distance. All positions on the microrobots’ travelling path are analyzed in order to remove unnecessary positions using the pseudo-code below.

for all positions in the path

if \(( (\text{distance}(a, b) + \text{distance}(b, c)) > \text{distance}(a, c) ) \land \text{trajectory}(a, c) \) satisfies the obstacle avoiding constraints

\{
    Delete path\((a, b)\) and path\((b, c)\)
    Add path\((a, c)\)
\}


Fig. 4 illustrates the example paths A and B before and after the path analysis. Paths (a to b) and (b to c) in Fig. A are replaced by the path (a to c) shown in Fig. B to minimize the distance traveled by the microrobot.

Figure 4. Path Optimization

F. Microrobots Control Mechanism Using ABC

The ABC algorithm introduced by Karaboga [13] is one of the popular approaches that has been used to find an optimal solution in optimization problems. This algorithm is inspired by the behavior of honey bees when seeking a quality food source [19]. The performance of ABC algorithm has been compared with that of other optimization methods such as the Genetic Algorithm (GA), the Differential Evolution (DE) algorithm, Evolution Strategies (ES), Particle Swarm Optimization, and Particle Swarm Inspired Evolutionary Algorithm (PS-EA). The comparisons of results [20] for several optimization problems have shown that the ABC algorithm can produce better optimal solutions and thus is more effective than the other methods. The ABC algorithm uses a set of computational agents called honeybees to find the optimal solution. The honey bees can be categorized into three groups: employed bees, onlooker bees and scout bees. Each solution in the search space consists of a set of optimization parameters which represent a food source position. The number of employed bees is equal to the number of food sources. In other words, there is only one employed bee investigating each food source. The quality of food source is called its “fitness value” and is associated with its position.

In the algorithm, the employed bees will be responsible for investigating their food sources (using fitness values) and sharing the information to recruit the onlooker bees. The onlooker bees will make a decision to choose a food source based on this information. A food source with a higher quality will have a larger probability of being selected by onlooker bees. An employed bee whose food source is rejected by employed and onlooker bees will change to a scout bee to search randomly for new food sources.

This process of a bee swarm seeking, advertising, and eventually selecting the best known food source is the process used to find the optimal solution. Notice that the food sources are selected based on group decision making by the swarm. Independence and interdependence in collective decision making are important factors in this mechanism.

We employ the ABC mechanism in finding paths of the microrobots. Fig. 5 illustrates the flow chart of the algorithm developed for finding the paths.

First, initial solutions consisting of a velocity (u) and an angle of rotation (θ) for each microrobot are generated. These parameter sets are treated as the food sources. Each food source is used to move the microrobot from the current position to the next position in a search space.

The food sources will be updated by the employed bees. The choices are based on the neighborhood of the previously selected food sources. The position of the new food source can be calculated from equation (7).

\[ x'_{ij} = x_{ij} + \Phi_{ij}(x_{ij} - x_{kj}) \]  

(7)

In equation (7), \( x'_{ij} \) is the new feasible food source, which is selected by comparing the previous food source \( x_{ij} \) and the randomly selected food source from the neighboring food source \( x_{kj} \). \( \Phi_{ij} \) is a random number between \([-1, 1]\) which is used to adjust the old food source to become the new food source in the next iteration. \( k \in \{1,2,3,..,SN\} \) and \( j \in \{1,2,3,..,D\} \) are randomly chosen indexes.

The microrobots use the food sources generated by the employed bees to update their positions. Collision detection will be performed and the objective score will be calculated using eq. (1). If the new candidate position does not collide with any obstacle and gives a better objective value than the old position, the microrobot will move to this new position.

The onlooker bees will then select food sources from the employed bees. Food sources of better objective values have higher chances of being selected. The probability that a food source will be selected is given by equation (8).

\[ P_i = \frac{f_{i}}{\sum_{n=1}^{N} f_{n}} \]  

(8)

where \( N \) is the number of food sources and \( f_{i} \) is the fitness value of the food source \( i \). A smaller objective value indicates better fitness value.

The onlooker bees will then select the food sources that produce better fitness values and update those food sources using the same algorithm as the employed bees. Microrobots will use these food sources to update their positions. The collision detection and the objective scoring processes will be performed repeatedly so that the microrobots will keep moving to better positions.

The microrobot that cannot avoid an obstacle within a certain period of time will backtrack to its previous position. The new food sources will then be randomly generated by the scout bees.
The process will be repeated until the microrobots reach the target or the number of iterations equals the maximum cycle number (MCN) and the final result will be improved by using the offline path distance optimization approach.

III. EXPERIMENTS AND RESULTS

The proposed methods were programmed in C++ and run on a PC with Intel Core i7 CPU, 2.0 GHz. The size of the search space is set as 150*1000, the starting point at (0,75) and the target point at (1000,75). The size of population was 10, and the MCN was 2000. There were 20 obstacles located at random positions in the search space.

The search space is initially created as shown in the Fig. 6. The microrobots will move from the starting point on the left of the search space to the target located on the right of the search space.

Fig. 7 presents the trajectory of the microrobot when the simulation has been completed. The result shows that a microrobot can avoid obstacles and move ahead to its target correctly using our designed method. The offline path distance optimization approach is then applied at the last step in order to optimize the path. The result is illustrated in Fig. 8.

To investigate the ability of finding the target and avoiding the obstacles, the microrobots are assigned to find the target under various obstacle environments. Results exhibited in Fig. 9 show that the proposed method gives good results for different number and locations of the obstacles.
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mimic a more realistic environment. The movement of obstacles will be considered in a future work. In addition, we plan to simulate the drag force experienced by a microrobot during its trajectory. For example, conservation laws, forces that drive or resist blood flow, Cauchy’s laws of motion applied to fluid, as well as pressure and flow in blood vessels, will be considered to mimic a more realistic environment.

However, obstacles are not static in the real environment. The movement of obstacles will be considered in a future work. In addition, we plan to simulate the drag force experienced by a microrobot during its trajectory. For example, conservation laws, forces that drive or resist blood flow, Cauchy’s laws of motion applied to fluid, as well as pressure and flow in blood vessels, will be considered to mimic a more realistic environment.

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