A Formation Control Algorithm by Modified Next-state Approximation to Reduce Communication Requirements in Multirobot Systems

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Abstract: Multiple robot systems are employed in various applications to get the complex tasks carried out by a group of robots. When Autonomous Underwater Vehicles (AUVs) are employed for underwater missions, they provide higher quality data, more coverage and reduces the mission time, thus resulting in huge cost savings. However, the formation control of such robots depends to a great extent on the communication requirements between the robots. In this paper, we propose a modified next-state approximation algorithm to control the leader follower formation of multiple AUV's which reduces the communication requirements. The controller drives each follower robot to the next desired position by eliminating the error between the next actual position of follower AUV, computed by considering its current and previous position and its next desired position by using a PID controller. Since this algorithm is independent of time step between states, the amount of information to be transmitted can be reduced by increasing the time steps. The design of the formation controller and its simulation studies for a group of AUVs are presented. The results confirm that the time step increase doesn't affect the path accuracy and hence the communication requirements get reduced.

1 INTRODUCTION

Multiple robots are used to perform various tasks in an efficient way. Multiple AUVs are increasingly being considered as a means to perform research, survey and defense missions in underwater. Their formation control has become an area that has evoked the attention of several researchers in recent times. Currently, there are three main approaches for formation control, namely, behavior based method (Balch and Arkin, 1998), virtual structure method (Ren and Beard, 2003), and leader follower method (Chen and Serrani, 2003). In behavior based approach several behaviors are taken into account and action is taken by weighing the relative importance of each behavior. The main problem of this approach is the difficulty in mathematical formalization and as a result convergence of formation to desired configuration cannot be easily guaranteed. The virtual structure approach considers the formation as a single virtual rigid structure. The difficulty with this approach is that a large inter robot communication bandwidth is required. In leader follower approach an AUV is assigned as leader and others as followers. The followers are supposed to maintain a desired distance and orientation with respect to the leader AUV, thereby forming a formation as a whole. The reference trajectory and the missions for the entire trajectory will be communicated only to the leader AUV. Thus there will be only local communication between leader and follower rather than global, thereby ensuring flexibility and mission safety.

Many of the existing formation controllers try to sense the current position of follower AUV and align it to desired path. This may result in slow response, and convergence to desired trajectory can be troublesome when there is an unexpected change in leader trajectory. In one of the earlier works, a state estimation algorithm was proposed where the follower AUV tries to estimate its future position and operating scenarios and drives itself to the desired future state (Neettiyath and Thondiyath, 2012). This method is advantageous when compared to other leader follower methods as it focuses on eliminating

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the error at the next position rather than at the current position. As a result of this, the response time decreases and alignment with desired path takes place quicker. However, the next-state estimation depends on the time-step and as the time step increases the path error increases. This necessitates very small time-steps to reduce error and it leads to increased communication between leader and follower. This is not at all desirable as underwater communication is generally slow and noisy.

In this paper we present an algorithm which is an improved version of state estimation based formation control algorithm presented in (Neettiyath and Thondiyath, 2012). Changes are brought about in the way the next state is estimated and also on how the error between the next estimated and desired position is reduced. The next position was computed by considering a general path for the motion of AUVs and stability was maintained by removing the error between the next desired position and estimated position by adapting and modifying the error removal method mentioned in (Consolini et al., 2008). This method reduces the communication among AUVs as the number of pose calculations are reduced. The paper is organized in the following way: Section 2 describes the algorithm in detail. The method of implementation and results are discussed in section 3. Section 4 summarizes the paper and indicates the scope and future work.

2 FORMATION CONTROL ALGORITHM

In Section 2.1 method of next state approximation for a leader-follower type formation control is explained and in section 2.2 method of stabilization by error removal is explained.

2.1 Next-state Estimation

According to (Neettiyath and Thondiyath, 2012), the next state is estimated as follows:

$$\eta_{Le}(t+1) = \eta_L(t) + (\eta_L(t) - \eta_L(t-1)) \quad (1)$$

$$\eta_{Fe}(t+1) = \eta_F(t) + (\eta_F(t) - \eta_F(t-1)) \quad (2)$$

where η_F and η_L represents pose (x, y, z, Roll (φ), Pitch (Θ) and Yaw (ψ) - Here 2 dimensional case is being considered, therefore z, Roll (φ) and Pitch (Θ) do not change and are taken to be equal to zero) of the follower and leader respectively and η_{Fe} and η_{Le} represents the estimated position of the follower and leader AUV and this is calculated for time t+1(next position).

