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Original Article

Obstacle Avoidance Algorithm Based on the Probability of Collision

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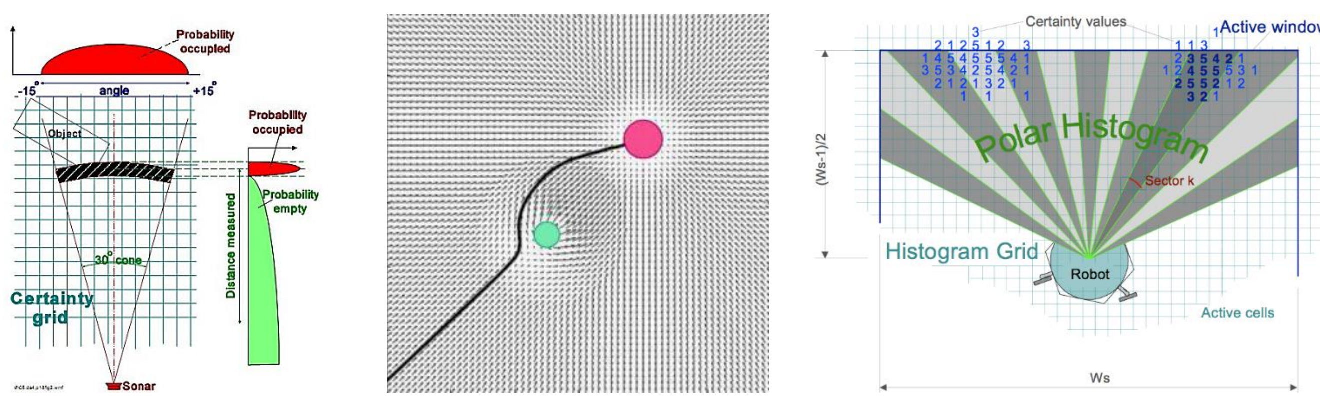
Abstract *- In this paper, a method of finding a path for a robot is proposed based on the calculation of the collision probability, partition of collision probability when a robot is being on its trajectory and the adjusted trajectory during the movement processing. The calculation of the collision probability and the partition of collision probability were provided to support the robot in deciding the movement process through a safety zone and avoiding obstacles at each time. In addition, the results of testing the model of the complement collision probability to build a safety trajectory for the robot with multiple obstacles had done. The results of the probability calculation and collision layer partition were tested, and obstacle avoidance was proposed.*

Keywords *- Collision avoidance, Predictive probability, Collision probability, Collision prediction, Collision risk.*

1. Introduction

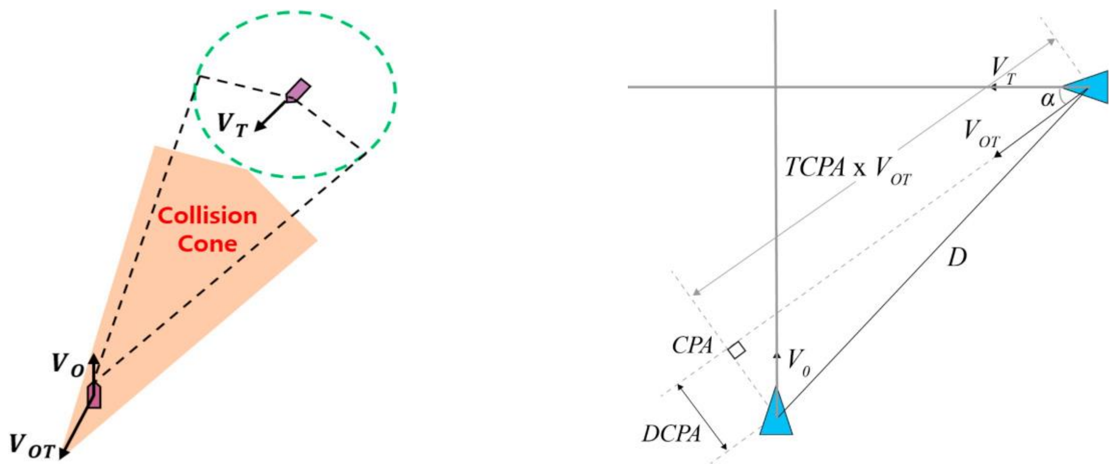
In robot control, avoiding collisions with objects in the working area is very important. The key problem is how to evaluate the robot's collision probability with the movements in space with complex orbits and moving obstacles.

In the field of collision avoidance research, many findings have been found [1,4,7,9,11], e.g. Certainty Grid- Moravec [2,3], Artificial Potential Field - Khatib [5,9], Virtual Force Field - Borenstein [6,7]... These methods are commonly applied to mobile robots but do not consider the dynamic limit, so, in many cases, when the robot moves in space like the shape of a bottleneck, it will not find a way out. Even the Elastic strips method proposed by Khatib [8] assumes that the robot's trajectory is an elastic band. The obstacle avoidance algorithm based on Elastic strips has been tested and shown to be suitable for real-time systems. However, there are still some limitations when it comes to practical implementation, which is specified in [10,11].



