Cooperation of coordinated teams of Autonomous Underwater Vehicles

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Abstract: This paper presents the initial stage of the development of an underwater localization system suitable for a flexible number of users. Multiple Autonomous Underwater Vehicles (AUVs) can work as a team and cooperate with other teams of AUVs without costly and acoustically active components, which saves energy and allows AUVs to remain silent. The main building blocks for such a system are: spiral wavefront beacon in conjunction with a standard (circular) acoustic modem, Chip Scale Atomic Clocks (CSAC), acoustic modems, state-of-the-art adaptive underwater networking and Cooperative Localization (CL) algorithms. Using the difference in time of arrival between the spiral wavefront and the modem circular wavefront, receivers will be able to determine the bearing to the source using only one hydrophone. Synchronizing vehicles Chip Scale Atomic Clocks (CSAC) with the beacon at the beginning of the mission and during the longer missions will ensure the vehicles ability to also calculate their distance from the beacon upon every message reception.

Keywords: Spiral beacon, atomic clock, acoustic modem, cooperative localization, underwater networking.

1. INTRODUCTION

Multi robot coordination and cooperation have a potential to significantly improve ocean exploration missions. For multiple AUV operations, coordination refers to AUVs keeping their formation and cooperation association to achieve specified mission objectives. Teams of coordinated autonomous underwater vehicles (AUV) can then cooperatively work with other teams of coordinated AUVs.

This vision for ocean exploration dates back two decades ago with Autonomous Ocean Sampling Network (AOSN), see (1); however, it is now a reality with several technological advancements. The integration of this technology will result in reduced total ownership cost of the AUV. Although the cost of small AUVs has significantly decreased; if coordinated teams are employed, expensive sensors previously required for precise AUV navigation are no longer necessary. For example, costly fiber-optic or laser-ring gyro can be replaced with MEMS counterparts and a Doppler Velocity Log (DVL), often considered as a main navigation sensor for AUV navigation, needs be installed only on one AUV that serves as the main node for the team of AUVs. Coordination can be accomplished with less sensor sophisticated AUVs with the aid of underwater communication and utilization of inexpensive, low power Chip Scale Atomic Clock (CSAC) (4) and decentralized distributed control and localization algorithms. Cooperation can be accomplished with advances in underwater networking schemes.

Ongoing efforts are aiming at similar goals. For example, The widely scalable Mobile Underwater Sonar Technology (WiMUST) (2) system will be composed of many AUVs carrying hydrophones to acquire sub-bottom profiling acoustic data. Instead of traditional arrays of sensors, that are either stationary or towed by the ship forming the fixed geometry of the acoustic antenna, new and exciting technology advances that will be integrated into WiMUST will allow for rapid, on-the-fly, changes to the geometry of the acoustic antenna. This has the potential to drastically improve ocean surveying.

A team of researchers from SPAWAR Systems Center Pacific (SSC PAC), the University of Rome, and the University of Calabria has recently demonstrated the utility of using synchronized atomic clocks for one-way ranging, which can be used for navigation updates to a team of AUVs broadcasting only one acoustic message. This message can be sent by an AUV equipped with more advanced...
navigation sensors (FOG gyros and DVL) and can contain its x and y position. By virtue of receiving a message from the “master” AUV, other inexpensive AUVs can update their position estimate.

Another technology that will be utilized in our upcoming tests is spiral beacon technology. The United States Naval Research Laboratory in Washington, D.C. (3) has developed an underwater acoustic analogy using a system that consists of a coaxial set of spiral and circular wave front beacons. This system operates similarly to the VOR (VHF Omni Directional Radio Range) system used in air traffic. The VOR uses a beacon whose mix of two signals informs the recipients of their bearing towards the beacon. In the same way, the underwater acoustic analogy provides a navigation aid to AUVs. Using this technology together with synchronized clocks enables both bearing and range from the “master” to be known at each AUV.

