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Formating Reshape Control Strategy for Multiple Amphibious Spherical Robots

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***Abstract* – It is difficult for a rigid formation composed of multiple robots to pass through a narrow waterway, which needs to be realized by formation reshape. The virtual linkage structure is used to solve the problem that the conventional virtual structure is not easy to deform. In order to ensure the robustness of formation control, a discrete information consistency algorithm is added to provide the desire trajectory, then controller will be used to track it. At the same time, due to the difficulty of hydrodynamic modeling and the large overshoot of PID (proportional integral differential) controller, the double loop controller based on ADRC (Auto Disturbance Rejection Controller) include position loop and speed loop is used to adjust the position, and the single loop controller is used to adjust the heading angle and depth. The results of simulation show that the three combined methods of 3D virtual linkage structure, discrete consensus and ADRC realize the formation reshape.**

Index Terms – Amphibious spherical robot, Formation reshape, 3D virtual linkage structure, Discrete information consensus, Auto disturbance rejection controller

I. INTRODUCTION

Due to the limited function of a single robot, it is difficult to complete complex tasks. The multi-robot has high efficiency, can complete many complex tasks, has broad application prospects and great practical value[1]. In recent years, the research on multi-robot cooperative work is growing more and more popular, especially on formation control. At present, formation problem has been studied for many years in the fields of multi-agent, mobile robot, UAV, unmanned vehicle, etc., but the research on formation problem of underwater robot is less.

At present, there are relatively mature formation algorithm: leader-follower[2][3], virtual structure method[4]-[7], artificial potential field method[8]-[11]

Cao and Liu use the improved leader-follower algorithm to control the formation of wheeled robots[2], Pratama et al. also uses the leader-follower algorithm, which is combined with the conventional PI(proportional integral) controller to control the formation of quadrotor[3]. This method is simple to implement. It only needs to provide a predetermined track for the leader, and the follower only needs to track the leader. But the robustness of this method is poor, if the formation becomes larger, it will produce error cascading.

The virtual structure method is adopted by Luo et al., and the switch strategy of UAV formation is proposed[4]; Chen et al. uses the virtual structure method to control the triangular formation of wheeled robot[5]; Li et al. combines the virtual structure method and leader-follower to control the UUV formation[6]. The virtual structure method needs to share the information of each member with other members, but it is difficult to synchronize the state information between members. Moreover, the conventional virtual structure method uses rigid geometry method, so it is difficult to adjust formation shape, so it is necessary to write the formation shape in advance in the program. Chang proposed the flexible virtual structure method to solve the problem that the conventional virtual structure method is not easy to deform [7].

The artificial potential field method uses the concepts of gravitation and repulsion in physics, and its principle is simple. It is very suitable for controlling the particle model.

Research of Zhang et al.[8], Wang et al.[9], Lv et al.[10] and Zhang et al.[11], all adopt the artificial potential field method to control the formation, the method especially is applied to the formation internal anti-collision or formation external obstacle avoidance. However, the artificial potential field method has a very big defect, it is the local minimum points problem, which causes the robot to stop moving when it reaches these point.

In recent years, great progress has been made in the research of virtual linkage structure[12]-[14] and consensus algorithm[15]-[17].

Aiming at the problem that rigid virtual structure is not easy to deform, Liu et al. puts forward the virtual linkage structure theory[12][13], which is suitable for formation reshape, according to the characteristics of connecting rod easy to deform. This theory can reshape formation by adjusting the angle of connecting rod center. The team used this algorithm in the air-ground formation to realize the rescue task, greatly improving the rescue efficiency[14].

Consensus algorithm avoids huge data interaction. Each robot only needs to get the status information of its neighbor robots, and has strong robustness. Dong et al. applies it to control the progress of UAV formation[15]. Yan et al. proposes a new consensus algorithm control protocol, which is applied to UAV formation trajectory tracking[16]. Li et al. combines the virtual structure method with the consensus algorithm, and proposes a large-scale formation control algorithm[17], all experiment of them have achieved good results.