(a) Certainty Grid **(b) Artificial Potential Field** **(c) Virtual Force Field**

Fig. 1 Collision avoidance method



(a) Velocity obstacle (VO) **(b) The DCPA and TCPA concept.**

Fig. 2 Collision avoidance method based on based on the probability computation

In recent years, a number of collision avoidance methods have been studied based on the probability of a collision, such as: Kuwata et al. [14] have used the Velocity Obstacles method to perform avoidance simulations for USV; Kim [13]and Chang [16] have performed studies using the Markov Decision Process as a collision avoidance measure based on the Markov decision-making model; Woo et al. [21] have tested the collision avoidance algorithm, which is based on deep reinforcement machine learning according to the Semi-Markov Decision Process model. All of these methods use probability to determine the fuzzy concept of collision risk calculations or estimate ambiguous states of the dynamic environment.

Chen et al. [15] studied a method using fuzzy logic using time and distance theory to the nearest approach point (TCPA, DCPA) for collision avoidance recognition; Park et al. [17] developed the models of support vector machine and relevance vector machine based on Bayesian theory for estimating collision risk index. Namgung et al. [18] used neuro-fuzzy to calculate the collision risk index. This study further examined the dynamic coefficients of obstructions; Fulgenzi et al. [20] performed dynamic environmental collision avoidance simulations by combining dynamic power grids provided by the sensor and the Probability Velocity of Obstructions.

A collision avoidance algorithm based on prediction probability using the Kalman filter was proposed by Kim et al. [22]. This method uses the Kalman filter to estimate the ship's state variables and calculates the probability of position prediction based on the state variable and the predicted probability distribution. The proposed algorithm can predict states and easily plan the optimal path by considering the object's state variables, calculated through the prediction step of the unscented kalman filter.

Most of the studies found that collision avoidance is based on the probability of focusing on the object's current state and calculating the risk of collision based on the velocity obstacle method. Determining the object's motion trajectory focuses on avoiding potential collision areas, so the robot's path is not optimal in terms of distance and time.

Therefore, we propose a method to optimize the robot's path based on calculating the collision probability and partitioning the collision probability level, thereby helping the robot choose the moving area and the safety trajectory.

2. Collision probability

In [23,24], research work on calculating the collision probability between objects is applied not only to solve the problem of avoiding obstacles (transport ships, self-driving devices, robots,...) but also in military science, such as calculating the exact point and exact area of collision (interceptor, target point of the weapon and missile..)

The robot model with a drive system consisting of two active wheels and one self-selecting wheel is introduced and shown on the Cartesian axis system in Fig 3. To perform the calculation of the collision probability between the robot and an obstacle. Assume that the robot and the obstacle are bounded by its sphere (3D-bounding sphere) and its circle (2D-bounding circle), which is its safety space of its.

Considering two objects, which are moving on two different trajectories at each time (t), each object will occupy a certain space determined by the center and radius of the object. The two objects will only collide when those two spheres have a non-empty intersection domain. Thus, based on the intersection volume, we can estimate the collision probability between them.

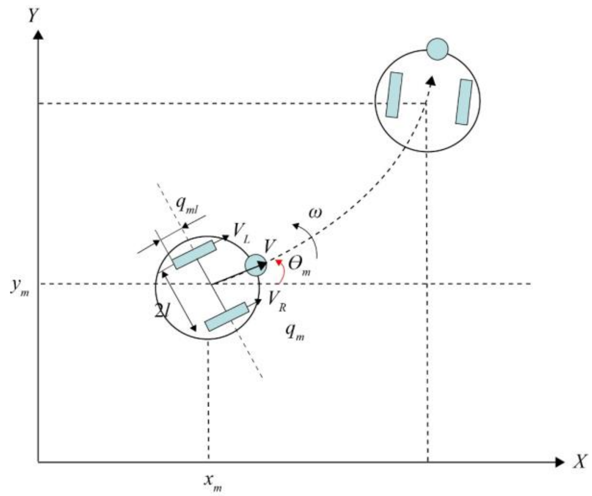


Fig. 3 Robot model and coordinate system

At each time (t), the intersection will certainly change if the velocity is changed. Therefore, the area of intersection also only characterizes the possibility of collision between two objects.

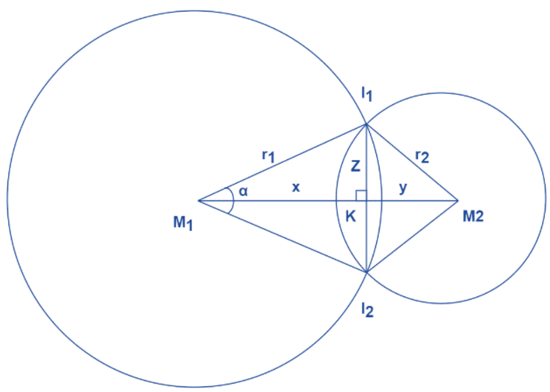


Fig. 4 Collision domain

Considering the object defined by two regions Ω_1, Ω_2, the measure of collision probability is determined by the formula (1), where V is the volume of the respective domains.

$$p[1,2,t] = \frac{V(\Omega_1 \cap \Omega_2)}{V(\Omega_1 \cup \Omega_2)} \quad (1)$$

In general, formula (1) is used to calculate the collision probability of the two objects. In the special case, when two objects closely coincide with each other, the probability is 1, and when separated, the probability is zero, and the greater the probability, the higher the probability of a collision.