These technologies not only have great potential for precise navigation of inexpensive AUVs but also significantly affect the endurance (mission time) of the AUVs as they do not need to transmit acoustic messages for navigation. Transmission of an acoustic message is much more costly compared to the reception of the message. It costs approximately 40 Watts for transmission and only 40 mWatts for reception. Low power onboard navigation sensors and the elimination of acoustic transmissions can enable AUVs to navigate underwater for weeks at the time and their mission time can come closer to currently employed underwater gliders so AUVs can be utilized for glider type of missions with much greater precision.

The rest of the paper is organized as follows. Section 2 explains our Distributed Kalman Filtering cooperative estimation. In Section 3 we present our AUV assets and the Spiral Wave Front Beacon concept. Section 4 describes our acoustic modems, our underwater networking algorithms, and planned improvements. Section 5 provides simulation results and Section 6 describes the results from the previous representative experiments. Finally, Section 7 discusses future research goals.

2. DISTRIBUTED LOCALIZATION AND COOPERATIVE CONTROL

Distributed estimation with the aid of local information is challenging because information is not available at each agent. When multiple AUVs are involved, state estimation at each vehicle with the aid of neighbors’ information is again extremely challenging because underwater communication is intermittent and low bandwidth. Distributed control of multiple vehicles has many benefits. However, controller design is challenging. In this paper, we consider distributed localization and distributed cooperative control of multiple vehicles.

2.1 AUV Model

Define a fixed inertia coordinate frame (I-frame) and also define a body frame (B-frame) for each vehicle, for vehicle j its position \( \eta_j = [x_j, y_j, z_j]^T \) is described relative to the fixed inertia frame and its orientation can be defined by a unit quaternion \( Q_j = [q_{0j}, q_{1j}, q_{2j}, q_{3j}]^T \). The linear and angular velocity of the vehicle are denoted by \( v_j \) and \( \omega_j \). The kinematics of vehicle \( j \) is

\[
\dot{\eta}_j = R(Q_j)v_j \\
\dot{Q}_j = \frac{1}{2} \left[ q_{0j}I_3 + S(q_{1j}) \right] \omega_j
\]

where \( S \) is the skew-symmetric matrix such that \( S(u)v = u \times v \) where \( \times \) denotes the vector cross product, and 

\[
R(Q_j) = I_3 + 2S(q_{1j})^2 - 2q_{0j}S(q_{1j}).
\]

The dynamics of the vehicle can be written as

\[
M_j \ddot{\eta}_j + C_j(\eta_j)\dot{\eta}_j + D_j(\dot{\eta}_j)\dot{\eta}_j + G_j(\eta_j) = B_j\tau_j
\]

where \( \nu_j = [v_j^T, \omega_j^T]^T \), \( M_j = M_j^T > 0 \) is a positive definite inertia matrix (which includes the added inertia), \( C_j(\eta_j) = -C_j(\nu_j)^T \) is a skew-symmetrical matrix containing the Coriolis and centripetal term, \( D_j(\dot{\eta}_j) > 0 \) is a positive definite damping matrix containing drag and lift terms (and possibly skin friction and viscous damping), \( G_j(\eta_j) \) denotes the gravitational and buoyant forces, \( B_j \) is the input matrix, and \( \tau_j \) is the external input.

2.2 Problem Statement

For a group of the above vehicles, in order to accomplish a mission the state of a vehicle should be known. The first problem considered in this paper is as follows.

**Distributed Localization:** Each vehicle’s available information is its own sensors’ information and the information received from its neighbors. Propose distributed estimation algorithms such that the state of each vehicle can be estimated as accurately as possible.

Given a virtual leader which is moving with a desired trajectory \( \eta^d(t) = [x^d(t), y^d(t), z^d(t)]^T \) and a desired formation which is defined by constant displacement vectors \( p_j = [p_{xj}, p_{yj}, p_{zj}]^T \) for \( 1 \leq j \leq m \), the distributed cooperative problem considered in this paper is defined below.

