Multi-AUVs Formation Control with Acoustic Communication Constraints

Hongli Xu
State Key Laboratory of Robotics
Shenyang Institute of Automation, CAS
Shenyang, China
xhl@sia.cn

Guannan Li
Institute of informa
Shenyang Ligong University
Shenyang, China
yzlgncd@163.com

***Abstract*—Formation control has received significant attention in the field of multiple autonomous underwater vehicles (AUVs) in recent years. There are many theoretical methods for solving this problem. But when applying these methods to an actual multiple AUVs system, communication constraints need to be considered because acoustic communication among multiple AUVs often is unreliable in actual ocean environment. This paper focuses on application and validation of a leader-follower approach on multi-AUVs formation maintenance with acoustic communication constraints. The communication interval between AUVs and packet loss rate are researched based on experiments. A leader-follower formation control algorithm based on a Line-Of- Sight guidance law is proposed. The simulation and experiment results show that the proposed method is effective and feasible when keeping a formation with a long delay of underwater acoustic communication, and it is also suitable for short-time communication interruption.**

Keywords—Formation control; multiple AUVs system;a leader-follower approach; acoustic communication constraints

I. INTRODUCTION

Cooperative control of multi-robot systems is a subject that has triggered the interest of the research community in recent years. In many applications, a given task can be too complex for a single robot, and hence a multi-robot system working cooperatively is required to complete the task. Compared to the single-robot system, multi-robot system is more robust because a team of robots provides certain amount of redundancy when some of the robots malfunction. Cooperative control has also received significant attention in the field of multiple autonomous underwater vehicles (AUVs) because of its potential applications in many fields, such as oceanographic research, seafloor survey, and underwater archeology and so on.

Formation control is a fundamental problem in multi-AUVs cooperation. When we have a set of moving AUVs that should travel according to a desired pattern, we say that we are in the presence of a formation control problem [1]. Typically, each AUV in the system should be able to keep a constant distance that separates it from its neighbors, or a distance and direction to a designated neighbor. There are many theoretical methods for solving this problem. But when applying these methods to an actual multiple AUVs system, communication constraints need to be considered because acoustic communication among multiple AUVs often is unreliable in actual ocean environment. This paper focuses on application and validation of a leader-follower approach on multi-AUVs formation maintenance with acoustic communication constraints.

A variety of approaches has been proposed for formation control, including virtual structure [2], leader-follower [3] and behavior-based [4]. Approaches similar to virtual structure include the action reference scheme [5] and virtual leader approach [6]. The basic idea of this approach is to specify a virtual coordinate frame or a virtual leader as a reference for the whole group, such that the desired states of each vehicle can be defined relative to the virtual coordinate frame or the virtual leader. As a result, single vehicle path planning and trajectory generation schemes can be employed [7]. Behavior-based approach designs intuitive and simple behaviors or motion primitives for each individual vehicle at first. By a weighted sum of these primitives, more complex motion patterns are generated through the interaction of several vehicles then [8]. In the leader-follower approach, the leader tracks a predefined path while the follower maintains a desired geometric configuration with the leader. The follower can in turn be designated as a leader for another vehicle, which results in a scalability formation. The advantage of this approach is that a reference trajectory is clearly defined and the internal formation stability is induced by the control law of individual vehicles [9]. There are also other strategies for multi-AUVs formation control. Saba Emrani presented an adaptive control rule mainly based on inverse dynamics of the plant to deal with the hydrodynamic parameter uncertainties of AUVs in formation [10]. D.B. Edwards proposed a leader-follower formation-flying control algorithm and applied it to one-, two- and three-dimensional formations of multiple AUVs [11]. Rongxin Cui studied the formation control problem of AUVs under fixed topology [12]. Jihong Li presented a stable formation control scheme for multiple underactuated AUVs where only surge force and rudder angle are available for the vehicle's horizontal motions [13]. However, the projects reported in literature usually do not take acoustic communication constraints into account, or have only been presented in simulation; few of them have been verified on experimental platforms.

