SIMULTANEOUS ACOUSTIC NAVIGATION OF MULTIPLE AUVS

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Abstract: Although the simultaneous use of multiple AUVs in some mission scenarios is advantageous when compared with single AUV operations, it poses some challenging questions regarding the coordinated control and navigation of multiple vehicle operations. This paper addresses the simultaneous navigation of multiple vehicles using the same acoustic network. We propose a configuration for a long baseline acoustic network that allows each vehicle to determine its position as well as the positions of all the other vehicles using the same network. The proposed mode of operation minimizes the number of additional signal exchanges. Furthermore, this is accomplished without the need of any communication link between the vehicles.

Keywords: Multiple AUVs, Acoustic navigation, Long baseline

1. INTRODUCTION

The simultaneous use of multiple AUVs in the same mission can be advantageous as compared to single AUV operation for very different reasons and in several operational scenarios. Among the most important ones are lower mission costs (by reducing operating time and the associated logistic costs), reduced coverage time (required for the study of phenomena with high temporal variability and for the collection of spatially distributed synoptic data) and resolution of spatio-temporal evolution ambiguities of data collected on different places at different times (Cruz and Matos, 2004). In some of these scenarios, the vehicles must operate in a coordinated way, meaning that each vehicle must know in real time, besides its own position, the position of the other vehicles.

Acoustic long baseline (LBL) positioning is the technique more commonly used to provide absolute horizontal navigation data to AUVs. A LBL network is composed by a set of beacons and each vehicle determines its position by measuring times of arrival of acoustic signals. These networks can be operated either in hyperbolic or spherical mode (Bellingham *et al.*, 1992; Matos *et al.*, 1999). Although each of these modes has it own advantages, none of them can effectively assure that each vehicle can determine its position and the positions of all the others.

The simultaneous acoustic navigation of multiple vehicles has already been the focus of some research. Although some special relevant problems have been addressed, namely the master-slave formation (Baker *et al.*, 2005), it seems that no general solution to this problems has been proposed yet.

In this paper we propose a configuration for an acoustic network that enables the simultaneous navigation of multiple vehicles in the same area and assures that each vehicle can determine its own position as well as the positions of all the other vehicles. This is accomplished without the need of any communication link between the vehicles.

2. MULTIPLE AUV NAVIGATION

The simultaneous navigation of multiple AUVs in the same acoustic network can be viewed as the composition of two different problems: on one hand each vehicle must be able to determine its position, and, on the other, it should be capable of tracking the position of the other vehicles in the area.

The direct adaption of single AUV navigation algorithms to the multiple AUV scenario is not a trivial task. In fact, the increase in the number of vehicles, forces the use of an increasing number a of different acoustic signals required or the definition of some sort of policy in the access to the shared transmission media. The first of these alternative solutions has a direct increase in the complexity of the acoustic system with obvious increase in costs and required space on board. The second solution, besides the technical difficulties associated to the necessary synchronization, also results in the decrease of the accuracy of the positioning.

Since LBL positioning relies of the measurement of times of arrival of acoustic signals, just times of flight or differences between times of flight can be used to determine positions of objects. Therefore, any solution for the simultaneous navigation of multiple AUVs must be based either on the hyperbolic, on the spherical, or in a mixture of these two modes.

In the hyperbolic navigation mode each AUV just listen to signals sent by the beacons and determine their horizontal position based of differences between the arrival times of signals from the different beacons. This mode of operation requires two beacons, if the vehicles carry a highly accurate clock synchronized with the beacons clocks or, as it is more usual, three different beacons and no clock synchronization. This mode of operation can be used for the self navigation of an arbitrary number of vehicles, but none of them can determine the position of the others, since all of them are completely passive.

In the spherical mode, each vehicle measures its distances to the different beacons by interrogation them, waiting for their replies and measuring the round trip time. This mode of operation is not very appropriate to the operation of multiple vehicles since the number of distinguishable signals rapidly increases with the number of vehicles (typically three different signals are required for each vehicle operating in the area). Furthermore, since the beacons usually have a lockout time after each transmission, the chance of loosing signals increases with the number of vehicles, degrading the overall performance.