**Distributed Leader-follower Control:** For a group of vehicles, the information from a virtual leader is available to one or more vehicles. We propose a distributed control law for each vehicle with the aid of its own information and its neighbors’ information such that the group of vehicles come into desired formation and the centroid of them moves along a desired trajectory, i.e.,

\[
\lim_{t \to \infty} (\eta_j - \eta_i) = p_j - p_i, \quad 1 \leq i, j \leq m
\]

\[
\lim_{t \to \infty} \left[ \frac{1}{m} \sum_{j=1}^{m} \eta_j - p_i \right] - \eta^d = 0
\]

In the next subsections, we will present the solution to the above two problems.

2.3 Solution to the Distributed Localization and Distributed Leader-follower Control problems

The dynamics of an AUV is nonlinear. For distributed estimation, we discretize the system in (1)-(3) to the following discrete-time system.
\[ x(k) = A(k)x(k-1) + B(k)\omega(k-1) + G(k)u(k) \]  
where \( x \) is the state of the system, \( u \) is the control input, and \( \omega \) is the noise and uncertainty.

Assume there are \( m \) sensors. The measurement of sensor \( i \) about this UAV is

\[ y_i(k) = H_i(k)x(k) + v_i(k) \]  
where

\[ E(\omega(w)w^T(j)) = Q(k)\delta_{kj} \]
\[ E(v_i(k)v_i^T(j)) = R_i(k)\delta_{kj} \]
\[ E(v_i(k)v_i^T(j)) = 0 \]
\[ E(\omega(w)w^T(j)) = 0. \]

Between sensors, there is communication. The communication between any two sensors can be described by a graph \( G = [A, V] \) where the node set \( A \) denotes the labels of \( m \) sensors and the edge set \( E \) denotes the communication between sensors. For simplicity, it is assumed the communication is bidirectional. Therefore, the graph \( G \) is a bidirectional graph. Two sensors are said to be neighbors if there is communication between them.

For sensor \( i \), its neighbors are formed a set and is denoted by \( N_i \).

Next, we present an algorithm on how to estimate the state of an AUV with the aid of neighbors’ information.

Let \( x_i^-(k) \) and \( x_i^+(k) \) be the prior and posterior estimates of \( x(k) \) to incorporating the measurement \( y_i(k) \) by sensor \( i \), respectively. Also we let \( \hat{x}_i(k) \) be the estimation of \( x_i(k) \) after all information has been incorporated. For sensor \( i \), we let the vector \( y_{si} \) denote the collection of its measurement \( y_i \) and its neighbors’ measurement \( y_j \) for \( j \in N_i \) and \( H_i \) denote the collection of its measurement matrix \( H_i \) and its neighbors’ measurement matrix \( H_j \) for \( j \in N_i \). Also, let \( R_i \) denote the collection of the variance \( R_i \) of its measurement noise and the variance \( R_j \) of its neighbors’ measurement noise for \( j \in N_i \), since the control input \( u(k) \) is not available for each sensor, it should be estimate at the same time. Let \( u_i(k) \) be the estimate of \( u(k) \) by sensor \( i \).

We propose the following three-step distributed estimation algorithm:

**Distributed Estimation Algorithm:**

For sensor \( i \),

- **Time update:**
  \[ \dot{x}_i^-(k) = \dot{x}_i^-(k-1) + G(k)u_i(k) \]
  \[ u_i(k) = -\sum_{j \in N_i} b_{ij}(u_i(k-1) - u_j(k-1)) - b_{i0}(u_i(k-1) - u(k-1)) \]
  \[ -\rho \text{sign} \left[ \sum_{j \in N_i} b_{ij}(u_i(k-1) - u_j(k-1)) - b_{i0}(u_i(k-1) - u(k-1)) \right] \]
  \[ P_i^-(k) = AP_i^-(k-1)A^T + BQB^T \]
where \( b_{i0} > 0, \rho \) is a sufficiently large positive constant, \( b_{i0} > 0 \) if \( u(k) \) is available to sensor \( j \) otherwise \( b_{i0} = 0 \).