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In this paper, the acoustic communication constraints in multi-AUVs system are tested based on experiments in Qiandao Lake. LinkQuest UWM2000 underwater modem is employed for communication among multiple AUVs during the lake tests. The communication interval between two nodes and packet loss rate are gotten based on experimental data. A leader-follower formation control method under the acoustic communication constraints is proposed. The formation control is modeled by a unified, distributed architecture. The hierarchical architecture consists of three layers: a leader, the formation controllers and the followers. In this architecture the assumption that in every control period each follower always knows the leader's state is rather restrictive in actual environment. So we present a predictive control method for the followers to estimate the leader state from available data and prior knowledge. And a leader based formation controller is proposed for keeping the desired formation geometry. The proposed formation control method is implemented and validated on a two-AUVs system in Qiandao Lake experiments. One is the leader that follows a scheduled path. And the other acts as a follower that keeps a virtual triangle formation with the leader. The experiment result shows that the follower can maintain a good formation with the leader. An improved algorithm is also proposed to reduce negative effect caused by communication constraints. Simulation shows the performance is improved in this way.

This paper is organized as follows. In Section 2, we introduce LinkQuset UWM2000 underwater acoustic modem and the communication test results. Section 3 presents the control architecture and proposes a formation control algorithm based on LOS (line of sight) guidance; an improved algorithm is also detailed in this section. Section 4 analyzes some of the achieved results, both in simulation and in real experiments. We finish by presenting discussion, conclusions and future work, in Section 5.

II. LINKQUEST UWM2000

LinkQuest's underwater acoustic modems have been used extensively in some commercial AUVs such as Hugin 3000 AUV, Boeing's Commercial Deepwater AUV, the advanced US Navy AUV, Gavia AUV and so on. The modems can be used to highly reliable command and control of the AUV and high speed data link for image and data transfer from the AUV to surface support ship [14]. The modem that we used is UWM2000, whose main specification is shown in Table I.

Two UWM2000 modems are placed downward from a mooring ship and acted as two static communication nodes in the experiments. The communication strategies between two nodes are following: 1) The No.1 modem is commanded to reset the protocol and status, and sends a request message to the No.2 modem; 2) the No.2 modem will immediately response a message including the AUV's state data when it receives the request message, and 10 seconds later run the reset command. 3) T seconds later, return to the first step.

Firstly we set T=13 and the result is that the No.1 modem mostly can't receive the response message from the No.2 modem. So we set T=20 and runs for 769 periods, in which the total is 747 times for succeed in communication and the packet loss rate is almost 2.86%。The many experiments' results show that the communication interval between two nodes is almost 20 seconds (T=20) for good communication with the almost 3% packet loss rate.

TABLE I. MAIN SPECIFICATION OF THE UWM2000 UNDERWATER ACOUSTIC MODEMS

RS-232 data rate:	9600 bits/second
Payload data rate:	6600 bits/sec
Acoustic link:	17.8 kbits/sec
Working range:	1200 m(omni-directional)
Maximum depth:	2000m
Beam width of transducer:	210 degrees
Operating Frequency:	26.77 to 44.62 kHz
Communication mode:	Half duplex
RS-232 Configuration:	9600bps, 1 start bit, 1 stop bit, no parity bit, and no flow control
Voltage:	12~24V

III. FORMATION CONTROL OF MULTIPLE AUVS

A. *Configuration and defination*

We use a leader-follower strategy to organize the AUV team. The team is modeled by a unified, distributed architecture. The hierarchical architecture consists of three layers: a leader, the formation controllers and the followers. The purpose of the leader AUV is to act as a team leader. It knows where the final destination of the team is, and heads straightly towards it. If the final destination is changed, the leader will change its path. The followers, however, have no global knowledge; they follow the leader, and keep a predefined distance and angle with respect to its leader. When all the vehicles are in the expected positions, the desired formation is established. In this architecture the assumption that in every control period each follower always knows the leader state is rather restrictive in actual environment. So we present a predictive method for the followers to estimate the leader state from available data and prior knowledge. And a leader-based formation controller is proposed to maintain the relative positions of the AUVs.