With 2D, $O(M_1,r_1)$, $O(M_2,r_2)$ are bounding circles; $d = \rho(M_1, M_2)$ is distance between the two centers; h_1, h_2 are the height of supply and demand.
So,

$$x = \frac{r_1^2 + d^2 - r_2^2}{2d}; y = \frac{r_2^2 + d^2 - r_1^2}{2d} \quad (2)$$

$$h_1 = r_1 - \frac{r_1^2 + d^2 - r_2^2}{2d}; h_2 = r_2 - \frac{r_2^2 + d^2 - r_1^2}{2d} \quad (3)$$

$$S_1 = \pi r_1^2 \frac{\alpha}{360} = r_1^2 \times ar\cos(\frac{r_1 - h_1}{r_1}) \quad (4)$$

$$S_2 = r_2^2 \times ar\cos(\frac{r_2 - h_2}{r_2}) \quad (5)$$

$$S(M_1 I_1 I_2) = x \times z = (r_1 - h_1) \times \sqrt{r_1^2 - (r_1 - h_1)^2} \quad (6)$$

$$S(M_1 I_1 I_2) = y \times z = (r_2 - h_2) \times \sqrt{r_2^2 - (r_2 - h_2)^2} \quad (7)$$

From (4), (5), (6), (7):

$$S(O_1 \cap O_2) = S_1 + S_2 - S(M_1 I_1 I_2) - S(M_2 I_1 I_2) \quad (8)$$

Then,

$$S(O_1 \cap O_2) = r_1^2 ar\cos\left(\frac{r_1 - h_1}{r_1}\right) - (r_1 - h_1) \times \sqrt{r_1^2 - (r_1 - h_1)^2} + r_2^2 ar\cos\left(\frac{r_2 - h_2}{r_2}\right) - (r_2 - h_2) \times \sqrt{r_2^2 - (r_2 - h_2)^2} \quad (9)$$

$$S(O_1 \cup O_2) = \pi r_1^2 + \pi r_2^2 - S(O_1 \cap O_2) \quad (10)$$

Finally, collision probability in 2D:
When

$$|r_1 - r_2| \le d < r_1 + r_2; p[1,2,t] = \frac{S(O_1 \cap O_2)}{S(O_1 \cup O_2)} \quad (11)$$

When

$$d \ge r_1 + r_2;\ p[1,2,t] = 0 \quad (12)$$

When

$$d < |r_1 - r_2|;\ p[1,2,t] = \frac{min(\pi r_1^2, \pi r_2^2)}{\max(\pi r_1^2, \pi r_2^2)} \quad (13)$$

Similar, the calculation of collision probability in 3D based on e.q(12) below:

When $|r_1 - r_2| \le d < r_1 + r_2$;

$$p[1,2,t] = \frac{\pi h_1^2 \left(r_1 - \frac{h_1}{3}\right) + \pi h_2^2 \left(r_2 - \frac{h_2}{3}\right)}{\frac{4}{3}\pi(r_1^3 + r_2^3) - \pi h_1^2 \left(r_1 - \frac{h_1}{3}\right) - \pi h_2^2 \left(r_2 - \frac{h_2}{3}\right)} \quad (14)$$

When

$$d \ge r_1 + r_2;\ p[1,2,t] = 0 \quad (15)$$

When

$$d < |r_1 - r_2|;\ p[1,2,t] = \frac{Min\left(\frac{4}{3}\pi r_1^3, \frac{4}{3}\pi r_2^3\right)}{Max\left(\frac{4}{3}\pi r_1^3, \frac{4}{3}\pi r_2^3\right)} \quad (16)$$

In which,

$$V(O_1 \cap O_2) = \pi h_1^2 (r_1 - \frac{h_1}{3}) + \pi h_2^2 (r_2 - \frac{h_2}{3}) \quad (17)$$

$$V(O_1 \cup O_2) = \frac{4}{3}\pi(r_1^3 + r_2^3) - V(O_1 \cap O_2) \quad (18)$$

$$h_1 = r_1 - \frac{r_1^2 + d^2 - r_2^2}{2d}; h_2 = r_2 - \frac{r_2^2 + d^2 - r_1^2}{2d} \quad (19)$$

is the height of the spheres

$$p[1,2,\ldots,m,t] = \frac{\sum_{i\neq j}^{m} V(\Omega_i \cap \Omega_j)}{\sum_{i\neq j}^{m} V(\Omega_i \cup \Omega_j)} \quad (20)$$

The calculation of collision probability between two objects in 2D space according to formulas (11), (12), (13) and in 3D space according to formulas (14), (15), (16) and between m objects at a time (t) is determined by the formula (20), where V is the volume of respective domains.