This is done on the assumption that the AUV undergoes uniform motion. For any general case the above equation is valid for Yaw (ψ) - Angular orientation at next position is equal to current plus the change between the current and the previous. But when this is done for both x and y coordinate the next position will lie on the straight line joining current and previous position. This means by default it is assumed that the trajectory is straight line, which is not true.

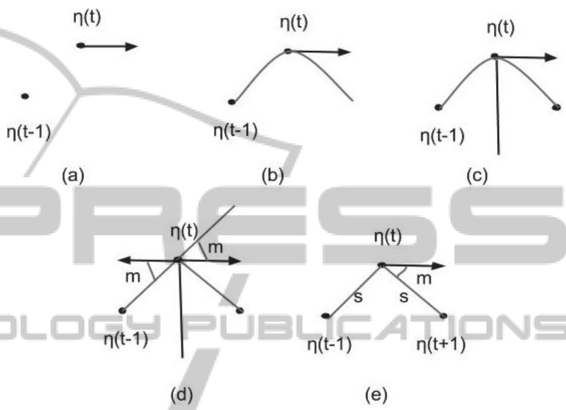


Figure 1: Next state estimation.

The next position (η (t+1)) should lie on an arc connecting previous (η (t-1)) and current position (η (t)), with the current orientation being tangent to the arc (Figure 1-(b)). By assuming uniform motion the next and previous positions (x, y) should be symmetric with respect to the normal to current orientation (Figure 1-(c)). The distance between the current and previous position should be same as that between the next and current position. Let 'm' be the angle the line joining current position with previous position makes with the negative of current orientation which is same as the angle that the line joining previous to current position makes with current orientation (Figure 1-(d)).

$$m = \tan^{-1}\frac{(y(t)-y(t-1))}{(x(t)-x(t-1)))} - \psi(t) \quad (3)$$

where x(t) and y(t) are x and y coordinates at time t. Symmetry condition shows that the angle between current orientation and the line joining current to next position should also be m (Figure 1-(e)).

Therefore final position is given by

$$\eta[1] = x(t+1) = x(t) + s * \cos(\psi(t) - m) \quad (4)$$

$$\eta[2] = y(t+1) = y(t) + s * \sin(\psi(t) - m) \quad (5)$$

where

$$s = ((y(t)-y(t-1))^2 + (x(t)-x(t-1))^2)^{0.5} \quad (6)$$

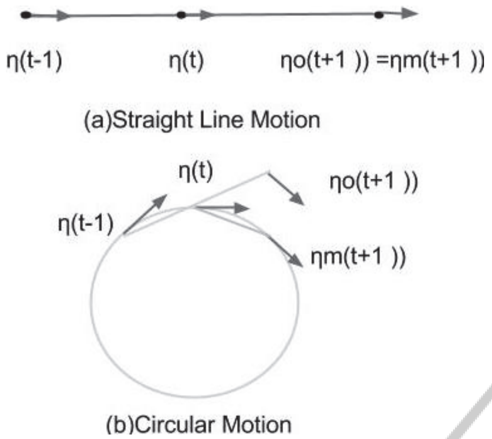


Figure 2: Comparison of Next state estimated by two methods.

The next position calculated by the method mentioned in (Neettiyath and Thondiyath, 2012) ($\eta_o(t+1)$) and the above mentioned modified method ($\eta_m(t+1)$) for two different cases of motion (straight line and circular) is shown in figure 2. It is clear from the figure that for straight line motion estimated position by both methods remains same but for circular motion it is evident that the modified method gives correct solution. Therefore we can conclude that the modified next state estimation method is better for a general case.