On the other hand, the spherical navigation algorithm allows for the external tracking of a vehicle position just by listening to the signals exchanged (Cruz *et al.*, 2001). This is of great interest not only for mission supervision but also for the multiple vehicle operation, since it allows every vehicle to know the horizontal position of the other ones, without the need of a communication link or additional positioning signals exchange.

This external tracking mechanism relies on the possibility of choosing the exact instants of time when the vehicle interrogates the beacons. By making this moments dependent on the vehicle position, it is possible to give other entities information about the position of the vehicle. This is, in fact, the most interesting feature of the spherical navigation regarding the multiple AUV operation.

3. ACOUSTIC NETWORK OPERATION

The mode of operation of the acoustic network proposed here is based on the hyperbolic navigation and allows the external tracking of each vehicle with minimal overhead. In fact, besides the different signals emitted by the beacons, just one different signal is required for each vehicle.

For the minimum setup, the network is composed by three different beacons: a master ($\mathbf{B}_0$) and two slaves ($\mathbf{B}_1$ and $\mathbf{B}_2$). Each one of them is deployed in the operation are and their locations are known by the vehicles. To simplify the explanation we will consider that each acoustic signal is completely characterized just by its frequency.

A new positioning epoch is initiated by the transmission of a signal f_0 by the master, lets say at time t_0. Each of the slave beacons replies to this signal with its own frequency. The replies are transmitted certain amounts of time after the receptions of the signal f_0 by the slave beacons, that is, at times t_1 and t_2 defined by

$$t_1 = t_0 + \frac{d_{01}}{c} + \Delta_1$$
$$t_2 = t_0 + \frac{d_{02}}{c} + \Delta_2$$

the slave beacons transmit their replies, of frequencies f_1 and f_2, respectively. In the above expressions d_{01} and d_{02} are the distances from the master to each of the slave beacons, c stands for the sound speed (assumed to be constant), and Δ_1 and Δ_2 are above mentioned delays.

It should be noted that it is possible, and in many cases desirable, to connect all the beacons to radio linked surface buoys. In that case, the emission of signals by the slave beacons can be programmed based on t_0, not requiring acoustic signal detection hardware in the beacons.

Each vehicle operating in the network is assigned a predefined frequency, known by all the entities in the area. To allow for the other vehicles to track its position, each vehicle emits a signal of its own frequency whenever it detects each of the signals sent by the beacons.

For each vehicle, the determination of its own position and of the positions of the other vehicles is based on the hyperbolic navigation algorithm, as explained below.

4. AUV NAVIGATION

Each vehicle operating in the area is able to compute its position in the horizontal plane just by listening to the signals f_0, f_1 and f_2, sent by the three beacons. At each epoch, the vehicle receives these signals, respectively at

$$\begin{aligned} t_{0A} &= t_0 + \frac{d_{0A}}{c}, \\ t_{1A} &= t_0 + \frac{d_{01}}{c} + \Delta_1 + \frac{d_{1A}}{c}, \text{ and} \\ t_{2A} &= t_0 + \frac{d_{02}}{c} + \Delta_2 + \frac{d_{2A}}{c}, \end{aligned}$$

where d_{0A}, d_{1A}, and d_{2A} are the distances between vehicle and each of the beacons, measured at the corresponding instants of time. The time differences $t_{1A} - t_{0A}$ and $t_{2A} - t_{0A}$ can then be used to estimate $d_{1A} - d_{0A}$ and $d_{2A} - d_{0A}$.

The horizontal position of the vehicle is estimated in real time by means of an extended Kalman filter (Gelb *et al.*, 1996) based algorithm, that fuses these distance differences with dead reckoning data. The filter state is $X = [x\ y\ w_x\ w_y]$, where x and y are the horizontal position of the vehicle A and w_x and w_y represent the north and east components of the water current velocity. The filter also maintains estimation error covariance matrix P, see (Matos *et al.*, 1999).

At each epoch, $X^-(t_{0A})$ represents the *a priori* estimate of the filter state at instant t_{0A}. The filter state $X^-(t_{1A})$ is obtained by integrating dead reckoning data from t_{0A} to t_{1A}. At that instant of time, $X^+(t_{1A})$ is obtained by considering the measurement $t_{1A} - t_{0A}$. Then, dead reckoning integration is also employed to determine $X^+(t_{2A})$ from $X^+(t_{1A})$. Finally, At that time the measurement $t_{2A} - t_{0A}$ is used to obtain $X^{++}(t_{2A})$ which is the estimate of the vehicle position taking into account the two independent time difference measurements available at that epoch. The estimate $X^-(t_{0A})$ of the next epoch is obtained from $X^{++}(t_{2A})$ by dead reckoning. It should be noted that the error covariance matrix is also updated at the same times of the state X.

