Poster Abstract: Navigation of Autonomous Underwater Vehicles with Covert Leaders

Xiaofeng Han Louis F. Rossi Chien-Chung Shen

I. INTRODUCTION

Oceans together with lakes and rivers cover more than 70% of the Earth, nurturing countless marine life, reserving huge amount of natural resources, and dominating Earth's overall climate. It is to human's best interest to monitor and act upon the well-being of these marine environments, and swarms of networked autonomous underwater vehicles (AUVs) have emerged as the primary tools to achieve such goals. In real applications, these AUVs may collaboratively form a scalable network through multi-hop wireless communication and facilitate many tasks such as oceanographic data collection, pollution monitoring, offshore exploration and tactical surveillance.

However, due to the typically large target operating area and high equipment cost, it is impractical to ubiquitously deploy AUVs in most applications. Therefore, investigating how to control the mobility of the AUVs to accomplish the assigned tasks becomes critical research issues. On the other hand, recent discoveries in biology have uncovered many interaction mechanisms existing in animal swarms, which can lead to complex and optimized behavior in diverse biological systems. Motivated by these facts, this work discusses a unique problem associated with autonomous navigation as well as covet leaders for AUVs in the context of underwater networking environment. We term this problem *autonomous navigation with covert leaders*, which aims to design a distributed algorithm to lead the networked AUVs from a starting area to another destination area under the assumption that only a small subset of AUVs (leaders) possess extra information that guides their movement and both such information and the identities of those leader AUVs must be kept covert for security or other concerns.

II. PREVIOUS WORK FOR WIRELESS ROBOT SWARMS

In our previous work [1], we have extended the swarming model in [2] and presented a distributed navigation algorithm for wireless robot swarms with cover leaders. This section briefly introduces this navigation algorithm.

First, each robot i divide its transmission range (a circle centered at i with radius being equal to the transmission radius r_t) into three zones from inside to outside, namely Zone of Repulsion (ZOR), Zone of Orientation (ZOO) and Zone of Attraction (ZOA), as shown in Figure 1. To coordinate with the neighbors in different zones, robot i will move away from the neighbors in ZOR to avoid physical collisions, or move along with the neighbor in ZOO while move towards the neighbors in ZOA. Specifically, robot x will calculate three decision vectors using following equations.

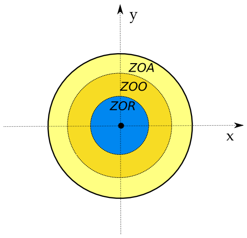

Fig. 1. Representation of single robot in the navigation algorithm. The transmission range is divided into three zones, Zone of Repulsion (ZOR), Zone of Orientation (ZOO) and Zone of Attraction (ZOA).

$$DR_i = \sum_{j \in \mathrm{S_{ZOR}}} \frac{R_{ij}}{|R_{ij}|}, DO_i = \sum_{j \in \mathrm{S_{ZOO}}} \frac{D_j}{|D_j|}, DA_i = \sum_{j \in \mathrm{S_{ZOA}}} \frac{R_{ji}}{|R_{ji}|}$$

where P_x and D_x stand for the position vector and moving direction vector of robot x, $R_{ij} = P_i - P_j$ is a displacement vector between the robot i and robot j. S_{ZOR}, S_{ZOO} and S_{ZOA} are the sets of indices of robots in $x's$ ZOR, ZOO, and ZOA respectively. Similarly, $\|Z\|$ denotes the cardinality of set Z.

Then, each robot i calculates a moving direction V_i according to the following rules. Here α is a non-negative constant used to balance the weight of DO_i and DA_i.

1) If $\|\mathrm{S_{ZOR}}\| \neq 0$ then $V_i = DR_i$. Break;
2) If $\|\mathrm{S_{ZOO}}\| \neq 0$ and $\|\mathrm{S_{ZOA}}\| = 0$ then $V_i = DO_i/|DO_i|$. Break;
3) If $\|\mathrm{S_{ZOO}}\| = 0$ and $\|\mathrm{S_{ZOA}}\| \neq 0$ then $V_i = DA_i/|DA_i|$. Break;
4) If $\|\mathrm{S_{ZOO}}\| \neq 0$ and $\|\mathrm{S_{ZOA}}\| \neq 0$ then $V_i = \alpha DO_i/|DO_i| + (1-\alpha)DA_i/|DA_i|$.

Finally, recall that in the problem associated with cover leaders, there are two types of robots, leaders and non-leaders. Only leaders possess extra information about the destination, which is represented by a vector $F_i = P_d - P_i$ pointing to the desired destination P_d. Therefore, if robot i is a leaders, i set its final moving direction D_i using Equation 1, where β is typically chosen to be 0.5.

$$D_i = \beta V_i/|V_i| + (1-\beta)F_i/|F_i| \tag{1}$$

Otherwise, robot i sets D_i using Equation 2,

$$D_i = V_i/|V_i| \tag{2}$$

While only a small fraction of the robots possess destination information, the distributed navigation algorithm effectively communicate this information to nonleaders through the rule-based dynamics of the swarm. Under proper conditions, the leaders will guide non-leader neighbors toward a consensus direction through convert leadership. Extensive simulation results in [1] indicate that a small percentage leaders (below 20%) can effectively lead the entire robot swarms to the destination.

The authors are with the Departments of Mathematical Sciences and Computer and Information Sciences, University of Delaware, U.S.A. Email: rossi@math.udel.edu,{han,cshen}@cis.udel.edu.

