Some Algorithms of Differential-Ranging Acoustic Positioning System Intended for AUV Group Based on a Particle Filter

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Abstract. The paper considers the problem of providing for Autonomous Underwater Vehicles (AUV) group navigation using an acoustic long-base line (LBL) differential-ranging (DR) positioning system. An algorithm is presented that solving the navigation problem of the DR acoustic positioning system (APS), based on the use of a particle filter (PF). The simulation results are presented using the developed algorithm, proving its effectiveness and capacity for operation.

1. Introduction
AUV groups are possible to increase the efficiency of the already familiar missions in comparison with the use of a single vehicle, and also opens up opportunities for solving new problems. AUV group navigation assumes the simultaneous determination of the coordinates of all AUVs included in the group. Using traditional asynchronous acoustic positioning system with a long-base line (LBL APS) does not allow solving this navigation problem since implementing alternate coordinating of single AUVs in the group. Synchronous APS requires expensive precision time systems [1-6]. Some systems for AUV group navigation include Autonomous Surface Vehicles (ASV) [7-16].

One of the ways to solve this problem is to use the differential-ranging (DR) APS. Various methods for solving the differential-range navigation task are widely described in [17-19]. In [20], two developed navigation algorithms are presented that implement exhaustive search and analytical methods for solving the DR problem. The simulation results are presented using the developed algorithms. The work [21] is devoted to the description of some algorithms for the AUV navigation located in the acoustic shadow zone of the LBL APS. For this, measurements of mutual distances between AUVs in a group are used simultaneously with measurements of distances to APS beacons.

The method of group navigation for the AUV using a synchronous LBL APS, operating in the differential-ranging mode, is considered in Section 1. Section 2 describes an algorithm for solving the navigation problem of the DR LBL, based on the use of a particle filter (PF). The study of the performance for the proposed algorithm was carried out by means of computer simulation, the results of which are given in Section 3.

2. Method of group navigation of AUV using differential-ranging LBL APS
The APS with DR LBL includes three acoustic beacons operating in a special mode. The first beacon is the leader and it sets the period of operation of the entire system. The leading beacon emits with a certain period a navigation package, which contains data including its own coordinates. The second and third beacons are slave. They and all AUVs of the group receive the navigation package and fix
the time of its arrival. After receiving of such a package slave beacons emit their own navigation packages in which they transmit information about themselves and their coordinates. Packages from beacons are received on all AUVs of the group with a fixation of the time of their arrival. In each cycle of LBL operation all AUVs determine the moments of arrival for signals from three LBL beacons, and also receive their coordinates. Before the operation of the DR APS, the coordinates of the beacons are determined with the required accuracy and recorded in the built-in memory of the beacons.

Figure 1 shows the paths of signal propagation from the master beacon M1 to the slave beacons M2 and M3 and to the AUV. Let us assume that the master beacon M1 emits the next signal at the moment $t_0$ and the time of signal propagation from it to the AUV is equal to $\tau_1$. The propagation times of signals from the master beacon M1 to the slave beacons M2 and M3 are $\tau_2$ and $\tau_4$, respectively. The propagation times of signals from the slave beacons M2 and M3 to the AUV are $\tau_3$ and $\tau_5$, respectively. Based on these data, the following equations can be drawn up for the arrival time $t_{A1}$ of the signal to the AUV from the master beacon M1 and the arrival times $t_{A2}$ and $t_{A3}$ of signals to the AUV from the slave beacons M2 and M3:

$$
t_{A1} = t_0 + \tau_1, \\
t_{A2} = t_0 + \tau_2 + \tau_3, \\
t_{A3} = t_0 + \tau_4 + \tau_5.
$$

Then, for the difference in the time of signals arrival to the AUV between M1 and M2 and between M1 and M3, we obtain:

$$
t_{A12} = \tau_2 + \tau_3 - \tau_1, \\
t_{A13} = \tau_4 + \tau_5 - \tau_1.
$$

Figure 1. Propagation path beacon signals from the master beacon M1 to the slave beacons M2 and M3 and to the AUV.