The next positions of leader and follower was calculated by above method. In the case of L- α method of formation control (Neettiyath and Thondiyath, 2012), the desired next position of the follower can be computed from expected next position of leader and from l and α values using pure geometry as

$$\eta_{Fd}(t+1)=\eta_{Le}(t)+\mathbf{R}(\psi(t+1))\ \mathbf{R}(\alpha)\begin{bmatrix} l \\ 0 \end{bmatrix} \tag{7}$$

Where $\mathbf{R}(\psi(t+1))$ is rotational matrix and $\psi(t+1)$ is the yaw angle of leader at ‘t+1’.

$$\mathbf{R}(x) = \begin{bmatrix} \cos(x) & -\sin(x) & 0 \\ \sin(x) & \cos(x) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{8}$$

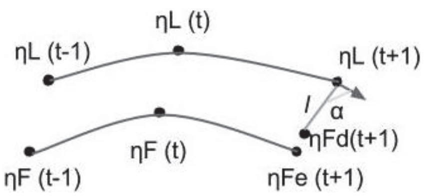


Figure 3: Position of leader and follower at different time.

2.2 Stabilization Making the Error Zero

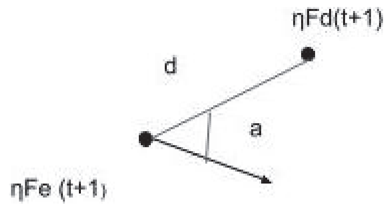


Figure 4: Estimated and desired position of follower.

As shown in figure 4 let 'd' denote the distance between the desired follower position and estimated actual follower position at time 't+1'.Let 'a' denote the angle this line makes with the orientation of the follower AUV. Then

$$\delta v = d * \cos(a) \tag{9}$$

$$\delta\omega = d * \sin(a) \tag{10}$$

Where δv and δω represents the linear and angular velocity error respectively.

This error was given as an input to the PID controller which finally reduces it to zero. Linear and Angular velocity at time t+1 can be written in terms of the current velocity and this error.

$$v(t+1)=v(t)+K_{pv}(\delta v)+K_{iv}\,\Sigma(\delta v)+K_{dv}(\Delta(\delta v)) \tag{11}$$

$$\omega(t+1)=\omega(t)+K_{p\omega}(\delta\omega)+K_{i\omega}\Sigma(\delta\omega)+K_{d\omega}(\Delta(\delta\omega)) \tag{12}$$

Several tuning methods are there to obtain Proportional Gain (K_p), Integral Gain (K_i) and Derivative Gain (K_d) where subscript v and ω indicate that it corresponds to linear and angular velocity respectively. Manual tuning was used in our experiment. The major advantage of stabilization by this method over that in (Neettiyath and Thondiyath, 2012) is that it does not depend upon time step between different states.

3 IMPLEMENTATION AND RESULTS

The proposed algorithm was developed and tested using simulation by modeling the system in Matlab/Simulink. Dynamics was taken into account while modeling the AUV. In the following sections the implementation method and few of the simulations implemented are explained.

3.1 Implementation

Figure 5 shows the formation controller

implementation for the leader follower formation. Formation controller (Global) is used to supply the formation parameters to the individual followers at each point of time, thereby holding the formation together. The parameters can be changed with respect to time to obtain different formations. The leader AUV has 'Trajectory Generator' block which generates the trajectory of motion, whereas follower AUV has Formation Controller (local) which uses the proposed algorithm to compute the velocity correction signal. AUV is maintained at a specified velocity by actuating the thrusters in the velocity controller. Kinematics and Dynamics of the AUV was modeled and incorporated as in (Neettiyath and Thondiyath, 2012; (Fossen, 1994); (Yuh, 2000).

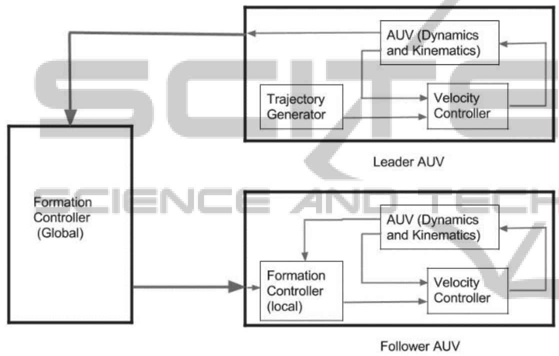


Figure 5: Formation controller implementation.