3. The algorithm for Partition of Collision Probability

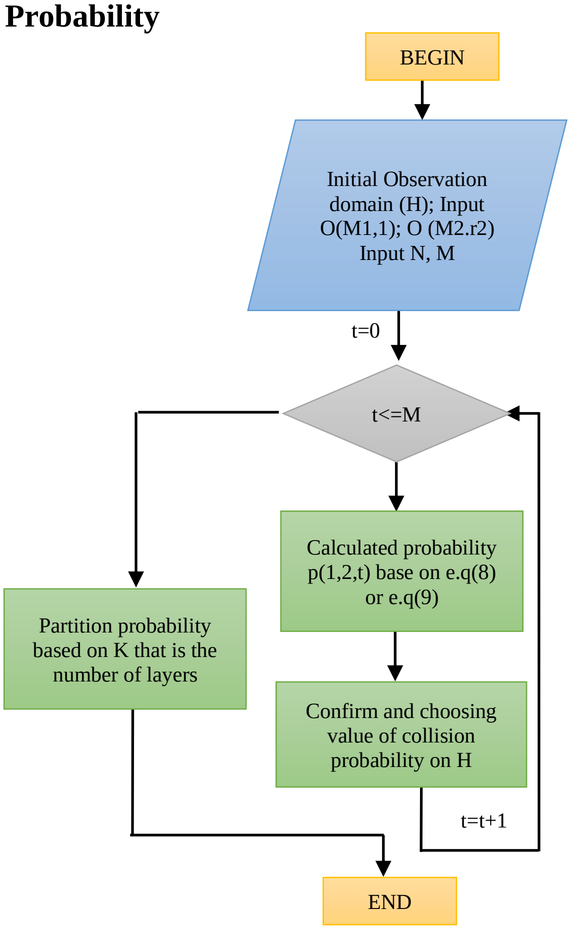


Fig. 5 The algorithm for partition of collision probability

4. Results and Simulations

At each time (t), calculate the collision probability and build the collision probability layer.

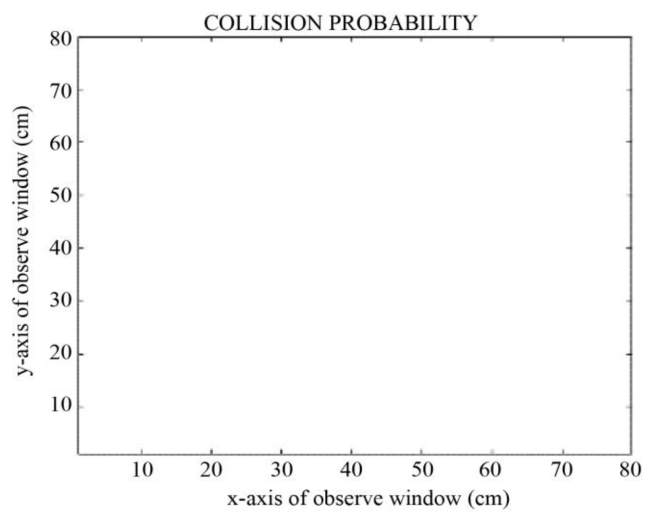
Input data:

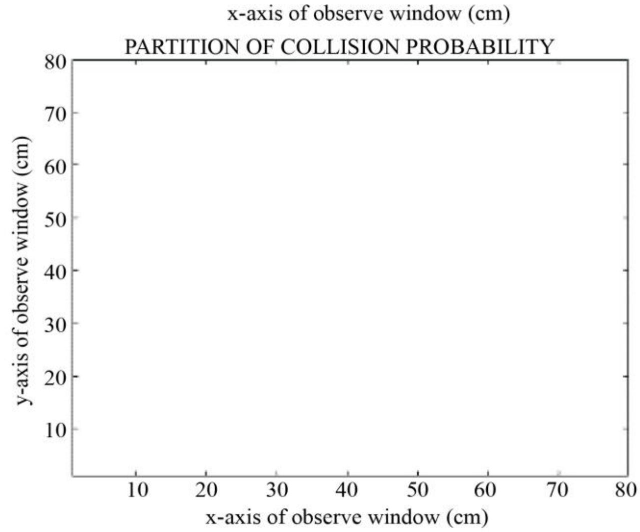
- xmax,ymax,zmax: the size of the observation domain (H)
- N: number of meshing points.
- x1(t),y1(t),z1(t),(u1,v1,w1): Trajectory, object velocity vector 1
- x2(t),y2(t),z2(t),(u2,v2,w2): Trajectory, object velocity vector 2
- R1, R2: Radius of 2 objects.
- T: The time period of motion of the objects.
- K: Number divided into congruent regions.

Output: Level domains Si (i=0..K).