- **Measurement update:**
  \[ \dot{x}_i^+(k) = \dot{x}_i^+(k-1) + K_{si}(k)(y_{si}(k) - H_{si}(k)\dot{x}_i^-(k)) \]
  \[ P_i^+(k) = (I - K_{si}(k)R_{si}(k)) P_i^-(k) (I - K_{si}(k)H_{si}(k))^T + K_{si}(k)R_{si}(k)K_{si}(k)^T \]
  \[ K_{si}(k) = P_i^+(k)H_{si}(k)^T[H_{si}(k)P_i^+(k)H_{si}(k)^T + R_{si}(k)]^{-1} \]

- **Fusion:**
  \[ \hat{x}_i(k) = \sum_{s \in N_i} \sum_{l \in \mathbb{N}_i} \frac{\delta}{\delta + \alpha} \dot{x}_l^+(k) + \sum_{l \in \mathbb{N}_i} \frac{\alpha}{\delta + \alpha} \dot{x}_l^+(k) \]
where positive constants \( \alpha \) and \( \delta \) satisfy the constraint \( \alpha >> \delta > 0 \).

Under some assumptions, it can be shown that the above distributed estimation algorithm can estimate the state of an AUV and the estimates of different sensors can reach consensus.

With the aid of the estimation algorithms proposed in the last section, the state of each vehicle can be estimated online and is available for controller design. For simplicity of presentation, in the controller design it is assumed that the state of each vehicle is known.

For the vehicles in (1)-(3), we design distributed control laws with the aid of its cascade structure in two steps for each type of vehicles. In the first step, we design some intermediate controller such that (4)-(5) are satisfied. In the second step, we design real control inputs for each vehicle with the aid of the results in the first step such that (4)-(5) are satisfied. 

**Step 1:** We design an intermediate controller for each vehicle.

We assume \( v_j \) is a virtual control input and design a controller for it. We propose that

\[ v_j = R(Q_j)^Tv_j^d \]  
\[ v_j^d = -e_j - \rho_j \tan \frac{\theta_j}{\epsilon} \]  
\[ e_j = \sum_{i \in \mathbb{N}_j} a_{ij}(\eta_j - p_j - \eta_i + p_i) + b_j(\eta_j - p_j - \eta_j^d) \]  

**Step 2:** We design the real inputs for each type of vehicles.

We choose a desired angular velocity \( \omega_j^d \) with the aid of other requirements. Let \( v_j^d = [v_j^d, \omega_j^d]^T \) and \( \tilde{v}_j = v_j - v_j^d \), then

\[ M_j \tilde{v}_j + C_j \tilde{v}_j = B_j \tau_j - G_j - D_j v_j - M_j \tilde{v}_j - C_j \omega_j^d \]  

We choose the control inputs

\[ \tau_j = B_j^{-1}[-K_{\theta_j} \tilde{\theta}_j + G_j + D_j v_j + M_j \tilde{v}_j + C_j \omega_j^d] \]  

where \( K_{\theta_j} \) is a positive definite constant matrix.

With the above design procedure, it can be shown that the distributed control laws in (13) ensure that (4)-(5) hold practically, i.e.,
\[
\lim_{t \to \infty} \| \eta_j - p_j - \eta_i + p_i \| \leq \epsilon, \quad 1 \leq i, j \leq m
\]  
(14)

\[
\lim_{t \to \infty} \left[ \sum_{j=1}^{m} \frac{\eta_j}{m} - \eta^d \right] \leq \epsilon
\]  
(15)

where \( \epsilon \) is a small constant.

In the proposed controls, we assumed that the state of each vehicle is measurable and is known exactly. If the state of each vehicle is estimated with the aid of the proposed distributed estimation algorithms, we can replace the state in the control algorithms with the estimated value.

3. AUV ASSETS AND SPIRAL BEACON

In the project and for its experiments we have several AUV assets available, briefly described in what follows.