When we only have two AUVs travelling in a formation, the position of the follower relative to the leader needs to be clearly defined, so a leader coordinate is defined as Figure 1. In this figure, the E-O-N coordinate represents the earth-fixed coordinate frame, and the x-L-y coordinate represents a leader coordinate frame. The input of the controller is the leader state L[Le, Ln], which is estimated through the data from the leader to the follower at a defined interval. The position of the follower is F[Fx, Fy] in the leader coordinate frame, while F[Fe, Fn] in the earth-fixed coordinate frame. M[Me, Mn] represents the destination of the leader, and it is changeable during the voyage. As L[Le, Ln] and M[Me, Mn] can change, relative relationship between the two coordinate can be changeable. So the orientation angle between them is defined as

$$\theta = \arctan\frac{M_n - L_n}{M_e - L_e} \quad (1)$$

The formation D is represented by the vector [Dx Dy]. The desired position of the follower is Fd[Fdx, Fdy]. The position of the follower is calculated by the formula:

$$F_x = (F_e - L_e)\cos\theta + (F_n - L_n)\sin\theta \quad (2)$$

$$F_y = (F_e - L_e)\sin\theta - (F_n - L_n)\cos\theta \quad (3)$$

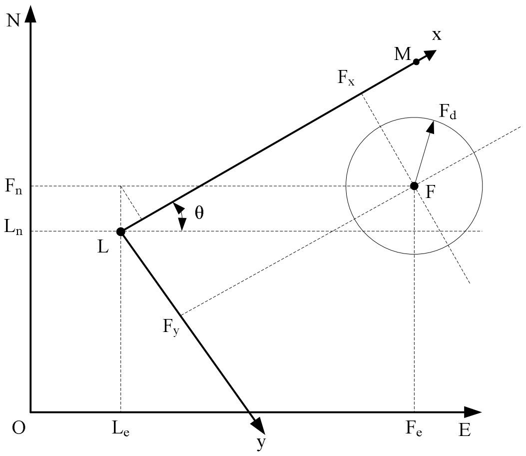

Fig. 1. The defination of the formation in the leader coordinates. L is leader and F is follower. F_d is the desired position of a follower.

B. Formation Control Algorithm Based on LOS Guidance

As can be seen from figure 1, the desired position of the follower is F_d, while the actual position of it is F. So the purpose of the formation control can be described as $F_x \to D_x$, $F_y \to D_y$. Besides, when follower arrived at its desired position, it should keep the same yaw angle as the leader, namely $\psi_F \to \psi_L$. So the formation control error is defined in two directions as:

$$e_x = F_x - F_{dx},\ e_y = F_y - F_{dy}$$

As the x axis of leader coordinate is defined by leader's position and its destination, this axis is in fact the path for the leader to follow. And the follower should follow a path parallel to it. So the desired path that the leader follows is $y = 0$ and the follower follows $y = D_y$. To regulate the formation control error to zero, we need to control the surge speed u and the yaw angle ψ. For the leader, it keeps surge at a constant speed u_l^d, and its yaw angle is zero in the leader coordinate. As the input of the controller is relative to the earth-fixed coordinate, the desired yaw angle for the leader is $\psi_l^d = \theta$. For the follower, the desired yaw angle is defined with the help of LOS guidance [15~16]. For LOS guidance, we pick a point lies a distance $\Delta > 0$ ahead of the vehicle, along the follower's desired path. The angle describing the orientation from the follower's position to the point picked is referred to as the LOS angle. The LOS angles can be given by the following expression:

$$\psi_{LOS} = \arctan\frac{e_y}{\Delta} \quad (4)$$

As the input of the controller is relative to the earth-fixed coordinate, the orientation angle between the two coordinate should be taken into account. So the desired yaw angle for the follower is:

$$\psi_f^d = \theta + \psi_{LOS} \quad (5)$$

Then it is:

