Location of Static Targets on the Seabed: A Study

Biyuan Yao[1], Xinghui Cao[2], Binjian Shen[2], Guiqing Li[1], Jianhua Yin[3]

[1] School of Computer Science and Engineering, South China University of Technology, China
[2] Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences, China
[3] School of Science, Hainan University, China
yaobiyuanyy@163.com, caoxinghui@idsse.ac.cn, shenbj@idsse.ac.cn, ligq@scut.edu.cn, yinjh@hainu.edu.cn

Abstract

The location of underwater targets is an important issue in military applications. To specifically target a stationary object, a comparative experiment is designed by using the weighted centroid localization algorithm in the non-ranging location and the least square localization algorithm in the location of ranging to determine the target range. Three issues are addressed: (i) the estimated position of the measured object, (ii) the positioning error of the estimated position and the actual position of the object measured, and (iii) the closest beacon to the measured object.

Keywords: Static target, Weighted centroid localization algorithm, Least square localization algorithm, Positioning error

1 Introduction

Location is an important component of marine spatial information. Location plays an indispensable role in marine military and scientific investigations, and effective development and utilization of marine resources [1]. Underwater positioning technology is the basis of current developmental and technological activities in ocean science. Ocean localization mainly resolves the challenges associated with the planimetric position and the depth of water of the target in real-time or asynchronously [2-4]. Detection and location of underwater targets require analysis of signal characteristics of underwater targets, as shown in Figure 1. Multipath and dispersion effects [5], unevenness of seawater, unevenness of boundaries, etc., will cause delays, distortions, losses, fluctuations and other changes in the propagation of acoustic signals. Currently, the difficulties of underwater positioning technology are as follows: (i) A small clock deviation leads to the distance error and reduces positioning accuracy and (ii) accuracy of the real-time position of the satellite as the reference point for positioning is a challenge. In this study, we consider that the weighted centroid location algorithm and the least square localization algorithm isn't completely effective in determining the location information consistent with the real-world targets. However, they can provide an approximate real-time location to the maximum possible extent and reduce the location error to a reasonable threshold.

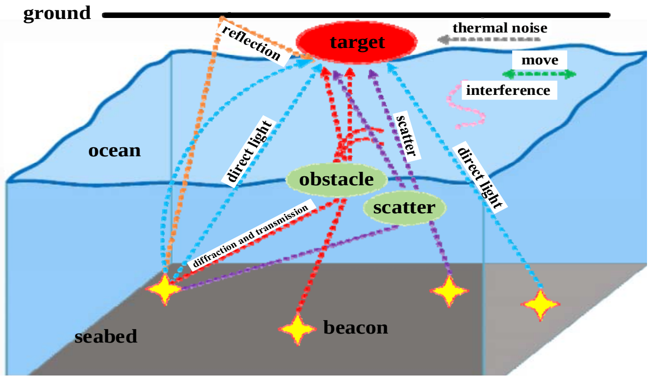

Figure 1. Propagation of underwater signals
Note. It is simplified and doesn't report the water-air diffraction phenomena. The meaning of each colored line is different from each other, such as orange representing reflection, blue projectivity, red diffraction and transmission, purple scattering, rose red interference, green movement and gray thermal noise.

The study is structured as follows: The second section reviews previous studies related to target positioning. The third section introduces the theory of weighted centroid localization algorithm and the least square localization algorithm. The fourth section describes model development. The non-ranging and ranging algorithms are used to estimate the static target position. The last section summarizes the study findings.

2 Related Works

In 1997, the test of Global Positioning System (GPS) in underwater navigation was carried out. The depth of the test water was 10-30 m. At a distance of 2 km, the positioning accuracy of the test water was 3 m [6]. In January 2004, the first underwater GPS high-precision positioning and the navigation system funded was

*Corresponding Author: Xinghui Cao; E-mail: caoxinghui@idsse.ac.cn
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successfully developed. Experiments conducted in Qiandao Lake in Zhejiang Province showed that the precision of underwater positioning of the system was 5 cm at a water depth of about 45 m. Bathymetric accuracy was 30 cm [7]. Aiming at the motion velocity prediction of moving obstacles in the unknown underwater environment, Yan Zheping et al. proposed a prediction method based on multi-beam forward-looking sonar [8]. In reference [9], an improved iterative weighted centroid grid positioning algorithm is proposed, which uses the grid to obtain the location of unknown nodes, and then uses the centroid algorithm to estimate the location coordinates of the location nodes. In reference [10], an enhanced centroid localization algorithm is proposed, which has the advantages of simple calculation, low communication overhead between nodes in the localization process and self-adaptability. Yang Xiaohan uses the positioning method of least square to estimate the transmission delay of the path, and combines the Newton iteration method to obtain the estimated position [11]. In reference [12], in the three-dimensional underwater environment with an equal-gradient sound velocity profile, the time of sound velocity is used to measure fixed nodes and track moving targets.

