Improved Leader Follower Formation Control of Autonomous Underwater Vehicles using State Estimation

Umesh Neettiyath and Asokan Thondiyath
Department of Engineering Design, Indian Institute of Technology Madras, Chennai, India

Keywords: Underwater Robots, Leader Follower Control, Formation Control, AUV, Multirobot Systems.

Abstract: Multi robot coordination and control for underwater robots is an area of significant importance in many underwater missions. A new approach for leader follower formation control of multi AUV systems is explored in this paper. The controller estimates the next desired position of the follower robot from the past and current positions of the leader and follower robots. The control signals are then issued to the follower robot to align it to the estimated trajectory. This control scheme has the capability to compensate for initial errors and follow the leader under various operational scenarios. The development of the controller and simulation results for selected scenarios are presented. The results show that the proposed method is simple and computationally efficient.

1 INTRODUCTION

Among technologies employed for underwater missions, Autonomous Underwater Vehicles (AUVs) play a major role. Their applications range from environmental research to military missions. As the complexity of the tasks increases, it becomes necessary to deploy more than one AUV to accomplish specific missions. MultiAUV systems are cheaper, more robust and provides better data quality compared to its alternatives (Yuh, 2000).

Success in a multi AUV system depends on having a good formation control scheme. Researchers have proposed methods such as behavioral, leader follower, artificial potential fields, and virtual structures. Leader follower systems are useful for smaller teams of robots (Desai et al., 1998; Fahimi, 2009). Much of the existing controllers try to sense the position of the follower and tries to align it to the desired path. This is slow and the convergence to the desired trajectory can be troublesome when there are unexpected changes in leader trajectory such as dynamic obstacle avoidance.

The proposed approach on the other hand tries to estimate its future position and tries to drive the robot to the desired future state. It is based on $l-\alpha$ controller which is a popular leader follower scheme. It also has the advantage of being able to operate with only local information collected from sensors, with having to rely upon external communication minimally. This is highly desirable in underwater systems which has to depend on slow noisy acoustic communication.

2 MODELING OF AUV

In order to represent the motion of an AUV in a 3-dimensional space, we usually resort to two coordinate frames. The inertial or global coordinate frame is located at a point of the user's convenience, for e.g. mother ship; it is considered to be non-moving. The body or local coordinate frame is located on the AUV and it moves along with the AUV.

2.1 Kinematics and Dynamics of AUV

A six dimensional space is required to fully represent the motion of an AUV in 3-dimensional space. The position coordinates are represented by η in the global coordinate frame and velocity coordinates are represented by ν in the body fixed coordinate frame (Antonelli et al., 2008; Fossen, 1994). Euler angles are used to represent orientation. Using above terms, kinematics of AUV can be written down as

$$\dot{\eta} = \mathbf{J}(\eta)\nu \tag{1}$$

where $\mathbf{J}(\eta)$ is called the Jacobian.

Neettiyath U. and Thondiyath A..
Improved Leader Follower Formation Control of Autonomous Underwater Vehicles using State Estimation.
DOI: 10.5220/0004042104720475
In *Proceedings of the 9th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2012), pages 472-475
ISBN: 978-989-8565-22-8

The dynamics of AUV can be expressed as (Fossen, 1994; Yuh, 2000)

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathrm{v})\mathbf{v} + \mathbf{D}(\mathrm{v})\mathbf{v} + \mathbf{g}(\eta) = \tau \tag{2}$$

where $\mathbf{M}$, is the inertia matrix, $\mathbf{C}(\mathrm{v})$ is the Coriolis and centripetal matrix, $\mathbf{D}(\mathrm{v})$ is the damping matrix and $g(\eta)$ represents the restoring forces and moments, which account for the gravitational and buoyancy forces.τ is the sum of external forces, i.e. thruster and control plane forces and underwater currents or other disturbances. The current work does not take into consideration, the environmental forces.

3 HIERARCHICAL CONTROLLER FOR AUV

The general control strategy proposed for the AUV formation is shown in figure 1. The multi layered hierarchical controller is designed so as to encompass the requirements of various missions and interoperability. Another important goal is to minimize or nullify the amount of data communication between robots. The method, though proposed for AUVs, may be used in other types of robots as well; this was not investigated in the scope of this work.