Because the hydrodynamic model of the underwater robot is very complex, there are many hydrodynamic parameters. Therefore, for the complex and difficult to identify controlled objects, the proportional integral differential(PID) controller is basically used to control them. According to statistics, the application of PID controller in motion control and process control is more than 90%. However, PID controller also has some disadvantages, such as the overshoot caused by regulation speed is large, and there will be a period of oscillation in the regulation process. According to the idea of PID, Professor Han proposed a new control method: Auto Disturbance Rejection Controller(ADRC)[18]. This controller has fast regulation speed, very small overshoot and almost no oscillation in the regulation time, so it has been widely used in the engineering field. Professor Chen et al. Classified and summarized ADRC controllers, and defined the development direction of ADRC controllers[19].

To sum up, this paper will combine the advantages of virtual linkage, discrete consensus and ADRC for the reshape of amphibious spherical robot formation to through a narrow waterway, as shown in Fig1. The second chapter will give a brief introduction to the formation of the amphibious spherical robot, the third chapter gives the problem description of formation reshape. The fourth chapter puts forward the formation reshape strategy, the fifth chapter gives simulation results based on the strategy proposed in the fourth chapter, the sixth chapter will make a summary according to the simulation results of the fifth chapter, and analyze its advantages and areas that can be improved.

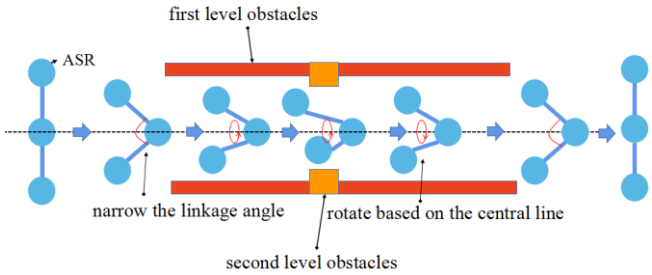


Fig.1 Procession of a multiple amphibious spherical robot formation go through a narrow waterway.

II. Multiple Amphibious Spherical Robot Formation Real Platform

The amphibious spherical robot(abbreviated as ASR) can be divided into two categories in terms of function, one has a binocular camera, which called double-eye amphibious spherical robot (abbreviated as ASR-2), the other carries four binocular cameras, which called 8-eye amphibious spherical robot (abbreviated as ASR-8). ASR-2 has only 120 degree horizon angle in front of the robot, while ASR-8 has 360 degree horizon angle without dead angle[20]-[23].

The mechanical structure of the two kinds of robots is the same. ASR-2 and ASR-8 have four legs, each leg has three joints, and the end of each leg is equipped with a water jet motor, which can walk on the road and swim in the water.

The hardware circuits of the two kinds of robots are slightly different. The internal circuit is divided into upper control circuit and lower control circuit. ASR-2 uses NVIDIA Jetson TK1 as the upper master chip. ASR-8 needs to process a large number of image data, so its upper master chip uses NVIDIA Jetson TX2, which has strong computing power. The bottom control circuits of the two kinds of robots are basically the same. STM32F407 is used as the main control chip to drive the servo motor, water spray motor, process the sensor data, and detect whether there is water in the spherical shell. The common serial communication is used in the data exchange of the upper and lower control circuits. The upper circuit sends control commands to the lower circuit, controls the land gait and underwater motion of the spherical robot, and the lower circuit sends sensor data, such as depth information, humid information. It also feeds back the alarm information to the upper controller when water enters the spherical shell.

The software of the two kinds of robots is basically the same. The upper control circuit of ASR-2 adopts the operating system of Ubuntu 14.04 with ROS indigo, and the upper control circuit of ASR-8 adopts the operating system of Ubuntu 16.04 with ROS kinetic. uCOS III is used in the operating system of the bottom circuit board, which can control the multi-channel servo motors at the same time.