5. EXTERNAL TRACKING

Since at each epoch the vehicle A detects these signals at t_{0A}, t_{1A}, and t_{2A}, respectively, the vehicle will send a signal of frequency f_A at each of these instants of time.

Let's also consider a device X, that might be another vehicle or a remote monitoring station, located in the same area, and possibly moving around. It will detect the three signals of frequency f_A at times

$$\begin{aligned} t_{AX,0} &= t_{0A} + \frac{d_{AX}}{c} \\ t_{AX,1} &= t_{1A} + \frac{d'_{AX}}{c} \\ t_{AX,2} &= t_{2A} + \frac{d''_{AX}}{c} \end{aligned}$$

where d_{AX}, d'_{AX} and d''_{AX} are distances between A and X.

Disregarding, for now, the time variation of these distances, we have

$$\begin{aligned} t_{AX,1} - t_{AX,0} &= t_{1A} - t_{0A} \\ t_{AX,2} - t_{AX,0} &= t_{2A} - t_{0A}. \end{aligned}$$

These are exactly the same time differences used by the navigation system of vehicle A to estimate its position! That shows that the horizontal position of vehicle A can be estimated externally, just by listening to the signals emitted by A.

Since all these signals have the same frequency,it is crucial that each detection is correctly matched with the corresponding emission. This requires that the emission of the three signals by vehicle A follows a predefined order. It is obvious that the first emission corresponds to the reception of the signal from the master beacon.

Furthermore, if the above mentioned delays Δ_1 and Δ_2 obey

$$\Delta_2 - \Delta_1 > \frac{2d_{12}}{c},$$

it can be easily shown that

$$t_{2A} > t_{1A}$$

wherever the vehicle A is. This means that every vehicle in the area will receive the signal from $\mathbf{B}_1$ before the signal $\mathbf{B}_2$, independently of its position. Since it is obvious that $t_{1A} > t_{0A}$, at each epoch, the three emissions of signal f_A by the vehicle A correspond to the replies to $\mathbf{B}_0$, $\mathbf{B}_1$, and $\mathbf{B}_2$, respectively. In the same way, the three detections of signal f_A by the device X correspond to the replies of A to $\mathbf{B}_0$, $\mathbf{B}_1$, and $\mathbf{B}_2$, respectively.

Since we are considering that each vehicle uses a single frequency and to prevent incorrect matches due to lost signals, it is mandatory that, at each epoch, the device X only updates is estimate of the vehicle A position after the reception of three signals of frequency f_A.

The time difference measurements $t_{AX,1} - t_{AX,0}$ and $t_{AX,2} - t_{AX,0}$, used to determine the position of A, are available at two different instants ($t_{AX,1}$ and $t_{AX,2}$), that can be a few seconds apart. It is then useful to consider a model of the vehicle A motion to predict its evolution between each two time difference measurements. Otherwise, the simple intersection of the two hyperboles corresponding to each pair of time differences will introduce a systematic error in the estimate of vehicle A position. Furthermore, such a model can also be used to predict the differences between the d_{AX}, d'_{AX}, and d''_{AX}, above ignored.

For the purpose of external tracking, since there is no dead reckoning data available, we will consider that the motion of vehicle A is described by the stochastic differential equation

$$\begin{cases} \dot{x} = v_x + n_x \\ \dot{y} = v_y + n_y \\ \dot{v}_x = -\beta v_x + n_{vx} \\ \dot{v}_y = -\beta v_y + n_{vy} \end{cases}$$

where (x, y) are the coordinates of the vehicle A in the horizontal plane, and (v_x, v_y) are the horizontal components of its velocity, with respect to a fixed frame. β is a non negative parameter (usually set to 0), and n_x, n_{vx}, n_y and n_{vy} are independent white noise processes, see (Matos and Cruz, 2004) for a justification of this model.

