Accurate Underwater Localization Using LBL Positioning System

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***Abstract*—The absolute position of an underwater target is difficult to pinpoint because the global positioning system (GPS) cannot penetrate water bodies. The long baseline (LBL) positioning system can extend GPS using high-precision calibrated underwater beacons as references. While traditional LBL systems give the target position without considering calibration error of deployed beacons. To solve this problem, we propose a method different from previous works, that combining all of the observations together. We use GPS outputs as true values to evaluate the localization performance. An LBL system with four beacons was installed in shallow water and deep sea to test the results. The positioning accuracy in shallow water and deep sea improves 0.06 m and 1.98 m respectively. The results suggest that beacon positioning errors have a great impact on localization precision, especially in deep sea, that is significant in high-precision positioning tasks.**

I. Introduction

Autonomous underwater vehicles (AUVs) have to meet stringent requirements in practical tasks such as geophysical field surveys, offshore industries, environmental measurements, and minefield detection. The autonomous operation of an AUV requires an on-board navigation system to provide real-time location, high precision data, and absolute position outputs [1]–[3]. Long baseline (LBL) acoustic positioning systems are commonly used for AUV navigation because of their high accuracy, which is independent of slant range and large-scale coverage [1], [2].

LBL systems consist of undersea beacons and a transceiver installed on the target. The beacons in LBL are similar to the satellites in the global positioning system (GPS). The beacons can be used as underwater references for target positioning. The target position can be determined via triangulation or trilateration using the distances to the beacons. The result is a position relative to the beacon array, that can be converted to geodetic coordinates with the absolute positions of the beacons. The localization is related to the range measurements between the target the and beacons and the calibrated positions of the beacon array. The precision of the position of a localized target is determined by the precisions of these two measurements. Matos et al. provides a relative precision without considering the precision of the calibrated beacons. The traditional methods of LBL focus on online tracking and offline calibration. To simplify the tracking process and lower the computational complexity, the output positioning error is only related to the range measurement error [4]–[6].

In this study, we use a method to determine the online target position by combining all of the observations together. The positioning error of a target includes the distance measurement error and beacon calibration error. The aim is to determine the absolute position of a target with overall errors. We add the calibration error expressed by a covariance matrix in the traditional method and estimate the target position. The results are compared with GPS outputs. We regard GPS outputs as the true positions and the deviations between our method and GPS outputs are used as evaluation metrics.

To test the performance of our method, an LBL system with four beacons was installed in shallow water and deep sea. Beacons were deployed in 50-m-deep water and about 4000-m-deep sea. We measured the distances between the beacons and the survey ship as the ship circled each underwater beacon while simultaneously collecting two-way acoustic ranges and GPS data. We then used the calibrated positions of beacons and measured distances between the target and the underwater beacons to localize the survey ship. The localization methods we propose and traditional LS were used to get position estimates that were then compared to GPS outputs.

The related positioning works are described in Section II. Section III gives the proposed target tracking method. The field test results in shallow water and deep are presented in Section IV and Section V. The conclusions are presented in Section VI.

II. Related works

Traditional methods of LBL can be categorized into least squares (LS), Kalman filter (KF), and other methods. LS is the most common method used in static target localization. Initial values of the target position are not required. The precision of the target position is determined by the number of observations and the precision of distance measurements [7], [8]. Compared to LS, KF is more applicable to mobile target localization. KF is a recursive localization method that is essentially a process of prediction and modification. KF is less robust than LS if inertial navigation inputs are not provided [4], [9], [10]. Other methods, such as maximum likelihood estimation, probabilistic and statistical methods always need a great deal of prior data before positioning. This makes them unsuitable for practical real-time applications [11], [12]. Traditional methods assume accurate beacon positions so the precision of the target position is only related to the distance measurement error.

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III. Basic principles of target tracking

During each positioning cycle, the transceiver on the target transmits interrogation signals. Each beacon receives the interrogation signals and transmits response signals. The target calculates the distances between the transceiver and beacons using the signal time differences and the sound speed to localize itself. The position is determined relative to the beacon arrays and can be converted to geodetic coordinates using the calibrated beacons.