III. Problem Description

A. *ASR Formation Problem Description*

Considering that there are (2n+1) robots, n ASR-8 and (n+1) ASR-2, they will change the formation shape in three-dimensional space. The formation shape is shown in the Fig. 2, whether in static state or in motion state.

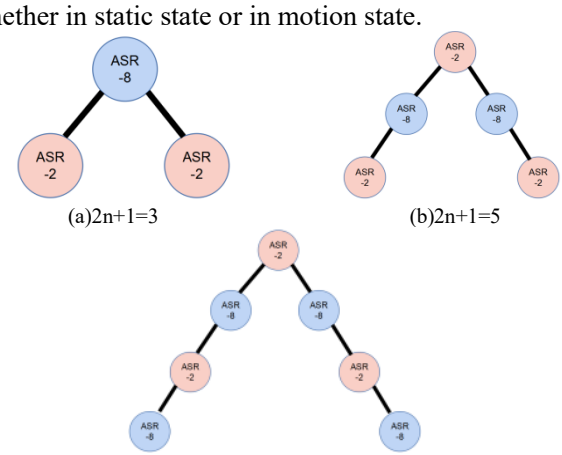
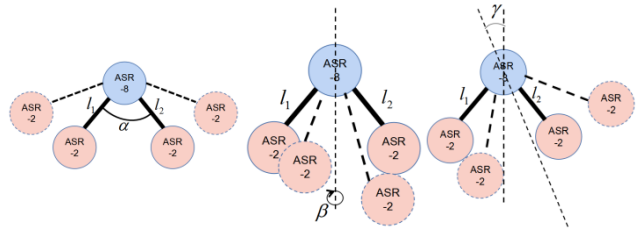


Fig.2 Virtual linkage structure used in ASR formation



(a)change the linkage angle (b)change the roll angle (c)change the yaw angle
Fig.3 Formation reshape method on ASR formation.

In order to ensure that the formation can smoothly pass some obstacles to carry out the task, the formation needs to make appropriate transformation, then the virtual linkage structure can be used to adjust the coordinates of these robots in three-dimensional space, and the adjustable parameters include the linkage angle α, the roll angle β of the formation, the yaw angle γ of the formation, and the length l_i of the sub-linkage of the virtual linkage structure, just shown in Fig.3.

From the actual situation, these parameters have corresponding restrictions. First, the angle between the connecting rods should not be too large or too small, which will lead to collisions between robots, the angle restriction is set: $90^o \le \alpha \le 270^o$.

Due to the chassis of the robot needs to be perpendicular to the Z axis, if the roll angle of the formation is too large, it will exceed the camera field of vision of ASR-8, then ASR-2 would not be recognize, even the whole formation can not run normally, so the roll angle of the ASR formation β is limited: $-\beta_{constrain} \le \beta \le \beta_{constrain}$

The length of the linkage also be limited accordingly. If the linkage is too long, ASR-8 will not recognize ASR-2. In order to avoid collision, the linkage length shall not be too short, and the limit of the linkage length and heading angle is set: $-180^o < \gamma < 180^o$, $0 < l_{\min} \le l_i \le l_{\max}$. Although the heading angle can be definite from 0 to 360 degrees, the definition from -180 to 180 degrees is more convenient.

B. *ASR formation graph*

1. Information flow graph

Information flow graph is actually a weighted digraph, which is recorded as $G_I = (V, E)$, $V = (1,2,3,...,n)$ is the node set of digraph, also can be regarded as the number of robot, $e_{ij} \in E$ is the set of edges from node i to node j, Each edge has its corresponding weight value. The sum of the weights of the in and out edges of node i is called degree $\deg(i)$, The degree matrix is a diagonal matrix, record as $\Delta = diag(\deg(1), \deg(2), ..., \deg(n))$, $A = [a_{ij}] \in R^{n \times n}$ is the weighted adjacency matrix of digraphs, if $e_{ij} \in E$, then $a_{ji} > 0$, otherwise $a_{ji} = 0$.