The simulation data:

Case	K	R1	R2	T	N
1	10	50	30	80	80
2	10	30	30	50	50
3	5,20	50	60	100	100
4	5,10,15,20	50	60	100	100





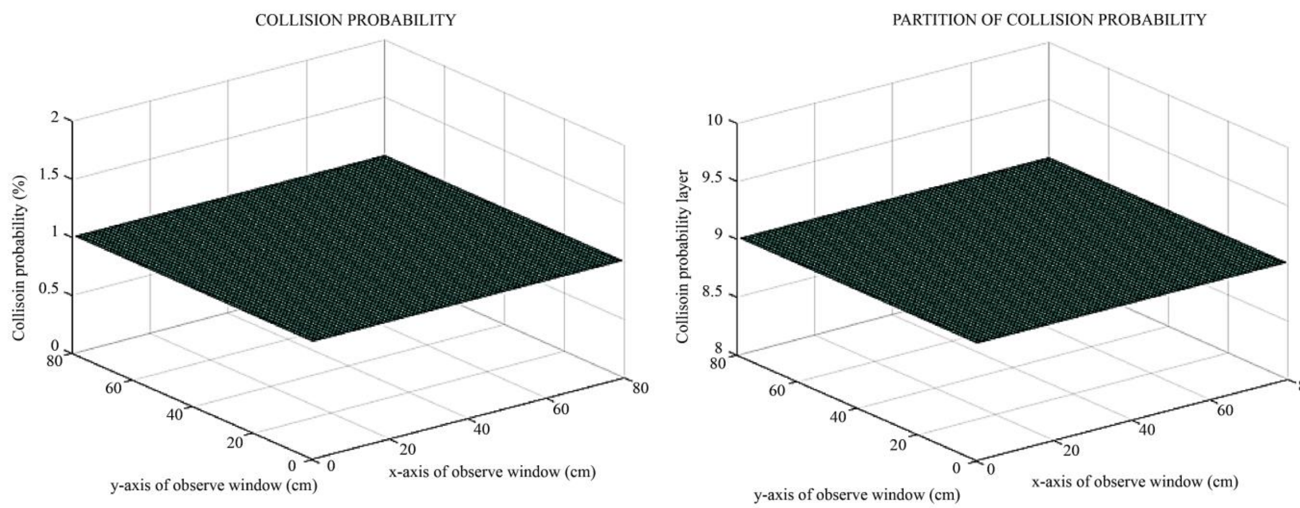


Fig. 6 Result of case 1

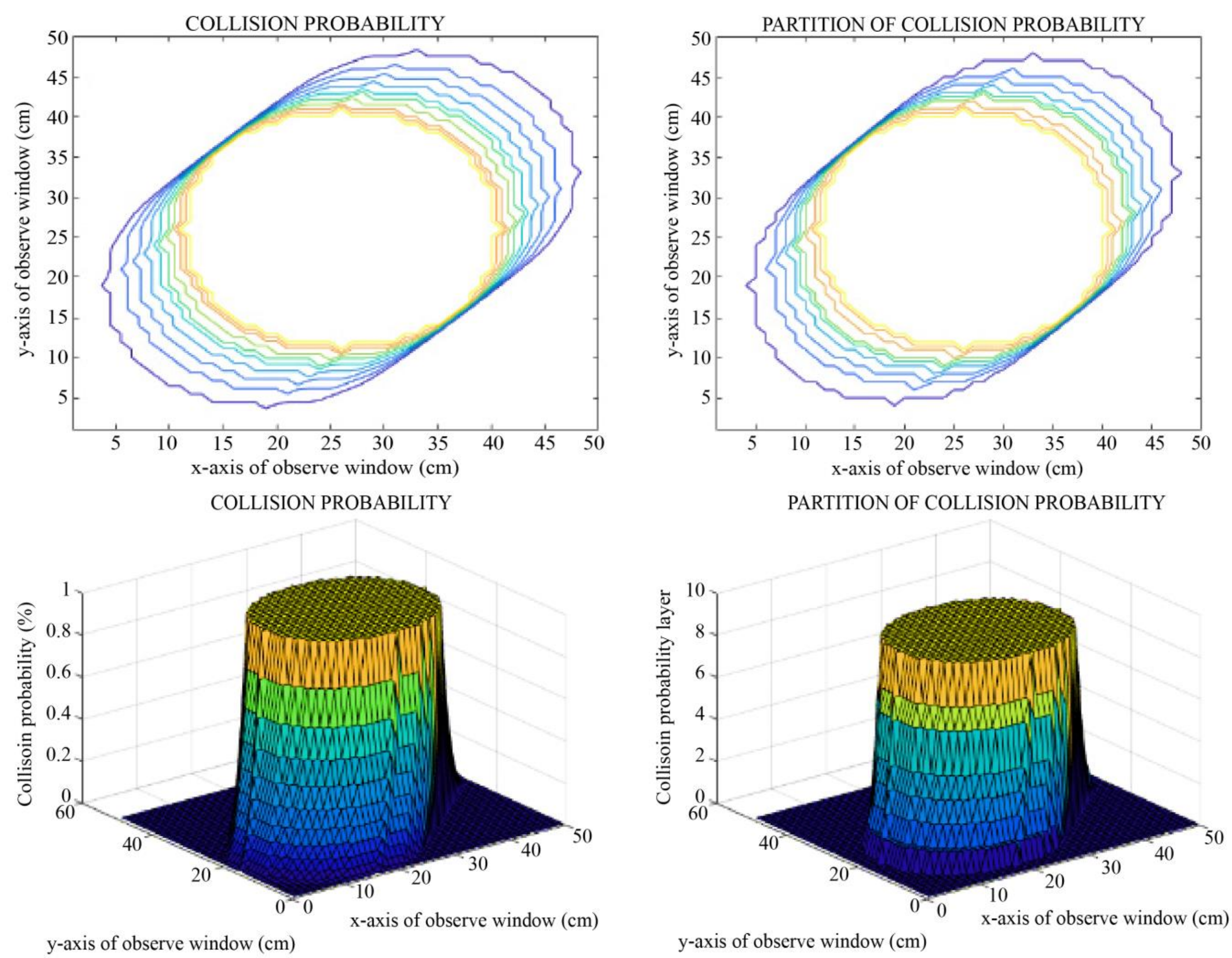


Fig. 7 Result of case 2

The calculation and simulation results of Case 1 are shown in Fig 6, where two objects that move closely coincide with each other; the probability is 1. The results of