3.2 Results

3.2.1 Comparison

A situation was considered when the leader initially moved in a straight line path and then in a semicircular arc (Figure 6-(a)). Two followers were made to follow the leader in same paths maintaining a constant formation [l=2 α = -90^0]. Follower 1 uses the proposed strategy whereas follower 2 uses the old one. Both follows the leader in the desired path when the leader underwent straight line motion. But when leader started moving in the semicircular arc follower 1 moved in the desired path whereas follower 2 started deviating from the path and finally ended up losing track. Follower 1 maintains the formation till the end with minimal error (l and α) (Figure-6 (b), (c)).

Even Follower 2 will maintain the desired path if the time step is decreased. But this means that an increase in the total number of computations. The effect is clearer when the time step increases exponentially. Initially time step [t_0] is considered such that follower 2 follows the leader (Figure 7-(a)).Then time step is made $10t_0$ (Figure 7-(b)) and $100t_0$ (Figure 7-(c)) during which follower 2 loses track when leader starts moving in circular part. In all three cases follower 1 moves in the desired path with minimum error.

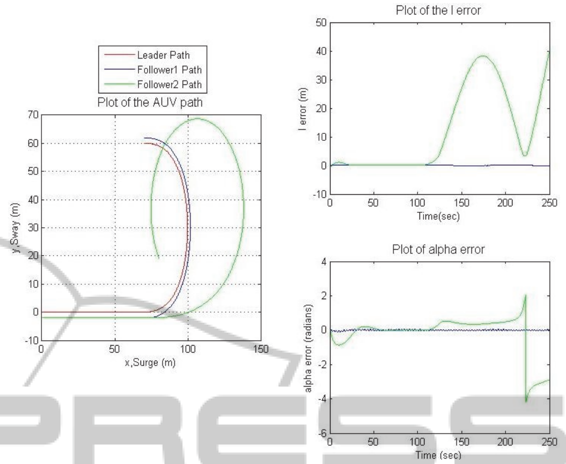


Figure 6: Comparison of both Algorithms under constant formation.

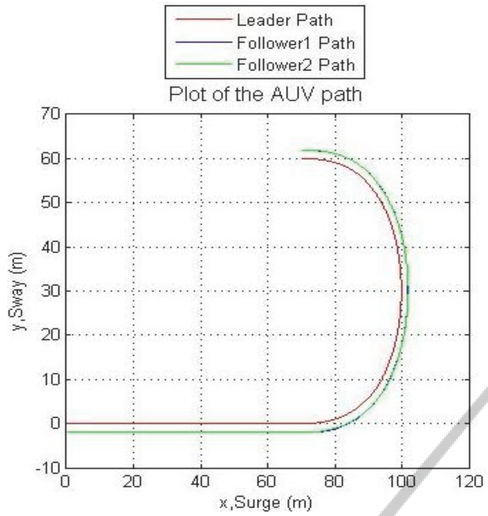
This result has large implications as the number of computations of the next state can be brought down by increasing time steps. This means that the number of times the follower communicates with the leader can be brought down which is highly desirable in underwater systems where communication occurs slowly and in a noisy environment.

3.2.2 Constant Formation

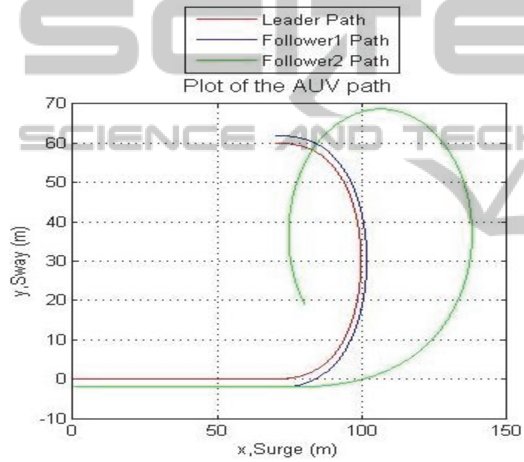
The position of each follower AUV in the formation with respect to the leader AUV was maintained constant. In Figure 8 leader was made to move horizontally initially, then in an upward inclined path followed by horizontal path and finally a path that is inclined downwards. Both followers were maintained at α = -90^0 and l value was 2 and 4 respectively for 1 and 2. It is seen that the follower maintains the formation.