The observation equation of the system is expressed in Equation 1. We use an LBL system with four beacons as an example to illustrate our solutions.

$$\|{}^G\mathbf{x}_t - {}^G\mathbf{x}_{\mathbf{B}_i}\| = r_i, i = 1,2,3,4 \tag{1}$$

where,

${}^G\mathbf{x}_t$ is a 3-vector representing the target position in geodetic coordinates,

${}^G\mathbf{x}_{\mathbf{B}_i}$ is a 3-vector representing the beacon position of beacon i in geodetic coordinates,

$r_i = ct_i, i = 1,2,3,4$ represents the measured distance between beacon i and the transceiver, c is the sound speed, and t_i is the measured time difference between the target and beacon i.

The observation equations of four beacons constitute a set of non-linear equations. Equations 2 to 9 provide the solution we propose with the beacon error expressed by the covariance matrix. Determining the target position requires an approximate position ${}^G\mathbf{x}_t^0$. This is used to calculate model predictions of the measured distances that are compared with the actual observed values l. This is an iterative procedure that continue until the corrections are below a specified threshold [5].

$$f({}^G\widehat{\mathbf{x}}_t, \widehat{r}) = 0 \tag{2}$$

where $f()$ is a function that relates the desired unknown positions ${}^G\widehat{\mathbf{x}}_t$ and the adjusted observables $\widehat{r}$.

The linear form considering the beacon error is given by

$$\mathbf{V} = \mathbf{A}\widehat{\Delta} - \widehat{\mathbf{R}} \tag{3}$$

where $\mathbf{A}$ is the coefficients of the matrices defined as

$$\mathbf{A} = (\frac{\partial f}{\partial {}^G\widehat{\mathbf{x}}_t, \mathbf{x}_{\mathbf{B}_i}})_{{}^G\mathbf{x}_t^0} \tag{4}$$

and the adjusted observables $\widehat{\mathbf{R}}$ is defined as

$$\widehat{\mathbf{R}} = [\mathbf{0},\mathbf{0},\mathbf{0},\mathbf{0},\widehat{r}]^T \tag{5}$$

where $\widehat{r}$ is the adjusted variables defined in 6

$$\mathbf{l} = l + \widehat{r} \tag{6}$$

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Applying the least-squares estimation method, the corrections are given by

$$\widehat{\Delta} = \widehat{\sigma}_0^2(\mathbf{A}^T\mathbf{P}_{overall}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{P}_{overall}\widehat{R} \tag{7}$$

where $\mathbf{P}_{overall}$ is a covariance matrix formed by the error of distance measurement and error of beacon calibration, and $\widehat{\sigma}_0^2$ is the reduced Chi-squared factor defined as

$$\widehat{\sigma}_0^2 = \widehat{R}^T\mathbf{P}_{overall}^{-1}\widehat{R}, \tag{8}$$

The covariance matrix of the unknown is

$$\mathbf{Q}_{\widehat{\Delta}} = \widehat{\sigma}_0^2(\mathbf{A}^T\mathbf{P}_{overall}\mathbf{A})^{-1} \tag{9}$$

IV. Field test in shallow water

To test the performance of the tracking method, an LBL positioning system with four beacons was installed in Songhua Lake, Jilin, China in October 2012. The beacons were deployed at a depth of 60 m. The experiment included calibration and tracking.

The calibration errors of beacons are listed in Table I in geodetic coordinate. X, Y, and Z are the coordinates in three dimensions and σ_X, σ_Y, and σ_Z are the localization errors in three dimensions. $\sigma_P = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}$ is the spatial positioning error.

TABLE I. Calibration error of beacons

	σ_X(m)	σ_Y(m)	σ_Z(m)	σ_P(m)
Beacon 1	0.009	0.010	0.007	0.015
Beacon 2	0.009	0.009	0.007	0.015
Beacon 3	0.011	0.012	0.007	0.018
Beacon 4	0.008	0.009	0.007	0.014

In the tracking procedure, a transceiver is installed at the same position as the GPS antenna. In each positioning cycle, the transceiver measures the distances to the beacons and uses them to calculate the transceiver position. Figure 1 shows the positioning trajectory. We use the positioning error listed in Table I and a distance measurement error of 0.01 m. A ray-tracing model was used to compensate for the error caused by the inaccuracy of the sound speed. Wideband signals in a frequency range of 20∼30 kHz with a resolution of 5 μs were used. Figure 2 shows the measured static distance between a transceiver and a beacon after compensation. From Figure 2 we can see the error is less than $\pm 0.01\,m(1-\sigma)$ so we choose the estimated error to be 0.01 m (within a 95% confidence region). Figure 1 shows that the trajectory is smooth and continuous. Each position has a positioning error expressed by an error ellipse.