The most intuitive way to describe a digraph is Laplace matrix, the relationship among L, Δ, A is:

$$L = \Delta - A \tag{1}$$

where L represents Laplace matrix.

2. Information transfer between ASRs

ASR-8 detects the position information of ASR-2 through a camera. ASR-2 and ASR-8 both have depth meters. ASR-2 will transmit the information of depth meters to ASR-8, and ASR-8 will send the fused data back to ASR-2. ASR in the center of the connecting rod is an absolute navigator, and the position mark in the formation is always (0,0,0), so it does not need to receive the location messages of other robots, so the communication topology of the whole formation is shown in the Fig.4.

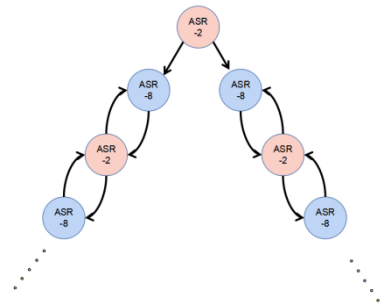


Fig.4 Information topology of the whole formation

Then the formation reshape has been transformed into a mathematical problem. In the next chapter, virtual linkage structure and discrete consensus algorithm will be considered as the planning layer, and ADRC based double closed-loop control will be considered as the executive layer.

IV. FORMATION RESHAPE STRATEGY

A. *Design of planning layer*

1. 3D virtual linkage structure modeling

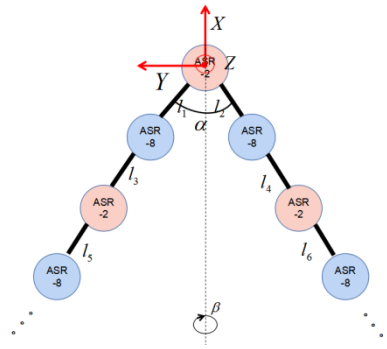


Fig.5 Mathematical model of virtual linkage structure

As the central robot is the absolute leader of the whole formation, the coordinate system is established. The direction of the coordinate system is as shown in the Fig.5, with the X axis forward, the Y axis left, and the Z axis up. If $\beta = 0$, Then the whole formation is a virtual linkage structure in two-dimensional plane, and the coordinates of all robots in the link left arm are:

$$x_i = \sum_{i=1}^{2k+1} l_i \cos\frac{360-\alpha}{2} \tag{2}$$

$$y_i = \sum_{i=1}^{2k+1} l_i \sin\frac{360-\alpha}{2} \tag{3}$$

$$z_i = 0 \tag{4}$$

$$(k = 0,1,2,3,...,n)$$

where α, l_i are defined in chapter III.

The coordinates of all robots in the right arm of the connecting rod are:

$$x_i = \sum_{i=2}^{2m} l_i \cos(-\frac{360-\alpha}{2}) \tag{5}$$

$$y_i = \sum_{i=2}^{2m} l_i \sin(-\frac{360-\alpha}{2}) \tag{6}$$

$$z_i = 0 \tag{7}$$

$$(m = 1,2,3,...,n)$$

when the whole formation rotates around the central axis at β angle, a new coordinate can be obtained:

$$\begin{bmatrix} x_i^{'} \\ y_i^{'} \\ z_i^{'} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}$$

The above formula is abbreviated as

$$\xi_i^{'} = R_x \xi_i \tag{8}$$

where $\xi_i^{'}$ and ξ_i are 3D coordinate of i-th ASR. R_x is a rotation matrix around x axis.