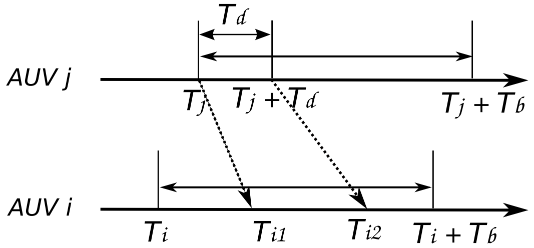

Fig. 2. Estimate the position of neighbors with long propagation delay.

III. NAVIGATION OF NETWORKED AUTONOMOUS UNDERWATER VEHICLES

This section extends the distributed navigation algorithm for wireless robots to facilitate the navigation of AUVs in underwater environment.

A. Position Estimation with Long Propagation Delay

In RF communications, the propagation delay is negligible and all beacon packets, which are used to exchange position information between neighboring robots, can be received immediately after their transmission. This assumption is no long valid in the underwater environment since acoustic channels have the characteristics of low data rate and long propagation delay. Moreover, the propagation delay is hard to determine in advance, since many factors, such as temperature, density and salinity, may significantly alter the travel speed of acoustic waves. Therefore, we present a distributed coordination mechanism to enable each robot to precisely estimate the position information of its neighbors with unknown propagation delay.

Our solution is based on the assumption in [3] that the propagation delay is only proportional to distance, and this proportional relationship remains stable within a short period of time (a few seconds). First, each AUV *asychoronously* divides the time into continuous time slots with fixed length T_b to avoid communication collisions. Then, at the beginning of a new time slot, based on the information collected in previous time slot, each AUV calculates its new moving direction according to the coordination rules and immediately broadcasts two beacon packets containing its current position [1] and new moving direction with time interval T_d. Then each robot will move along the decided direction until the next time slot.

Figure 2 depicts how AUV i can use the two beacon packets to estimate the updated position information of its neighbors. For the ease of description, let $P_x(T_y)$ stand for the real-time position of AUV x at AUV $i's$ local time T_y. Initially, AUV i maintains a neighbor cache which is reset to empty at the beginning of each time slot. During a particular time slot starting at time T_i, when AUV i receives two beacon packets from AUV j at local time T_{i1} and T_{i2}, which contains the position P_{j1} and P_{j2} of AUV j at $j's$ local time T_j and $T_j + T_d$, respectively, and $j's$ moving direction D_j. AUV i first computes the position $P_j(T_{i2})$ of AUV j at the time T_{i2} by estimating the displacement of AUV j during time period of the propagation delay using Equation 3, where V is the moving speed of AUVs.

$$P_j(T_{i2}) = P_{j2} + \frac{D_j}{|D_j|} \times V \times \frac{|P_i(T_{i2}) - P_{j2}|}{\frac{|P_i(T_{i2})-P_{j2}|-|P_i(T_{i1})-P_{j1}|}{T_{i2}-T_{i1}-T_d}} \tag{3}$$

Then AUV i records the position $P_j(T_{i2})$ and moving direction D_j of AUV j together with a local timestamp T_{i2} in its neighbor cache. Based on the information in the neighbor cache, at the beginning of the next time slot starting at $T_i + T_b$, AUV i can precisely estimates the new position of $P_j(T_i + T_b)$, using Equation 4 since AUV j will keep moving along direction D_j until $T_j + T_b$, which must be later than $T_i + T_b$.

$$P_j(T_i + T_b) = P_j(T_{i2}) + (T_i + T_b - T_{i2}) \times \frac{D_j}{|D_j|} \times V \tag{4}$$

With the position and moving direction of each neighbor, AUV i can calculate its new moving direction following the rules described in Section II. Note that each AUV will execute this algorithm independently until the AUV swarm reach the destination. Moreover, since the algorithm only uses the local time, there is no need to synchronize the entire AUV swarm.

B. Obstacle Avoidance and Kinetic Constraints

We further consider other constraints existed in realistic underwater scenarios, such as obstacles and kinetic constraints.

1) Obstacle Avoidance: Given the harsh operating environments, the AUV swarms may need to avoid certain obstacles during the navigation. Therefore we further assume each AUV is capable of detecting obstacles within certain detection range, which is represented as a circle centered at each AUV with detection radius r_d. For each AUV i, assume D_i is the direction resulted from the distributed navigation algorithm. Denote O_j ($1 \leq j \leq m$) as the position of j-th obstacles existing in $i's$ detection range. Then AUV i will use Equation 5 to calculate its final moving direction Di_{final}, where W is positive integer balancing the weights of the vectors moving away from the obstacles.

$$Di_{final} = D_i + \sum_{j=1}^{m} \frac{P_i - O_j}{|P_i - O_j|} \times \frac{(r_d - |P_i - O_j|) \times W}{r_d} \tag{5}$$

2) Kinetic Constraint: We also notice that each AUV i may have kinetic constraint, i.e., a maximum turning angle σ. Therefore, after computing its final moving direction Di_{final}, AUV i must compare Di_{final} with σ and only turn with angle $min(Di_{final}, \sigma)$.

IV. CONCLUSION AND FUTURE WORK

In this work, we extended our previous work for wireless robots and presented an distributed navigation algorithm for networked autonomous underwater vehicles with cover leaders. Our future work would be to evaluate our algorithm with extensive simulations and discover the best configurations of the related parameters, such as the number of AUVs, moving speed and beacon intervals for our algorithm.

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[1] The position information can be achieved through GPS or other localization algorithms (see [4] for a survey).