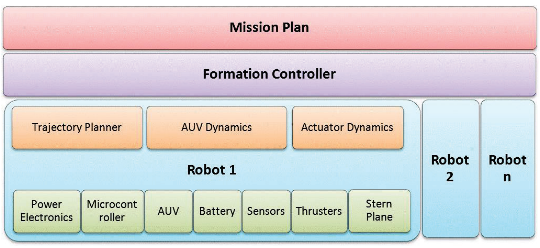

Figure 1: Multi layered architecture for the controller.

A mission plan specifies all the details required for the task such as the number of robots, their role in the formation, desired trajectory for the leader and the inflection points, i.e, when there is a predefined change of formation. These details must be programmed before the start of mission by a human operator.

Formation controller can reside either globally (as shown in figure 1) or in the leader AUV. It gets activated only at an inflection point to change the formation type or parameters. Otherwise, the robots follow their leader without any explicit communication.

The two lowest layers functions in all the AUVs. The upper layer takes the commands from the formation controller and initiates actuation. The trajectory planner takes into consideration all the dynamic and kinematic parameters to calculate the control signals for the low level subsystems. The lower layer inside the vehicle contains all physical resources of the vehicle including sensors, actuators and the electronic circuitry.

3.1 Improved $l-\alpha$ Controller

The proposed improved $l-\alpha$ controller, forms part of the trajectory planner in the follower robot. It takes the pose information from the leader and follower and process them to estimate the future positions. For this purpose, a time history of a number of previous positions are stored in the controller.

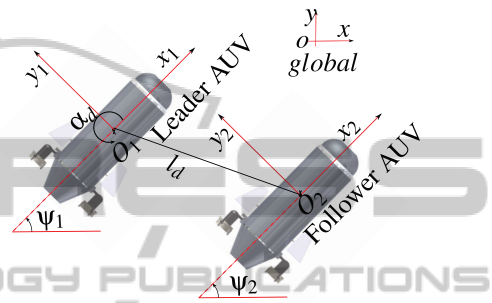

Figure 2: Parameters for a leader follower scheme.

This can be explained using figure 2. The leader AUV is located at O_1 and moves along a predefined trajectory. The follower AUV is located at O_2 and tries to follow the leader. The line O_1O_2 is expected to be maintained at length l_d and at an angle α_d with the local x axis of the leader. To achieve this, the desired next position of the follower is determined from the expected next position of the leader as

$$\eta_{\mathbf{2d}}(t+1) = \eta_{\mathbf{1}}(t+1) + \mathbf{Tr}(\psi(t+1))\mathbf{Tr}(\alpha_d)\begin{bmatrix} l_d \\ 0 \end{bmatrix} \tag{3}$$

where $\mathbf{Tr}(\psi(t+1))$ denotes the rotational transformation matrix., defined as(Xiang et al., 2009)

$$\mathbf{Tr}(\chi) = \begin{bmatrix} \cos\chi & -\sin\chi & 0 \\ \sin\chi & \cos\chi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

3.2 Next State Estimation

The controller estimates the next positions of the leader and follower as shown in figure 3. The robot is assumed to have a constant velocity in all directions for interval of time from the past measured time instant to the next time instant to be measured. The sampling time is also assumed to be constant. The expected next position of the leader robot is estimated using equation 5.

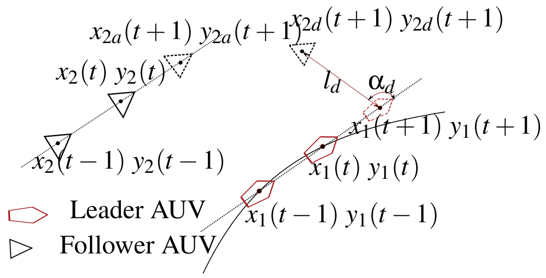

Figure 3: Estimation of next position of leader and follower.