3 Basic Theory

3.1 Weighted Centroid Location Algorithm

The centroid localization algorithm [13] proposed by Nirupama Bulusu et al. of the University of Southern California obviates the need to measure the actual distance based on network connectivity. The basic idea is that the beacon nodes periodically transmit a beacon signal to neighboring nodes. The signal contains the beacon ID and the position coordinates. The unknown node stores the received beacon packet, and calculated the centroid of the polygon comprising the received beacon node to estimate the location of the unknown node. The centroid localization algorithm determines the region containing the unknown nodes, and calculates the centroid of the region as the estimated location of the unknown nodes. The positioning process of centroid algorithm is shown in Figure 2 and Figure 3. The coordinates of the vertices of the hexagonal *ABCDEF* are *A* (x_1, y_1, z_1), *B* (x_2, y_2, z_2), *C* (x_3, y_3, z_3), *D* (x_4, y_4, z_4), *E* (x_5, y_5, z_5), *F* (x_6, y_6, z_6), with the following centroid coordinates:

$$(x,y,z)=\left(\frac{x_1+x_2+x_3+x_4+x_5+x_6}{6},\ \frac{y_1+y_2+y_3+y_4+y_5+y_6}{6},\ \frac{z_1+z_2+z_3+z_4+z_5+z_6}{6}\right) \quad \textbf{(1)}$$

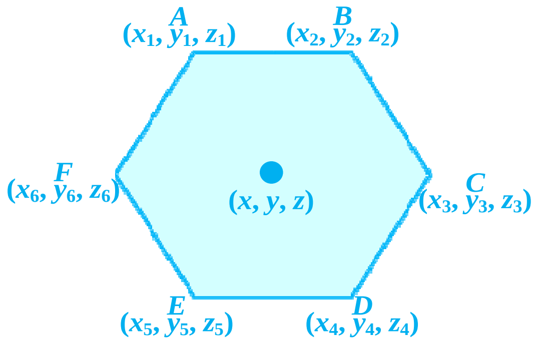


Figure 2. Centroid location algorithm diagram

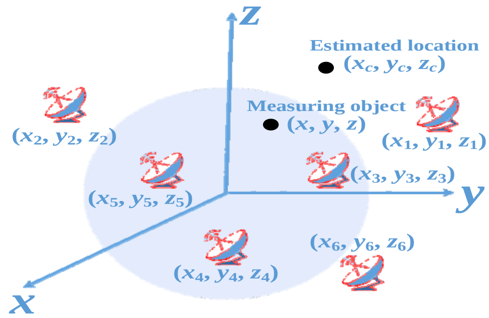


Figure 3. Location calculation of the measured object

During target determination, the sensor evaluates the distance of the target based on the intensity of the detected signal and uses this intensity as a weight in the centroid localization algorithm. The weighted centroid localization algorithm can be expressed as follows [14-15]:

$$\begin{cases} x_c=\dfrac{\sum \omega_i x_i}{\sum \omega_i} \\ y_c=\dfrac{\sum \omega_i y_i}{\sum \omega_i}, \quad \omega=\dfrac{1}{(r+n)^2}, \quad SNR=20\log_{10}^{\frac{S}{N}} \\ z_c=\dfrac{\sum \omega_i z_i}{\sum \omega_i} \end{cases} \quad \textbf{(2)}$$

In Equation (2), the $(x_c,\ y_c,\ z_c)$ [km] parameter represents the position of the target estimate, and (x_i, y_i, z_i) [km] denotes the position of the i^{th} beacon. The function ω is the weight value, *r* [km] refers to the distance between the target and the beacon, and *n* [dB] is the noise, and indicating that the intensity of the wireless signal received and the sound signal measured by beacon were affected by noise. *SNR* [dB] represents the signal-to-noise ratio, with *S* [dB] denoting the received signal strength value and *N* the variance of the noise. The algorithm flow of weighted centroid location is shown in Figure 4.