At each epoch, the measurements $t_{AX,1} - t_{AX,0}$ and $t_{AX,2} - t_{AX,0}$ are used to provide new information about the state of the dynamic system defined above at the instants of time t_{1A} and t_{2A}. The estimation is based on an extended Kalman filter. At each of these times, the position components of the state of the dynamic system are used to predict the measurement, and the difference between the predicted and the actual measurement is used to correct the state and the error covariance. The algorithm employed is a simplified version of the one mentioned above for the navigation of an AUV, since now the dead reckoning integration turns out to be quite trivial.

6. SENSITIVITY ANALYSIS

One factor that affects the performance of the positioning algorithm is its sensitivity to errors in range measurements. Since, for the proposed solution, both the AUV navigation and the external tracking rely on a hyperbolic navigation algorithm, we discuss briefly the sensitivity of this algorithm to errors in range difference measurements.

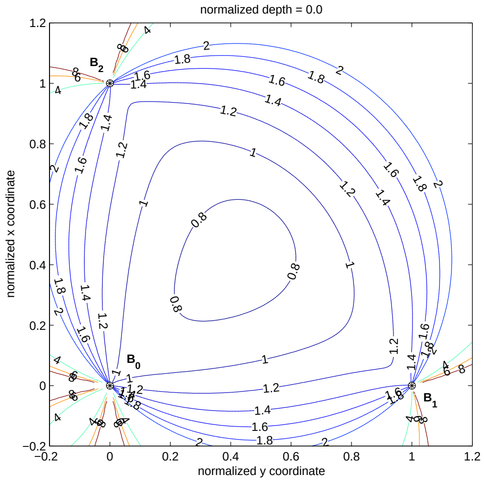

Fig. 1. Sensitivity to distance differences errors.

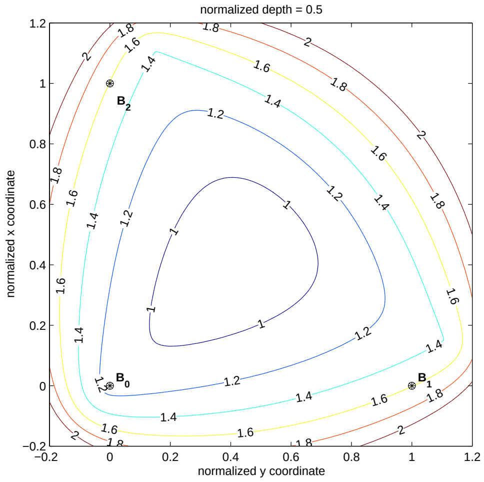

Fig. 2. Sensitivity to distance differences errors.

Let's consider that the three beacons are respectively located at positions $(0, 0, 0)$, $(x_1, y_1, 0)$, and $(x_2, y_2, 0)$. Consider also that the vehicle position is (x, y, z). In the hyperbolic navigation, the horizontal position is computed from the distance differences measurements

$$A_1 = d_1 - d_0$$
$$A_2 = d_2 - d_0$$

where

$$d_0 = \sqrt{x^2 + y^2 + z^2}$$
$$d_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2 + z^2}$$
$$d_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2 + z^2}$$

are the distances between the vehicle and each one of the acoustic beacons.

When the measurements (A_1, A_2) are affected by small errors $(\delta A_1, \delta A_2)$, the computed horizontal position (x, y) will be affected by an error $(\delta x, \delta y)$. These are related by

$$\begin{bmatrix} \delta A_1 \\ \delta A_2 \end{bmatrix} = M \cdot \begin{bmatrix} \delta x \\ \delta y \end{bmatrix}$$

where M is the jacobian matrix given by

$$M = \begin{bmatrix} \frac{\partial A_1}{\partial x} & \frac{\partial A_1}{\partial y} \\ \frac{\partial A_2}{\partial x} & \frac{\partial A_2}{\partial y} \end{bmatrix}.$$

The sensitivity of the hyperbolic navigation to errors in the distance difference measurements in then given by $\|M^{-1}\|_2$. Figures 1-2 present a plot of this sensitivity when $x_1 = y_2 = L$ and $y_1 = x_2 =$ for the cases $z = 0$ and $z = L$. As can be easily noticed the sensitivity is smaller inside the triangle defined by the three beacons and increases outside this triangle. If should also be noted that as the distance of the vehicle from the plane defined by the beacons increases, the minimum value of sensitivity increases too, but at the same time the dependence of sensitivity with the vehicle position is reduced.