$$\psi_f^d = \theta + \arctan\frac{(F_y - F_{dy})}{\Delta} \quad (6)$$

The desired surge speed of the follower can be given as:

$$u_f^d = u_l^d - \chi(e_x) \quad (7)$$

The follower's desired speed is consisted of two parts, u_l^d represents basic speed while χ represents an adjustment on error along the desired path. Function χ should meet the following requirements: 1) $\chi(-x) = -\chi(x)$; 2) $\chi'(\bullet) \geq 0$; and 3) $|\chi(\bullet)| < m$, m is a predefined positive value. Then the adjustment can be $\chi(\bullet) = a \times \arctan(\bullet)$ for instance.

C. Improved algorithem

Simulation results show that the algorithm proposed above can work well following a straight path, even with a large delay of underwater acoustic communication. But at the turning phase, it fails to perform as expected. So an improved algorithm is proposed.

In the original algorithm, the follower's desired yaw angle is (6), and Δ is regard as a constant value. It doesn't matter when follows a straight path, but at turning point, the pre-determined Δ may become improper, and there's no way to change it. So in the improved algorithm, it can be auto-adjusted according to comparison between e_x and e_y. Then

$$\Delta = k_c + \varphi(e_x - e_y) \quad (8)$$

In this formula, k_c represents a constant value and φ denotes an adjustment. For example, φ can be $k_a \times \text{sgn}(e_x - e_y)$. With this adjustment, the follower's desired yaw angle relate to not only e_y but also e_x . So speed is increased in the direction with a bigger error, and error is decreased in that direction. This method may sacrifice the control accuracy in the other direction, but the global performance is improved, especially at the turning phase.

IV. Expriental Results

This section presents our experimental results of the formation control. We first show the simulation results derived in MATLAB, and then experimentally implement and validate the proposed formation control on a multi-AUVs platform. The experiments are conducted with a single leader-follower system.

A. Simulation Results of the original algrithm

We show the simulation results of how well the proposed algorithms work with acoustic communication constraints. The simulation results prove that the control algorithms theoretically work with communication delay and packet loss. The formation is defined as $D=(-20,-30)$ and other parameters are defined as following:

$$\Delta = 10m \, , u_l^d = 1.5m/s \, , \chi(\bullet) = \frac{3}{\pi}\arctan(\bullet)$$

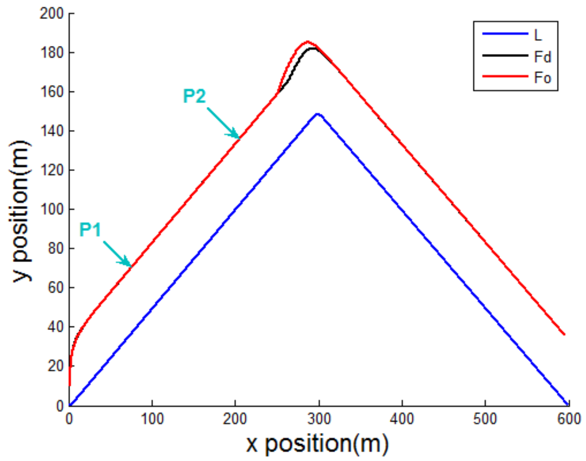

Fig. 2. Trajectory of the system. L denotes the trajectory of the leader AUV, F_d denotes the trajectory of the follower without acoustic communicaiton constrains, while F_o denotes the trajectory of the follower with acoustic communication constrains.

As has been discussed above, the communication interval between nodes is almost 20 seconds for good communication with 3% packet loss rate, so the communication delay between leader and follower is set as 20 seconds. Packet loss should also be taken into account. As packet losses usually happen continuously, so they are set continuously at two phases, one is at line-path phase while the other is at turning phase. Situation without acoustic communication constrains is also simulated as a contrast. The simulation results are shown in figure 2 and figure 3.