calculating the collision probability and partition collision probability are the same.

With the dataset of Case 2, Fig 7 shows that the collision probability calculation results and the collision partitioning are clearly shown when comparing the collision probability simulation results without partitioning and after partitioning, with the value k=10;

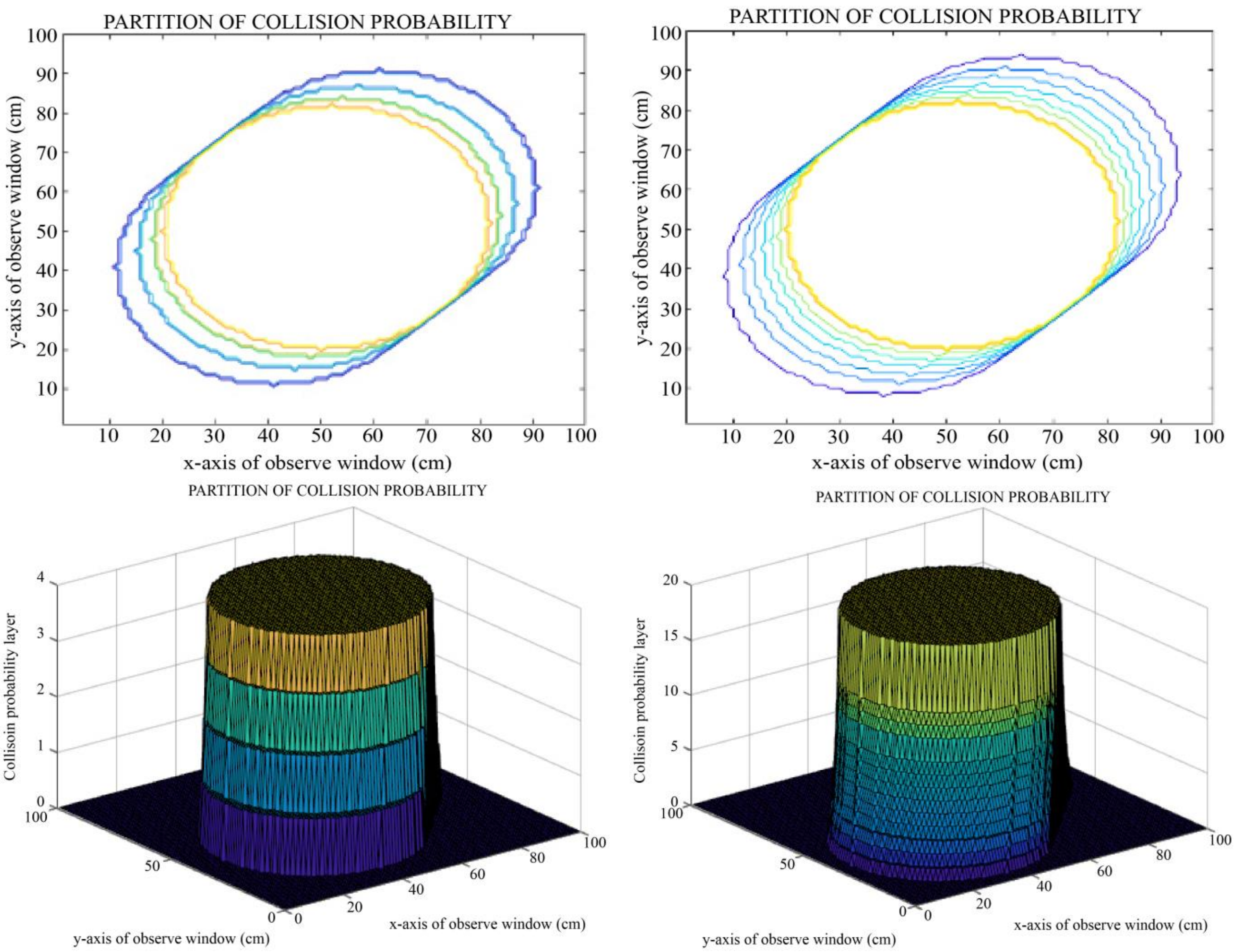
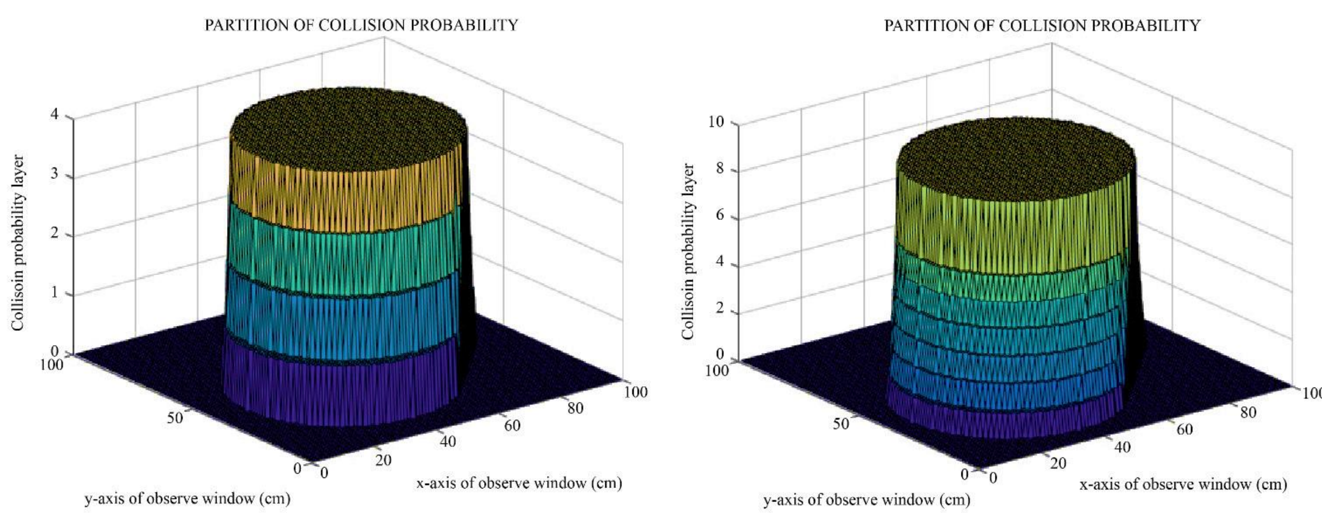