7. SIMULATION RESULTS

To illustrate the proposed mode for the acoustic network we present a simulation of its operation. In the presented scenario two vehicles, A and B, operate in an acoustic networks composed by beacons $\mathbf{B_0}$, $\mathbf{B_1}$, and $\mathbf{B_2}$. Vehicle A is describing a rectangular trajectory while B describes a circle. Figure 3 shows the trajectories of both vehicles as well as the real time estimate of the position of A computed by vehicle B. It can be observed that this estimate (blue line) is close to the actual trajectory of this vehicle.

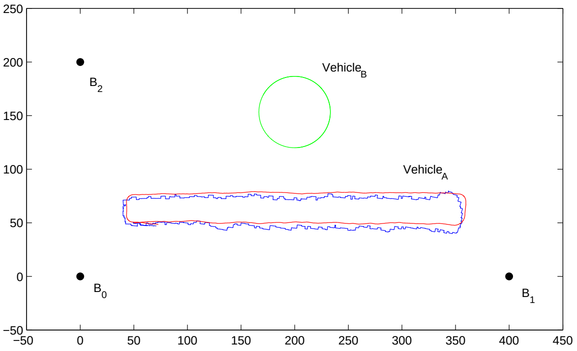

Fig. 3. Trajectories of vehicles A and B.

To better assess the performance of the external tracking, figure 4 presents the distance between the real position of vehicle A and its estimate computed by vehicle B.

Finally, figure 5 presents the evolution of the major and minor axes of the uncertainty ellipse

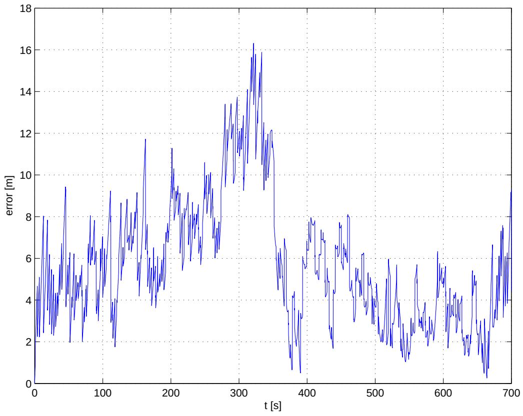

Fig. 4. Position estimation error.

of the external tracking solution. These axes are scaled to the value that would be obtained if direct position measurements in x and y coordinates were made, with the same error as the range difference measurements.

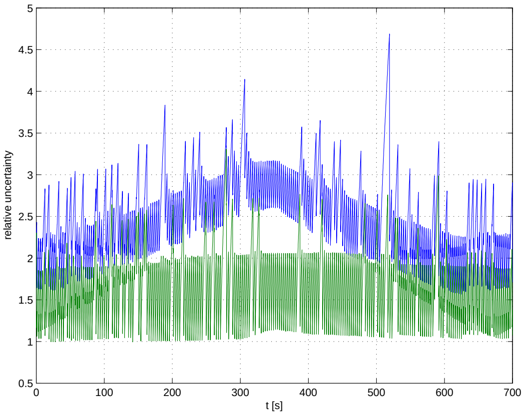

Fig. 5. Uncertainty of positioning.

8. CONCLUSIONS

The mode of operation for the acoustic network proposed here allows for the simultaneous navigation of multiple vehicles in an efficient and effective way. Besides the basic signals required for each vehicle to determine its own position (by an hyperbolic positioning algorithm), only one new signal is required for each vehicle. This is certainly the simplest general solution for the simultaneous navigation of multiple vehicles since the external tracking of one vehicle will necessarily required an additional signal.

Furthermore, this solution can be easily adapted to the navigation of master-slave formations. In that case all the vehicles will navigate using an hyperbolic algorithm, and only one additional signal will be necessary for the master vehicle to notify all the others of its instants of detection of the acoustic signals from the beacons.

Finally, it should be noted that all the presentation was made for the external tracking of only the horizontal position of a vehicle. For shallow water operations this is much more important than the vertical position. Nonetheless, the presented method can be easily extended for tridimensional external tracking by considering another slave beacon not in the same plane defined by the other three beacons.

9. ACKNOWLEDGEMENT

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