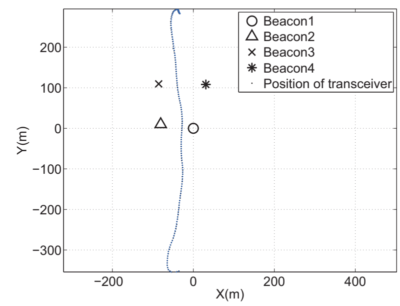

Fig. 1. Positioning trajectory (Note: the coordinate system uses the position of beacon 1 as the origin)

The impact of beacon calibration errors can also be estimated. Figure 3 shows a comparison of the positions without

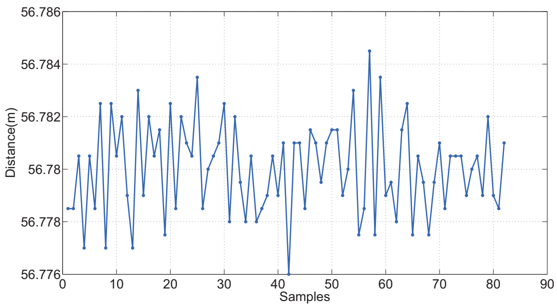

Fig. 2. Distance measurement between a static transceiver and a beacon

considering calibration errors, with calibration errors, and the GPS output in horizontal projection. The three trajectories are nearly the same. Since the transceiver has the same position as the GPS antenna, we use the GPS outputs as the true position to calculate the horizontal distances between the positions solved by these two methods and the true positions.

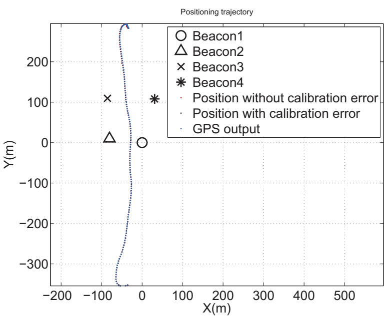

Fig. 3. Comparison of different trajectories

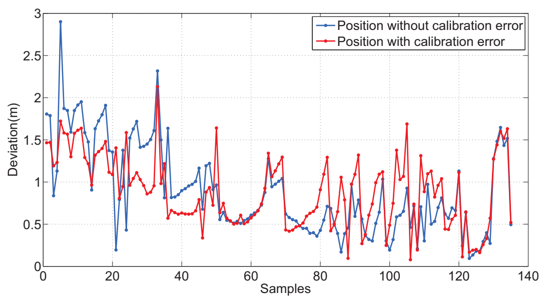

Fig. 4. Deviation between estimated position and GPS output

Figure 4 shows the deviations between the estimated positions and GPS outputs. The deviations without considering the calibration errors have a maximum of nearly 3 m while the deviations with calibration error have maximum less than 2.5 m. The average of the deviations are also calculated. The average of the blue and red lines are $0.891\,m$ and $0.885\,m$, respectively. The results are reasonable because adding the calibration and distance measurement errors produces estimated positions that are close to true positions.

V. Field Test in Deep Sea

To test the performance of localization in deep sea, we had an experiment with LBL positioning system in South China Sea in March 2015. The beacons were deployed at a depth of nearly 3600 m. The experiment worked the same as shallow water, which also included calibration and tracking.

The calibration errors are listed in Table II. We use the working frequency range of 8∼16 kHz and distance measurement error is $\pm 0.01\,m(1-\sigma)$. Figure 5 shows the deployed beacons with a projection of rectangle and drifting trajectory of ship. Figure 6 shows a comparison of the positions without considering calibration errors (blue lines), with calibration errors (red lines), and the GPS output (black cross line) in horizontal projection. From Figure 6 we can see the red lines are nearly same with GPS output, that have more approximation to GPS output. Figure 7 shows the deviations between the estimated positions and GPS outputs. The deviations without considering the calibration errors have a maximum of nearly 8 m while the deviations with calibration error have maximum less than 7 m. The average of the deviations of the blue and red lines are 3.522 m and 1.547 m respectively. Compared to the results of shallow water, the performance of the method we propose have great improvement. That because the calibration precision in deep see is meter order that can result in a great deviations to true values.