Fig. 8 Result of case 3



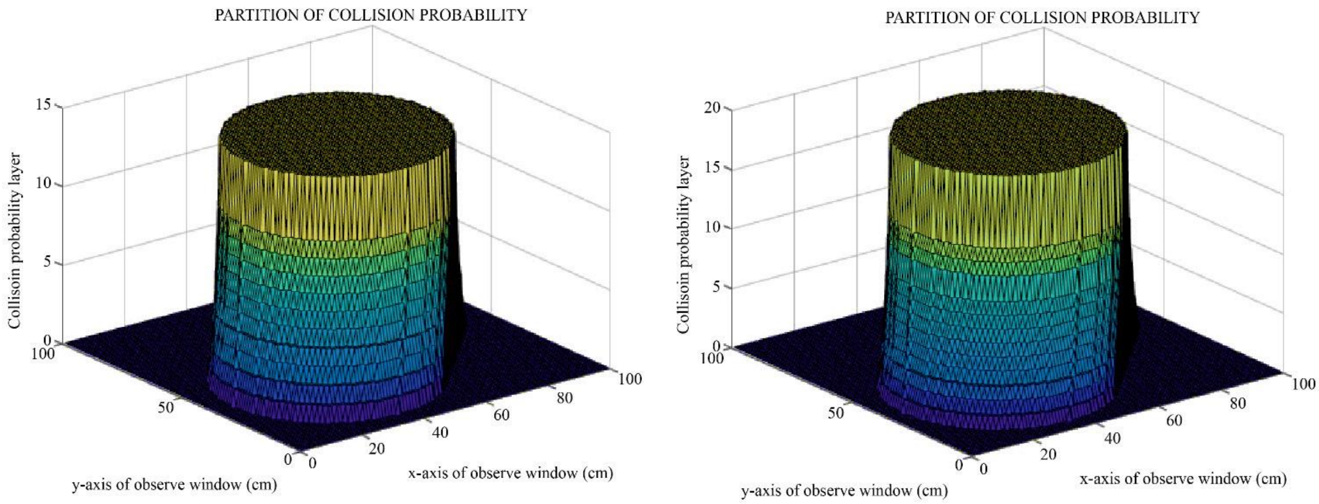


Fig 9. Result of case 4

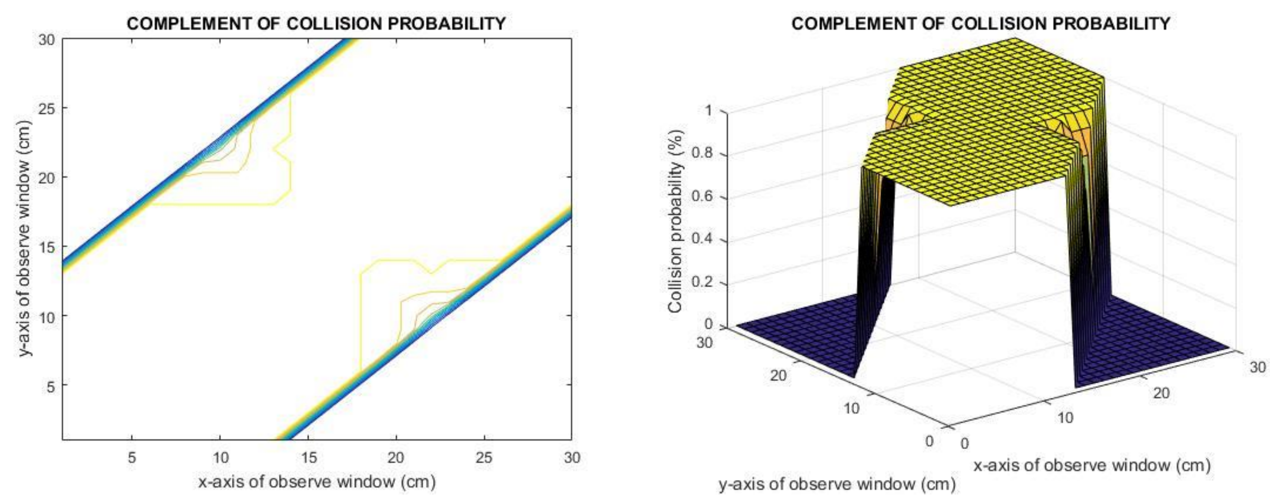


Fig. 10 (1-P) the model with Case 3

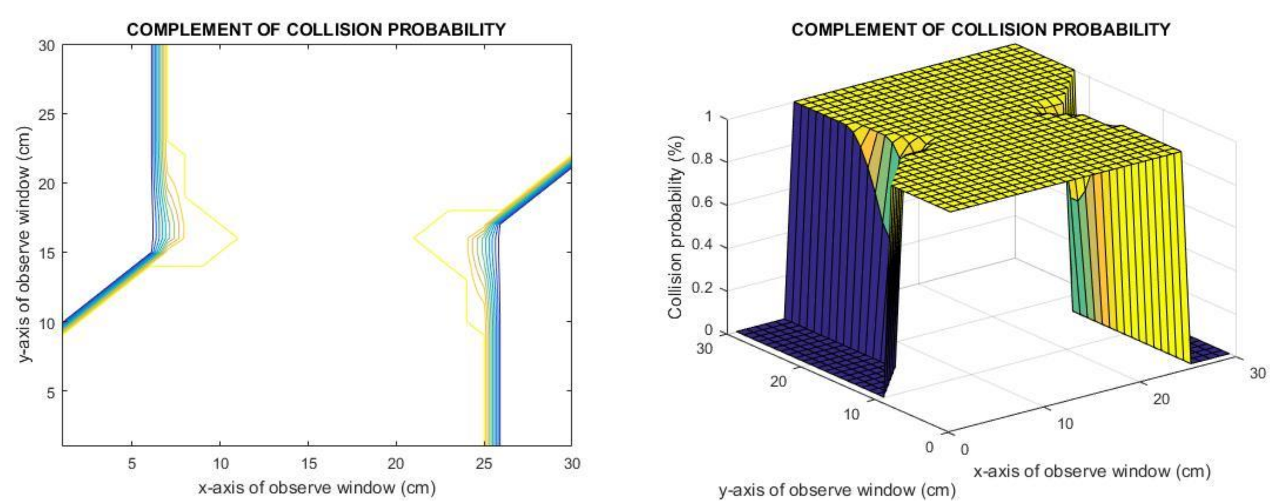


Fig. 11 (1-P) the model with multiple obstacles

In Case 3, with the same input data set, and changed the number of collision partitions with k1=5 and k2=20. The results showed that the calculation probabilities of both cases, k1, k2 were the same. However, the collision probability partitioning was specified, and the smaller the number of partitions, the thicker the endpoints of an area would be, which means that the decision-making for the robot to choose the penetration area will be safer when we partition it into more layers. Fig 8.

Case 4 is a contribution to the robot's path-finding algorithm. Here, with the same data set, different numbers of partitions: k1=5,k2=10,k3=15,k4=20. Calculation results of collision probability and probability contour partitioning have been done. It is remarked that when the number of partition layers is less, the calculation speed is faster, but the accuracy is low. The risk is high in the robot's decision-making. On the contrary, if the number of collision probability partitions into more regions, the robot has more safe choices for moving, and the calculation speed will be slower.

Testing the model of the complement collision probability (1-P): the results are the basis for building the safety trajectory. Fig 10 shows the result of the (1-P) model in Case 3; Fig 11 shows the result with multiple obstacles.

5. Discussion

The method of optimizing the path for the robot is based on collision probability, and the collision partitioning method was presented, which is the basis for the robot to make a decision to move through the safety zone and build its trajectory. The calculation results of collision probability and contour partitioning verified the mathematical model in the above formulas. After that, we continued researching the problem of collision avoidance with moving objects, including environmental factors. At the same time, we improved the collision contour partitioning algorithm for the robot's collision prediction problem so that the robot made accurate, safe and reliable decisions.

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