2. Discrete consensus formation algorithm

$\xi_i^{'}$ enough to guide each robot to its own target position. However, the addition of consensus algorithm can improve the robustness of keeping formation shape. According to single integral consensus algorithm, the formula is:

$$\dot{\xi} = -(L_m \otimes I_n)\xi \tag{9}$$

where L_m is the Laplace matrix of order $m \times m$, I_n is the $n \times n$ order identity, $\xi = [\xi_1, \xi_2, ..., \xi_n]$ is the robot current position, $\otimes$ is the Kronecker product, All robots will converge to the weighted average of each robot's initial position if and only if the formation graph has a directed spanning tree.

Let $\tilde{\xi} = \xi - \xi^{'}$, then

$$\dot{\tilde{\xi}} = -(L_m \otimes I_n)\tilde{\xi} \tag{10}$$

The Equation(10) is used for formation control. If and only if the formation graph has a directed spanning tree, the formation will converge to a specific shape.

Discretize the Equation(10):

$$\tilde{\xi}(k+1) = (D_m \otimes I_n)\tilde{\xi}(k) \tag{11}$$

Where D_m is row random matrix, and its transformation relationship with Laplace matrix is

$$D_m = I_m - \Delta_m^{-1} L_m \tag{12}$$

The formation will converge to a specific shape, If and only if the graph has a directed spanning tree.

Because the spectral radius of D_m is 1, $(D_m \otimes I_n)^n$ will not diverge, but it can not be guaranteed to converge to 0. The following is an improved discrete consensus formation algorithm.

TABLE I

IMPROVED DISCRETE CONSENSUS ALGORITHM.

step1: calculate $\xi_{\exp}(k+1)$ $\xi_{\exp}(k+1) = \xi^{'}(k+1) + (D_m \otimes I_m)(\xi(k) - \xi^{'}(k))$
step2: When the robot reaches the designated position, assign $\xi_{\exp}(k+1)$ to $\xi^{'}(k)$.
step3: execute step1.

$\xi_{\exp}(k+1)$ are the expected position of the ASRs in formation. The above process can not only ensure the robustness of formation, but also ensure the accuracy of formation trajectory tracking.

B. Design of executive layer

In fact, the executive layer is used to control the robot's position. Position Control of X, Y directions are realized by double closed-loop controller based on ADRC , Z direction and yaw angle are controlled by single loop controller based on ADRC. According to the current position, speed, heading angle, depth and other information of the robot, each ADRC controller calculates the forward force, downward force and heading torque of the robot. Combining the above force and torque of the robot, the thrust and angle of each propeller of the robot can be calculated by using the internal dynamics calculation module of the robot to ensure that the robot moves towards the expected target point.

V. SIMULATION AND RESULTS

According to the hydrodynamic test results of the robot, the hydrodynamic reference model of the robot is given below.

$$\ddot{x} = a_1 \dot{x} + b_1 \dot{x}^2 + c_1 u_1 \cos\varphi \tag{13}$$

$$\ddot{y} = a_1 \dot{y} + b_1 \dot{y}^2 + c_1 u_1 \sin\varphi \tag{14}$$

$$\ddot{z} = a_2 \dot{z} + b_2 \dot{z}^2 + c_2 u_2 \tag{15}$$

$$\ddot{\varphi} = a_3 \dot{\varphi} + b_3 \dot{\varphi}^2 + c_3 u_3 \tag{16}$$

where a_1, b_1, c_1, a_2, b_2, c_2, a_3, b_3, c_3 are all hydrodynamic parameters measured by experiments, u_1 is the thrust on the xoy plane, u_2 is the thrust alone the z axis direction, and u_3 is the torque around the z axis. In the following obstacle avoidance simulation, an original obstacle avoidance trajectory is given first, and the original trajectory points are optimized by three-dimensional virtual linkage structure and discrete consensus algorithm, then the trajectory points are tracked by single loop ADRC and double loop ADRC. Use 3 ASRs formation which are institute by 1 ASR-8, 2 ASR-2 to accomplish this simulation.