P1 represents 2-times continuous packet losses (from 60s to 100s) in the line-path phase, while P2 represents 3-times continuous packet losses (from 200s to 260s) in the turning phase. As is shown in Figure 2 and Figure 3, communication delay and packet loss have a negative effect on the formation control, but the algorithm can ensure that the system maintains the formation at last.

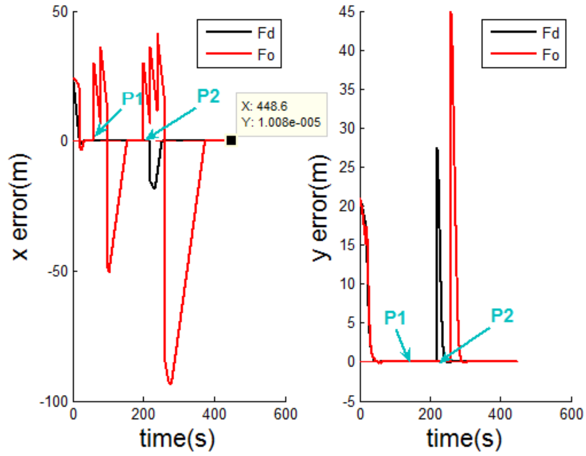

Fig. 3. The formation variebles of the system. x error and y error respectively denote the error along x axise and y axise. F_d denotes the error without communication constrains while F_o denotes the error with communcaiton constrains.

B. Experimental Results

The proposed formation control method is implemented and validated on a two-AUVs system in Qiandao Lake experiments. One is the leader that follows a scheduled path. And the other acts as a follower that keeps a virtual triangle formation with the leader.

Dx and Dy is initialized by -50 and 50. The leader needs to sail from point A to B with the desired velocity of 3 knots. The experiment results are shown in Figure 4 and Figure 5. The follower can maintain a good formation with the leader, and the transverse formation error is less than 10%, the longitudinal formation error is less than 5% in steady state.

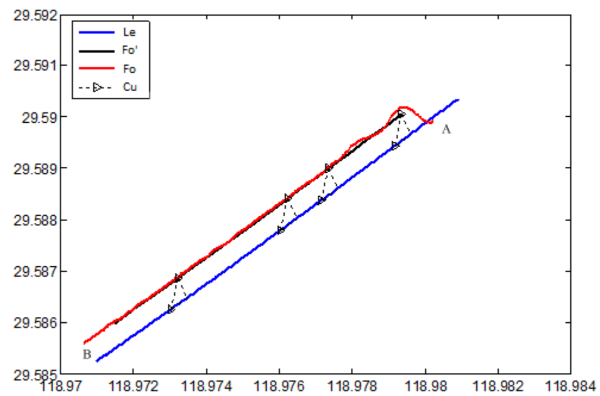

Fig. 4. The trajectories of two AUVs keeping a virtual triangle formation in a lake experiment. Le denotes the trajectory of the leader AUV. Fo' denotes the desired trajectory of the follower AUV. Fo denotes the trajectory of the follower AUV. Cu denotes the positions of two AUVs when the follower receives the leader's message through acoustic communication.