In these expressions, the unknown time $t_0$ of the moment for signal emission by the master beacon M1 is absent. It is necessary to develop an algorithm that will allow forming an estimation of the location for the AUV with the required accuracy, based on the measurement data $t_{A12}$ and $t_{A13}$, obtained in each cycle of the LBL operation.
3. The range-difference solution of the problem using an algorithm based on the particle filter

The paper uses an approach to the implementation of the algorithm for estimating the AUV location, based on a particle filter. The particle filter allows estimating the location of the AUV based on information about the times of arrival for signals from the beacons to one of the AUVs of the group and data received from the onboard reckoning system. For AUV position evaluation the particle filter creates a set of particles, which at the start of operation are located in the area of the most probable AUV position. At each iteration of the observation cycle, the filter rejects particles that do not pass the reliability check. Thus, after a certain time, particles with the highest weights that are closest to the true value of the AUV location will be selected from the set of particles.

The particle filter algorithm consists of several stages:

Initialization. Before proceeding with iterations, the particle filter should be initialized - set the parameters, the initial distribution, and other conditions for the filter operation. The main parameter of the particle filter is the number $N$ of particles. The initial distribution of particles depends on a priori information. The more particles, the more accurate the filter allows to estimate the location of the AUV and the more long calculations need to be done at each iteration. We know the area of the most probable location of the AUV at the beginning of work, therefore, the particle cloud is located in the specified area with a given radius. The coordinates of the AUV dive point are fixed using a satellite positioning system, and the radius of the circle is selected taking into account the possible uncontrolled drift of the AUV during the dive due to the presence of currents and dead reckoning errors.

Figure 2. Trajectories of the AUV in the process of model experiments.
The main parameter of each particle is its weight. The particle weight determines the probability that the coordinates of this particle coincide with the coordinates of the AUV. Since we assume that the total set of particles describes the position of our vehicle, the total weight of all particles is equal to one. In this case, the weight of all particles at the initial moment of time is taken to be the same and equal to 1/N.

**Motion.** At this stage, the AUV is moving and, since the reckoning of the location occurs with inaccuracies, the error in determining its location increases. Since each particle is a model of an AUV position, it must move accordingly, like an AUV. In this case, a random error is added to the vector of motion of each particle. Information about the motion of the AUV comes from the onboard dead reckoning system.

**Correction.** After measuring the distances from the AUV to the hydroacoustic navigation beacons M1, M2 and M3, the time differences of the signal arrivals between M1, M2 and AUV and between M1 and M3 and AUV are calculated. Then, these differences are calculated for the current location of each particle in accordance with the expression:

\[
T_{A12} = (d2 + d3 - d1)/c,
T_{A13} = (d4 + d5 - d1)/c.
\]  

(3)

where \( c \) is the speed of propagation of a sound signal in water, \( d1, d2, d3, d4 \) and \( d5 \) are the corresponding distances between M1, M2, M3 and i-th particle, calculated in accordance with the expressions:

\[
d1 = \sqrt{(x_{M1} - x_i)^2 + (y_{M1} - y_i)^2 + (z_{M1} - z_i)^2}
\]

\[
d2 = \sqrt{(x_{M1} - x_{M2})^2 + (y_{M1} - y_{M2})^2 + (z_{M1} - z_{M2})^2}
\]

\[
d3 = \sqrt{(x_{M2} - x_i)^2 + (y_{M2} - y_i)^2 + (z_{M2} - z_i)^2}
\]

\[
d4 = \sqrt{(x_{M1} - x_{M3})^2 + (y_{M1} - y_{M3})^2 + (z_{M1} - z_{M3})^2}
\]

\[
d5 = \sqrt{(x_{M3} - x_i)^2 + (y_{M3} - y_i)^2 + (z_{M3} - z_i)^2}
\]

(4)

where \((x_{Mj}, y_{Mj}, z_{Mj})\) are coordinates of beacons \((j=1,2,3)\), \((x_i, y_i, z_i)\) are coordinates of the i-th particle.