A. Simulation I: relatively wide waterway

If the waterway is relatively wide, only to reduce the linkage angle. As is shown in Fig.6, this figure is a scenario of passing this waterway. The pink circle represent the ASR-2, and the blue circle is ASR-8.To go though this waterway, this formation only need to regulate the linkage angle, and restore the linkage angle when go finish this waterway.

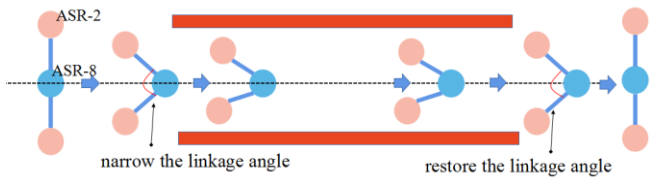


Fig.6 A scenario of formation go through a relatively wide waterway

There are 2 spherical obstacles in the water area, as shown in Fig.7, with a center distance of 4m and a radius of 0.5m. A small formation composed of three ASRs will pass through this obstacle, and the length of virtual linkage is 2m. The reference route of the formation is x-axis, which is processed by virtual linkage structure and discrete consensus algorithm, and then three trajectories are obtained and assigned to the corresponding ASR. Considering that the robot itself is not a particle, it has the corresponding shape and size, the connecting rod angle is set to 60 degrees, so that the center distance between the two ends of the formation is 2 meters, enough to pass through the obstacle distance of 3 meters. Each robot uses its own dual loop ADRC controller to track its own trajectory points. So as to realize formation reshape control.

As shown in Fig.7, before the formation pass the obstacle, it first changes the connecting rod angle from the original 180 degrees to 60 degrees. The change of the angle causes the change of the each trajectory. The "*" in the figure represents the trajectory point of three robots. Three ASR are all regulating their own position toward the trajectory point. Fig.8 is the top view of the process of formation reshaping, it is more intuitively shows that the 3 ASR are passing through these spherical obstacles. The results of the two figures show that the formation passed through the relatively wide channel smoothly through reshaping.

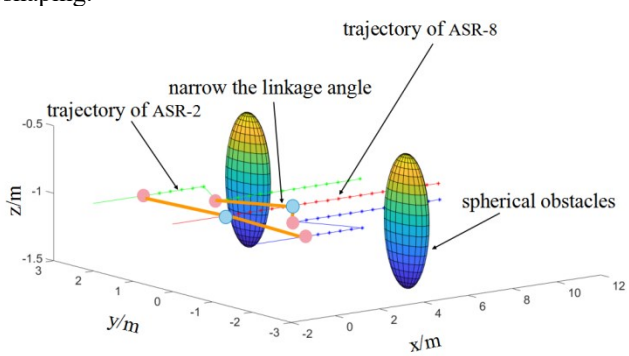


Fig.7 3D view of process of an ASR formation goes through 2 spherical obstacles

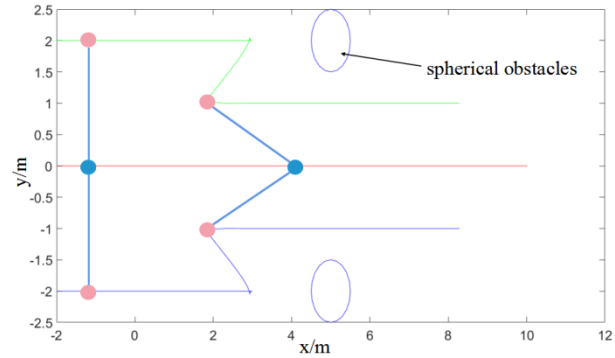


Fig.8 2D top view of process of an ASR formation goes through 2 spherical obstacles

B. Simulation II: relatively narrow waterway

If the waterway is relatively wide, not only to reduce the linkage angle, but also need to rotate the roll angle to avoid collision. The scenario is shown in Fig.9, this formation need to restore the linkage angle and roll angle when finish going through this relatively narrow waterway.