3.1 Bluefin 9 AUV

SSC PAC has two Bluefin Sealion II AUV. Standard commercial off-the-shelf (COTS) Sealion II AUV is a 2-man-portable vehicle weighing in at about 60 Kg. As opposed to the COTS Sealion II, a payload nose section was added for integration of additional sensors into the existing Sealion II UUV platform (Fig. 1(a)). The new payload nose will hold a payload pressure vessel with a spiral beacon and acoustic modem. The Sealion II Standard Payload Interface (SPI) software was upgraded to provide capabilities comparable to the current Bluefin Robotics standard and will support “backseat driver” functionality so Distributed Localization and Cooperative Control algorithms presented in Sec. 2 can be implemented.

3.2 Spiral Wave Front Beacon

Spiral Wave Front Beacon uses a coaxial set of a spiral wave front beacon and a circular wave front beacon. The circular wave front beacon can be a classic beacon or even an acoustic modem, while the spiral wave front can be generated using a physical spiral beacon or a circular array of beacons fired in a rotational manner in order to synthetically create a spiral wave front. The difference in phase (or time) between the spiral wave front signal and the circular wave front signal informs the recipient of its bearing towards the beacon (See Figure 2). The separation between those two signals can be done in time, frequency or a mix of the two methods. Furthermore, in the synthetic spiral method, a changing chirp signal in relation to bearing can be used (as it is normally used in scanning sonar and radar systems) to increase angular resolution and robustness. The spiral beacon was recently received from DBTech Acoustics, LLC and it is being integrated.

3.3 Riptide Micro AUVs

SSC PAC has three Riptide Autonomous Solutions Micro AUVs. Two of them are shown in Fig. 1(b). The micro AUV is a new, highly flexible, open source autonomous undersea vehicle that provides users a state-of-the-art, low cost development solution ideally suited for developers of autonomous behaviors, power systems, subsea sensors, and new payloads. The micro-UUV features open hardware and software interfaces to provide users a reliable and robust platform to advance technology development. The vehicle design is optimized for high efficiency with the best hydrodynamic signature in its class. Sea Modems with CSAC (presented in Sec. 4) and a MEMS IMU will be added to the Micro AUVs for the development of Distributed Localization and Cooperative Control and underwater networking algorithms.

4. UNDERWATER ACOUSTIC COMMUNICATION, NAVIGATION AIDING, AND NEW ADAPTIVE NETWORKING ALGORITHMS AND POLICIES

The Control Engineering Group of the Autonomous Systems Laboratory at the DIMES Department of the University of Calabria has developed, in collaboration with Applicon s.r.l., a compact low-power underwater acoustic modem for AUV navigation and communication applications (6). SeaModem is the commercial name of this
modem actually produced by Applicon s.r.l. It is a FSK underwater acoustic modem well suited for shallow water communications. The working frequency band ranges between 25 to 35 KHz, with selectable data rates of 750 bits/sec, 1500 bits/sec and 2250 bits/sec. A UART interface is used to host the modem. SeaModem has two expansion connectors both pin-to-pin compatible with the Linux embedded platform BeagleBone developed by BeagleBoard.org Foundation. The BeagleBone board is an open-source embedded PC based on an ARM Cortex CPU running a Linux operating system. The BeagleBone acts as a host and uses the integrated UART interface to communicate with the modem. The integration with BeagleBone makes the SeaModem a stand-alone system with all the functionalities of a Linux system. Moreover, new high-level functionalities can be developed on the BeagleBone that can use the modem as a communication device. To avoid loss in accuracy due to the typical clock drifts arising in the standard real-time clocks integrated in the DSP and embedded platforms, Seamodem hardware is being extended with a CSAC. CSACs have a very low drift will enable the Seamodem clock to remain synchronized for many hours without remarkable error in the range calculation. The SeaModem and CSAC are shown in Fig. 3.

4.1 New adaptive networking algorithms and policies

The Underwater Group of the Senses Lab at the Computer Science Department of the University of Rome “La Sapienza”, has developed, in collaboration with WSENSE S.r.l., a novel framework named SUNSET, for “Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing,” enabling to seamlessly simulate, emulate and test in real-life novel communication protocols (7). To fully support the Applicon SeaModem (Section 4) operations a new driver has been developed in SUNSET to control and reconfigure the modem, locally or via acoustic links. This driver allows to set the transmission gain, the FSK modulation, the Viterbi algorithm for forward error correction, the guard period and the chirp threshold, etc. SUNSET enables the concept of Software Defined Communication Stack (SDCS), named SUNSET-SDCS (S-SDCS) where different network protocols running at the same layer of the protocol stack can be selected and used according to the network conditions and application scenario in both autonomous and manual ways. Special algorithm, named Policies, can be designed and developed to automatically switch among the different protocols to achieve higher performance of the overall system.