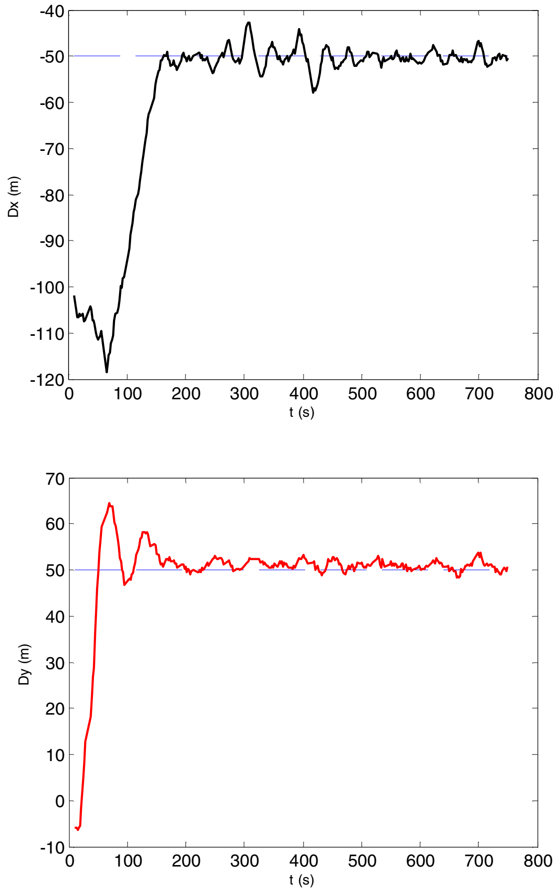

Fig. 5. The formation varieble of two AUVs. Dx and Dy respectively denote the transverse and longitudinal distance.

C. *Simulation of the improved algorithem*

The simulation of the improved algorithm is shown in Figure 6 and Figure 7. The desired formation is defined as $D=(-20,-30)$, $k_c=15$ and $\varphi=5\times\mathrm{sgn}(e_x-e_y)$. So the desired yaw angle for the follower is:

$$\psi_a^d=\theta+\frac{y_f-y_f^d}{15+5\times\mathrm{sgn}(\left|x_f-x_f^d\right|-\left|y_f-y_f^d\right|)}$$

And the desired speed for the follower is:

$$u_a^d=u_l^d-\frac{3}{\pi}\arctan(x_f-x_f^d)\,.$$

The original algorithm is also simulated as a contrast.

As can be seen from the figures, the performance is improved.

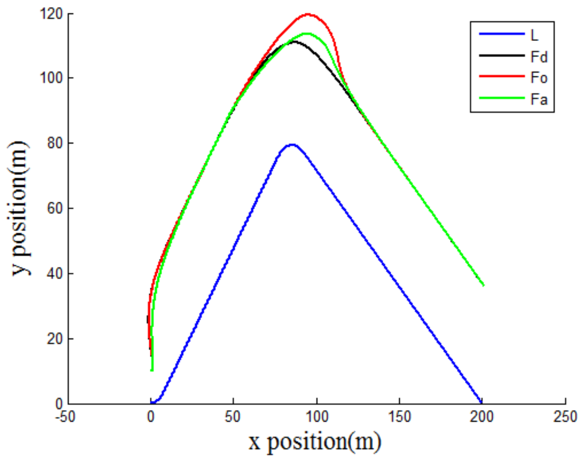

Fig. 6. Trajectory of the system. L denotes the trajectory of the leader AUV, F_d denotes the desired trajectory of the follower. F_o denotes the trajectory of the follower with original algrothem while F_a the improved algrothem.

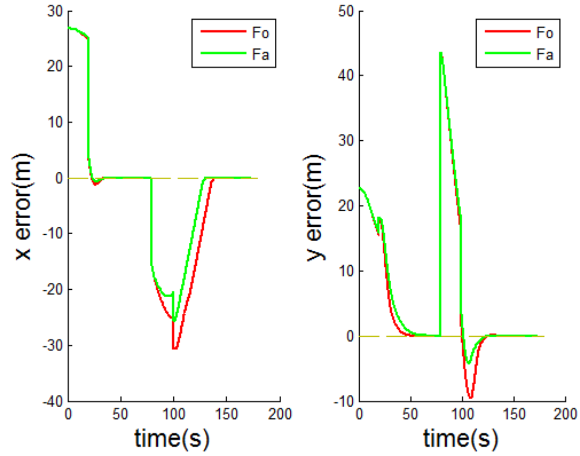

Fig. 7. The formation varieble of the system. x error and y error respectively denote the error along x axise and y axise. F_o denotes error with the original algrothem while F_a the improved one.

V. Conclusion and Future Reasearch

In conclusion the proposed method is effective and feasible when keeping a formation with a large delay of underwater acoustic communication. The experiment results show that it is suitable for the short-time communication interruption. In the following research we will continue to improve this method for formation control with less or no communication data.

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