Four spherical obstacles are set in the water area. The first group of spherical obstacles is the same as the situation in the front. The center distance of second group of spherical obstacles is 3m, and the radius of the spherical obstacles is 0.5m. The shape, configuration and route of the formation are the same as those in the front, and the controller parameters of each robot are the same as those in the front.

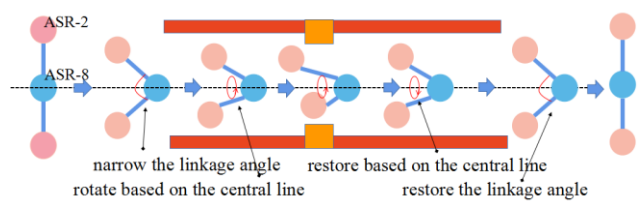


Fig.9 A scenario of formation go through a relatively narrow waterway

Fig.10 shows that the linkage angle is reduced to 60 degrees before passing the first group of obstacles. After successfully passing the first group of obstacles, in order to ensure passing the second group of obstacles, the formation rolled 35 degrees along the x-axis. Fig.11 represents a top view along the z-axis, it clearly shows the process of formation passing through obstacles. It could be seen that each robot tracks its own trajectory points accurately. The formation successfully passed two groups of obstacles.

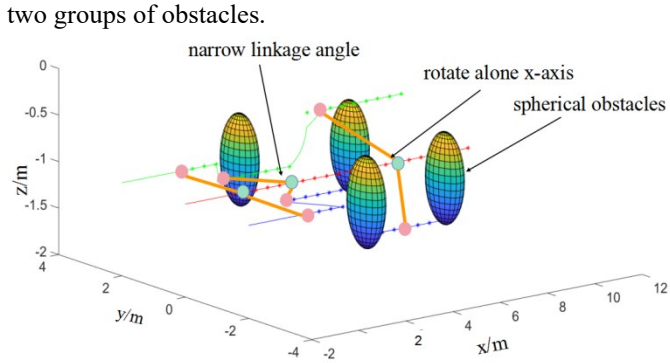


Fig.10 3D view of process of an ASR formation go through 4 spherical obstacles

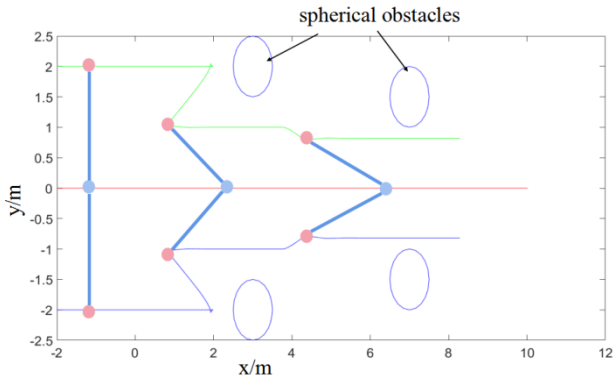


Fig.11 2D top view of process of a ASR formation go through 4 spherical obstacles

VI. CONCLUSION

Two sets of simulation clearly show that 3D virtual linkage structure has better performance than 2D. Although 2D virtual linkage structure can deal with some non-strict obstacles, compared with the relatively narrow waterway, 2D virtual linkage structure shows some problems, such as limited degree of freedom, which can only be deformed in the 2D plane; when passing through the narrow obstacles, the angle between the links cannot be further reduced, which will lead to the robot collision inside the formation.

Due to the planned trajectory point is not the optimal trajectory point, it may be far away from each robot, so it always takes a long time for multiple robots to adjust to a formation with a specific shape. The discrete consistency algorithm will combine the trajectory of initial planning with the real-time position of the robot to calculate the new trajectory points that can make the formation converge to a specific shape faster. This not only saves the adjustment time of the robot, but also improves the robustness of the formation.

In addition, the simulation results show that the double loop ADRC has better tracking performance. The ADRC controller with both external and internal loops not only has high regulation accuracy, but also almost no overshoot in the regulation process.

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