5. SIMULATION

5.1 Distributed Estimation

For aerial vehicles and surface vehicles, IMU and GPS receivers are equipped. The integrated INS/GPS system can estimate the state of the vehicle with reasonable precision. For a underwater vehicle, IMU is installed in the vehicle. However, GPS signal cannot be received if the vehicle is under water. Due to the accumulated error of IMU based estimation, the estimate based on IMU measurements is not accurate. To solve this problem, the proposed distributed estimation can be applied to improve the accuracy of the state estimation with the aid of neighbors’ information.

Assume there are two surface vehicles (labeled as vehicle 1 and vehicle 2) and one underwater vehicle (labeled as vehicle 3). The surface vehicles are equipped with IMU/GPS navigation systems. The state of each surface vehicle can be estimated with the aid of their INS/GPS system with reasonable precision. The underwater vehicle is equipped with IMU based inertia navigation system. Its state can be estimated with the aid of the INS system. However, the estimation error becomes larger and larger as time goes. To improve the estimation accuracy of the underwater, the proposed distributed Kalman algorithms can be applied to estimate the state of the underwater with the aid of neighbors’ information. Consider vehicles 1, 2, and 3 as three sensors labeled as 1, 2, and 3, respectively. The kinematics of vehicle 3 is defined by

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\psi}
\end{bmatrix} = \begin{bmatrix}
u \cos \psi - v \sin \psi \\
u \sin \psi + v \cos \psi \\
r
\end{bmatrix} + w. \tag{16}
\]

The measurement of three vehicles is as follows:

- For vehicle 1, the measurement is
  \[y_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2}, \psi \] + v_1 \tag{17}
- For vehicle 2, the measurement is
  \[y_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2}, \psi \] + v_2 \tag{18}
- For vehicle 3, the measurement is
  \[y_3 = \sqrt{(x - x_1)^2 + (y - y_1)^2}, \sqrt{(x - x_2)^2 + (y - y_2)^2}, \psi \] + v_3 \tag{19}

The communication digraph between vehicles is shown in Fig. 4(a). The available information for vehicle 1 is the measurement \((y_1, y_2)\) and the estimation of the state by vehicle 2. The available information for vehicle 2 is the measurement \((y_2, y_3)\) and the estimation of the state by vehicle 3. The available information for vehicle 3 is the measurement \((y_3, y_1)\) and the estimation of the state by vehicle 1. The system in (16) is a nonlinear system. We apply the proposed extended distributed Kalman filtering algorithm. Figures 4(b)-5(b) show the tracking errors of \((x_j - x), (y_j - y), (\psi_j - \psi)\), respectively.
Different in-field activities have been carried out in October 2015 in waters south of Cartagena, Spain, during the TJMEX’15 campaign (Trident Juncture MCM Experiment 2015). TJMEX 15 experiments demonstrated the utility of using synchronized atomic clocks for one-way ranging which can be used for navigation updates to team of AUVs broadcasting only one acoustic message. Several experiments have been performed to estimate the accuracy of both two-way and one-way ranging estimation to localize underwater nodes. It can be seen from Table 1 that both the ranging techniques achieve very good results, with a minimum standard deviation of 0.11 and 0.28 meters when using one-way and two-way ranging, respectively.

Table 1. Distance estimation using One-Way and Two-Way travel time ranging.

<table>
<thead>
<tr>
<th>Day</th>
<th>One-Way (meters)</th>
<th>Two-Way (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 19</td>
<td>AVG=478.8, STD=0.11</td>
<td>AVG=478.7, STD=0.28</td>
</tr>
</tbody>
</table>

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