$$\eta_1(t+1) = (\eta_1(t) - \eta_1(t-1)) + \eta_1(t) \quad (5)$$

Similarly, we can estimate the next position (henceforth referred to as the driven position) of the follower AUV as

$$\eta_{2a}(t+1) = (\eta_2(t) - \eta_2(t-1)) + \eta_2(t) \quad (6)$$

3.3 Follower Control

The methodology used to control the follower AUV can be explained using figure 4. The follower robot is now left with two future positions - the driven position ($D(x_{2a}(t+1), y_{2a}(t+1))$), which it will reach if no correction is done and the desired position ($G(x_{2d}(t+1), y_{2d}(t+1))$), which is the ideal position. Now the task of the controller is to issue a correction signal so that the AUV is driven from the current position ($C(x_2(t), y_2(t))$) to the desired position within the specified time.

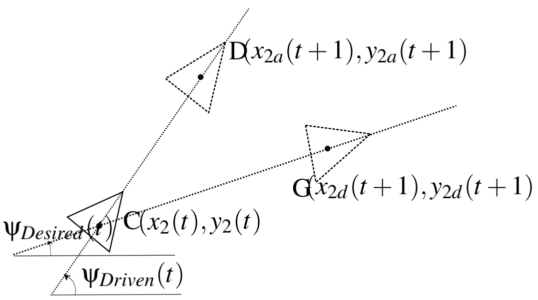

Figure 4: Follower is driven towards the desired position.

The distance to be travelled in each case is calculated as the Cartesian distance from current position to next positions as given in equations 7 and 8.

$$d_{Driven} = \sqrt{((x_{2a}(t+1) - (x_2(t))^2 + ((y_{2a}(t+1) - y_2(t))^2} \quad (7)$$

$$d_{Desired} = \sqrt{((x_{2d}(t+1) - (x_2(t))^2 + ((y_{2d}(t+1) - y_2(t))^2} \quad (8)$$

Based on this, a correction term for linear velocity of the follower is calculated as

$$\delta v = K_v(d_{Driven} - d_{Desired})/\Delta t \quad (9)$$

where Δt is the time step between two states.

Similarly, the desired and driven yaw(heading) is calculated from the position values as

$$\tan\psi_{Driven} = \frac{y_{2a}(t+1) - y_2(t)}{x_{2a}(t+1) - x_2(t)} \quad (10)$$

$$\tan\psi_{Desired} = \frac{y_{2d}(t+1) - y_2(t)}{x_{2d}(t+1) - x_2(t)} \quad (11)$$

The correction term for angular velocity is calculated as

$$\delta\omega = K_w(\psi_{Driven} - \psi_{Desired})/\Delta t \quad (12)$$

We get the new desired values of velocity by adding the correction values to the previous values (equation 13).

$$v(t) = v(t-1) + \delta v \quad (13)$$
$$\omega(t) = \omega(t-1) + \delta\omega \quad (14)$$

These correction values are updated to the low level controller of the robot.

4 IMPLEMENTATION

For simulation purposes, a vehicle system containing two AUVs is considered. The leader AUV is considered to be an ideal vehicle that follows the assigned trajectory without position or velocity error. The trajectory is generated using the method given in section 4.1. The follower AUV is driven by the previously described controller. It tries to follow the leader by maintaining the l and α values.

4.1 Trajectory Generation

Cartesian space trajectory planning is employed for the position variables in the global coordinate frame. For planar trajectory planning, out of the 3 degrees of freedom (x, y and yaw) 2 are selected (x and y) and a sixth order time parametrised function is defined for each of them. This ensures that the path is continuous and differentiable. If the position variable is ζ, the polynomial defined is

$$\zeta(t) = a_{i1} + a_{i2}t + a_{i3}t^2 + a_{i4}t^3 + a_{i5}t^4 + a_{i6}t^5 \quad (15)$$

Differentiating the polynomial, we get the velocity relation as:

$$\dot{\zeta}(t) = a_{i2} + 2a_{i3}t + 3a_{i4}t^2 + 4a_{i5}t^3 + 5a_{i6}t^4 \quad (16)$$

Three points are selected along the trajectory and the desired position and velocity at these points are calculated. These values can be substituted into equations 15 and 16 and they are solved to get the parameters of the trajectory.