3.2.3 Variable Formation

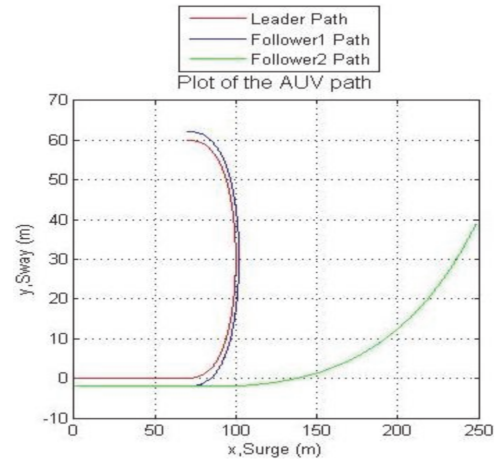
Simulation was done for the case when formation varies with respect to the leader. A situation was considered when the leader moves in a straight line and the followers undergoes circular motion around the leader. The radius of rotation changes from 4 (l=4) to 2 (l=2) for both followers at the same time α changes from -90^0 to 990^0 for the first follower whereas it changes from 90^0 to 1170^0 for the second. Each follower completes 3 rotations around the leader AUV. A 3D plot of the same is shown in figure 9.



(a)



(b)



(c)

Figure 7: Comparison of motion for different time steps.

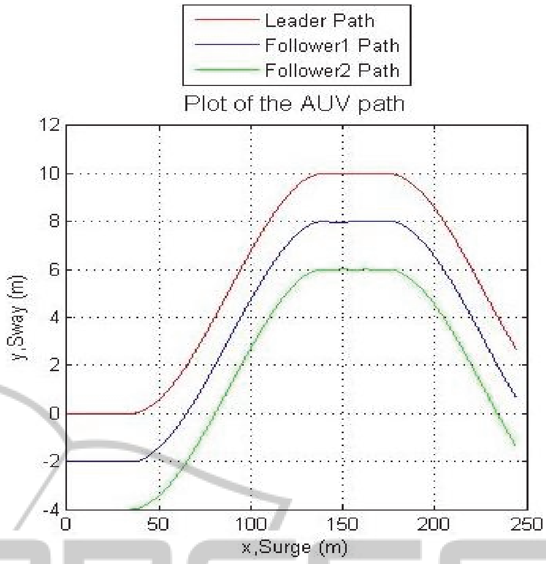


Figure 8: AUV Motion when the formation is fixed.

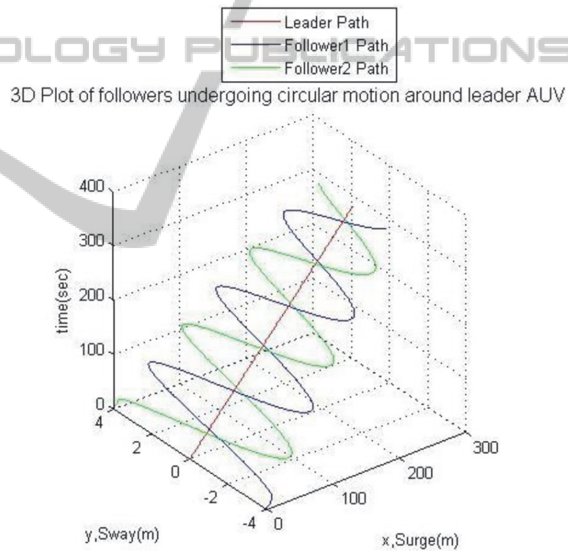


Figure 9: 3D plot when followers undergoes a circular motion around leader.

4 CONCLUSIONS

An improved state estimation algorithm is proposed and simulations have been done to prove its validity. The main advantage of this algorithm over the already existing one is that the communication between leader and follower AUVs can be brought down, which is a highly beneficial result as underwater communications are generally slow and noisy. This also results in reduction in the number of computations and the dependency on time step between states has been eliminated. This algorithm is mainly applicable in situations where the number sudden changes in direction of motion is low in the entire path of motion. Future work would be to extent this algorithm to 3 Dimensional motion of robots.

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