Then the increment of particle weights \( \Delta w_i \) is calculated, which takes into account the degree of correspondence of particle coordinates to the obtained measurements of ranges to them:

\[
\Delta w_i = (1 - w_i / \sum w_i)/(N - 1).
\]

(5)

where \( w_i = \sqrt{(T_{A12i} - t_{A12i})^2 + (T_{A13i} - t_{A13i})^2} \). After that the newly obtained particle weights are normalized.

**Particle regeneration.** In the course of long-term operation of the particle filter, only a small number of particles will have significantly different weights from zero: most of the particles degenerate (their weights decrease and become negligible). Particles with small weights are removed, and new particles are created in a certain area around the remaining particles in proportion to their weights.

The estimation of the AUV location is considered either the coordinates of a particle with a maximum weight exceeding a given threshold, or the average weighted value of the coordinates of all particles.

The work of the particle filter ends when particles with a total weight greater than a given threshold are localized in a small area of a given size, the size of which characterizes the accuracy of the AUV position estimation.
4. Some algorithms of differential-ranging acoustic positioning system intended for AUV group based on a particle filter

To investigate the above-described algorithm a simulation system was developed based on a language C ++ using the Qt Creator. This simulation system investigates the AUV positioning algorithm based on the PF for the range-difference task solution.

Several model experiments with different parameters were performed to compare the accuracy of the AUV location estimation algorithm. Figure 2 shows trajectories of its movement when the AUV is maneuvering at a depth of about 2000 meters. It performs "meander" mission inside triangle with beacons in its vertices, outside triangle and on its border, going in and out of the triangle.

In the first case (Figure 3, c) the AUV moved along a meander trajectory from a point with coordinates (-1497.96; -500) with a part of its trajectory outside and a part inside the beacons base. The second AUV trajectory (Figure 3, a) repeats the meander trajectory from the point with coordinates (-498.616; -500) and the trajectory lies completely inside the triangle of the beacons base. The third trajectory of AUV (Figure 3, b) is outside triangle and represents a meander from the point with coordinates (1000.474; 500). The AUV moves with constant velocity of 1 m/s. LBL beacons are static and located at coordinates M1 (1500; 0; 2325), M2 (-1000; -1500; 2000) and M3 (-1000; 1500; 2150).

The period of APS operation was taken equal to 8 sec. The mission duration was 3.5 hours. Cloud of 10,000 particles was used in the process of modelling the algorithm based on the particle filter.

The slant range measurements between the AUV and the beacon were distorted by a normally distributed random variable with a zero mean and a standard deviation of 0.1% of the true distance value. An AUV’s velocity measurements were distorted by adding the noise to the program value, which was a normally distributed random variable with a constant bias of 0.01 m/s and a standard
deviation of 0.05 m/s. Heading measurement errors of the AUV were modelled by a normally distributed random value with a constant bias of 0.1 deg. and standard deviation of 0.5 deg. Based on the data obtained, we can conclude that the error in the estimation of AUV coordinates during the algorithm run time for case 3 (a) - does not exceed 0.5 meters, for case 3 (b) - 1 meter, and for case 3 (c) - 2 meters, respectively.

After each cycle we discard about 10% of the total number of particles. We sort them by weight from larger to smaller and sum the weight, if the weight is 0.9 we stop summing and discard the remaining particles. Figure 4 shows motion and decrease of the particle cloud size as the AUV moves, hence AUV location estimation is more precise.

![Figure 4](image_url)

**Figure 4.** Processes of AUV coordinate estimation using particle filter during AUV mission, when it was moving along the trajectory inside the beacons base. The graph shows the change and movement of the particle cloud: a). - after generation, b). - after 1 observing cycle, c). - after 10 cycles of observing and (d). - after 100 observational cycles.

5. Conclusion
The described RD approach allows simultaneous navigation for all AUVs in a group, because it does not require each of the AUVs to be allocated a time window for interrogating the LBL beacons. The PF-based algorithm developed and described in this work allows effectively solving the problem of AUV coordinates determination when using the described RD APS.

6. References
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