5 RESULTS

The controller described above was tested through simulations for dynamic conditions. Simulations were conducted for various initial errors (initial position or yaw) and for various values of l and α and performance was studied.

Initially, the leader AUV was commanded a straight line trajectory. The desired l was set as 2 and desired α was set as $\pi/2$. The gain values were set as 1 and 10 for Kv and Kw respectively. The system was simulated for different initial position errors i.e, 1m, 2m at different angles.

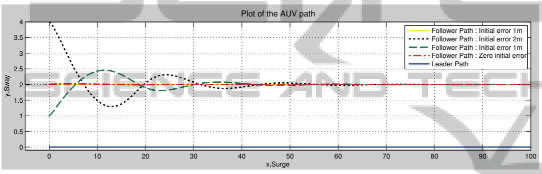

Figure 5: Simulation results for formation with initial position error.

As observed in figure 5 that relatively small errors in the initial position of the follower AUV is corrected and the follower trajectory exponentially converges to the desired trajectory. It can be seen that as error increases, settling time increases.

Another set of simulations were done with a more complex trajectory to check the performance under conditions with an initial yaw error. The formation parameters and control gains were kept as the same as the previous case. The results are shown in figure 6. It was seen that the AUV could converge to desired trajectory despite considerable initial yaw errors.

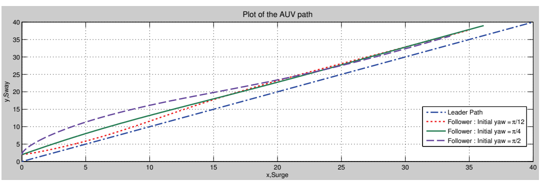

Figure 6: Simulation results for formation with initial yaw error.

In order to check the effectiveness of the controller, a blended path is given to the leader. The path consisted of a curve fitted to the end of a straight line trajectory at end of which the robot will make a 180 degree turn. These paths are generated using techniques mentioned in section 4.1. This made it sure that there is no sudden jump in velocity of the robot.

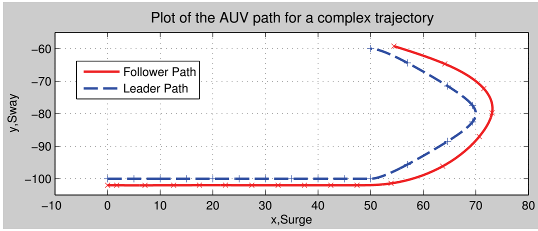

Figure 7: Simulation results for AUV following blended paths.

The simulation results shown in figure 7 showed that the AUV is able to follow the complex trajectory easily, except at changeover points where the AUV took some time to align to the trajectory.

During simulations, it was observed that the gains Kv and Kw have a large impact in stabilising the trajectory. Therefore careful gain tuning is required. This can be treated as a multivariate optimisation problem, which is a possible extension of this work.

6 CONCLUSIONS

An improved formation control strategy is presented for the control of a multi AUV system which tries to estimate the future states of the robots. The proposed algorithm is found to satisfy the requirements of formation control under various situations. Further efforts to implement this controller in real time is under way.

REFERENCES

Antonelli, G., Fossen, T. I., and Yoerger, D. R. (2008). Underwater robotics. In Siciliano, B. and Khatib, O., editors, *Springer Handbook of Robotics*, chapter 44, pages 987–1008. Springer Berlin Heidelberg, Berlin, Heidelberg.

Desai, J. P., Ostrowski, J., and Kumar, V. (1998). Controlling formations of multiple mobile robots. In *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, volume 4, pages 2864–2869 vol.4. IEEE.

Fahimi, F. (2009). *Autonomous Robots Modeling, Path Planning, and Control*. Springer.

Fossen, T. I. (1994). *Guidance and control of ocean vehicles*. Wiley.

Xiang, X., Lapierre, L., Jouvencel, B., and Parodi, O. (2009). Coordinated path following control of multiple nonholonomic vehicles. In *OCEANS 2009 - EUROPE*, pages 1 –7.

Yuh, J. (2000). Design and control of autonomous underwater robots: A survey. *Autonomous Robots*, 8(1):7–24.