TABLE II. Calibration Error of Beacons

	Latitude Error(m)	Longitude Error(m)	Depth Error (m)
Beacon 34	±2.818	±2.364	±1.619
Beacon 35	±1.271	±3.440	±1.608
Beacon 36	±2.886	±2.267	±1.640
Beacon 37	±4.269	±1.592	±2.103

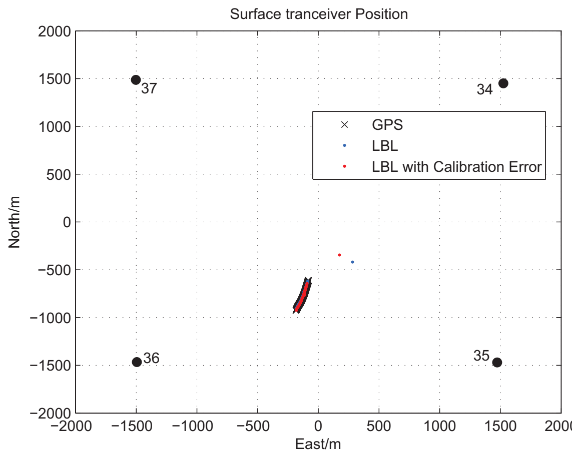

Fig. 5. Deployed beacons and drifting trajectory of ship

The experimental results show the comparison with GPS in shallow waters and deep ocean. While in deep ocean, the calibration error is higher with the order of meters. This is because calibration is a procedure to extend GPS underwater, the distance measurement is mainly affected by sound speed changing. The sound speed in deep sea that changes severely from surface to bottom. In tracking procedure, the target usually works with the height nearly same to deployed beacons, so the distance measurement error is relatively small compared

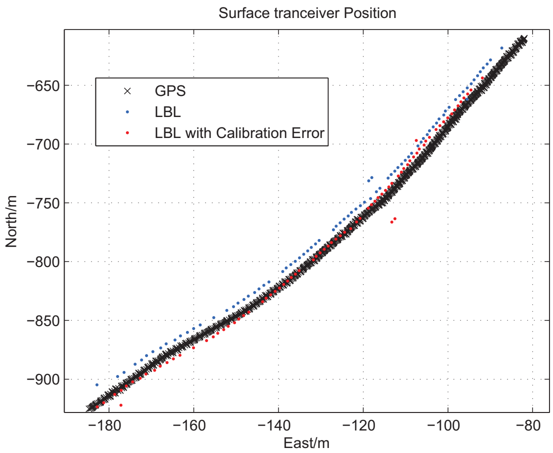

Fig. 6. Comparison of different trajectories

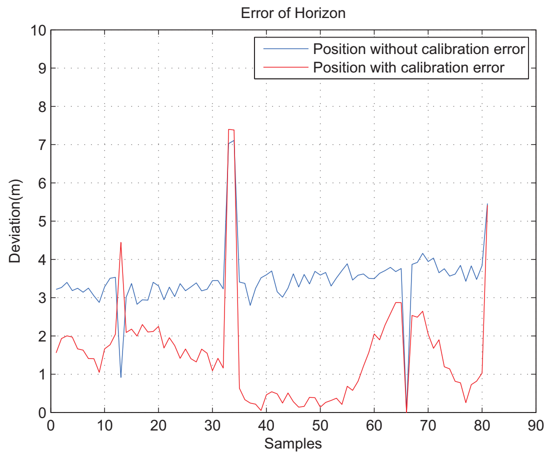

Fig. 7. Deviation between estimated position and GPS output

to calibration error. In shallow water, using the calibration error of $\pm 2\,cm(2-\sigma)$ can reduce the deviation from $0.891\,m$ to $0.885\,m$ compared to GPS outputs. In deep sea, using the calibration error of meters can reduce the deviation from $3.522\,m$ to $1.547\,m$ compared to GPS outputs. The error after propagation increases many times in target positioning error. In deep oceans, it is significant adding calibration error in solving equations to have accurate target position.

VI. Conclusion and Future Work

We use the actual data of LBL positioning system to prove great impact of the calibration error on accurate underwater target localization. The localization results were compared to the GPS outputs, which were taken as true values. The source of localization errors were analyzed to determine the error leading to tracking and calibration. From theory and experimental results, the method we propose combing overall observation errors can produce more accurate results than traditional method. Future work will test the performance with integrate Doppler velocity logs and inertial navigation system (INS) to achieve more accurate positions.

VII. Acknowledgement

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