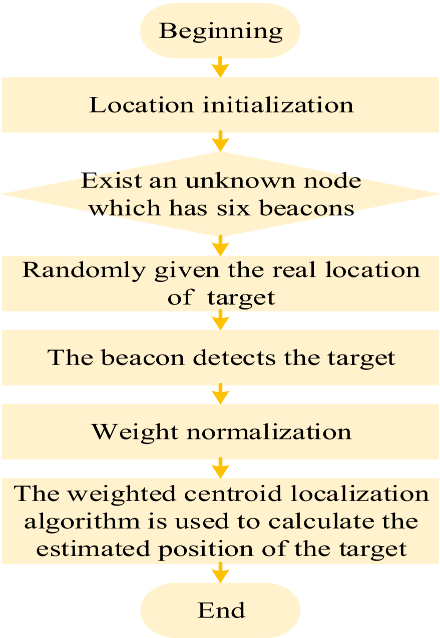


Figure 4. Algorithm flow of weighted centroid location

3.2 Least Squares Localization Algorithm

Considering the target as *M* (*x*, *y*, *z*), the *n* beacons in the monitoring area are (x_1, y_1, z_1), (x_2, y_2, z_2), …, (x_n, y_n, z_n). The distance from the target to the beacon is represented by $d_1, d_2, \ldots, d_n$, as follows [16]:

$$\begin{cases}(x_1-x)^2+(y_1-y)^2+(z_1-z)^2=d_1^2\\(x_2-x)^2+(y_2-y)^2+(z_2-z)^2=d_2^2\\\vdots\\(x_n-x)^2+(y_n-y)^2+(z_n-z)^2=d_n^2\end{cases} \quad (3)$$

To estimate *M* (*x*, *y*, *z*), the least squares estimation of the target position can be obtained using the least squares principle, as follows:

$$X=(A^TA)^{-1}A^Tb \quad (4)$$

where

$$A=2\begin{bmatrix}x_2-x_1 & y_2-y_1 & z_2-z_1\\x_3-x_1 & y_3-y_1 & z_3-z_1\\\vdots & \vdots & \vdots\\x_n-x_1 & y_n-y_1 & z_n-z_1\end{bmatrix}, b=\begin{bmatrix}d_1^2-d_2^2+x_2^2+y_2^2+z_2^2-x_1^2-y_1^2-z_1^2\\d_1^2-d_3^2+x_3^2+y_3^2+z_3^2-x_1^2-y_1^2-z_1^2\\\vdots\\d_1^2-d_n^2+x_n^2+y_n^2+z_n^2-x_1^2-y_1^2-z_1^2\end{bmatrix}, X=\begin{bmatrix}x\\y\\z\end{bmatrix}.$$

The process of the least square positioning algorithm is shown in Figure 5.

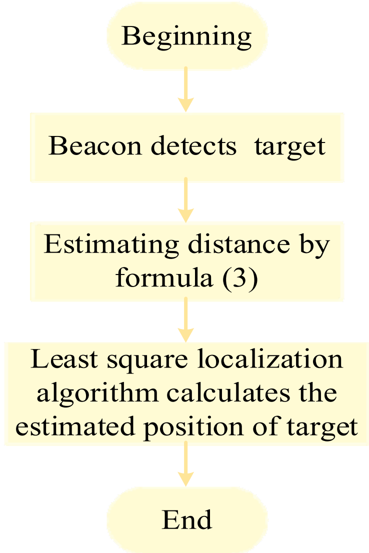


Figure 5. Process of least square positioning algorithm

4 Model Establishment

In the positioning process, the location of the beacon is fixed and static. The target is held stationary in a certain position, and the target location is estimated using the non-ranging and ranging algorithms.

4.1 Non-ranging Location Algorithm

4.1.1 Analysis of Beacon Quantity to Positioning Error

In order to describe the effect of different beacons on the accuracy of target localization, then 6, 12, 18 and 24 beacons are randomly deployed in the seabed 10 km × 10 km × 10 km. Therefore, the weighted centroid positioning algorithm is used to calculate the position error of the number of beacons to the target estimation and the running time of the algorithm, as shown in Table 1. Calculated from Table 1, the average estimation errors of the beacons (6, 12, 18 and 24) are 1.272 km, 1.008 km, 0.739 km, 0.787 km, respectively.

Table 1. Position error and running time of the number of beacons on the measurement object

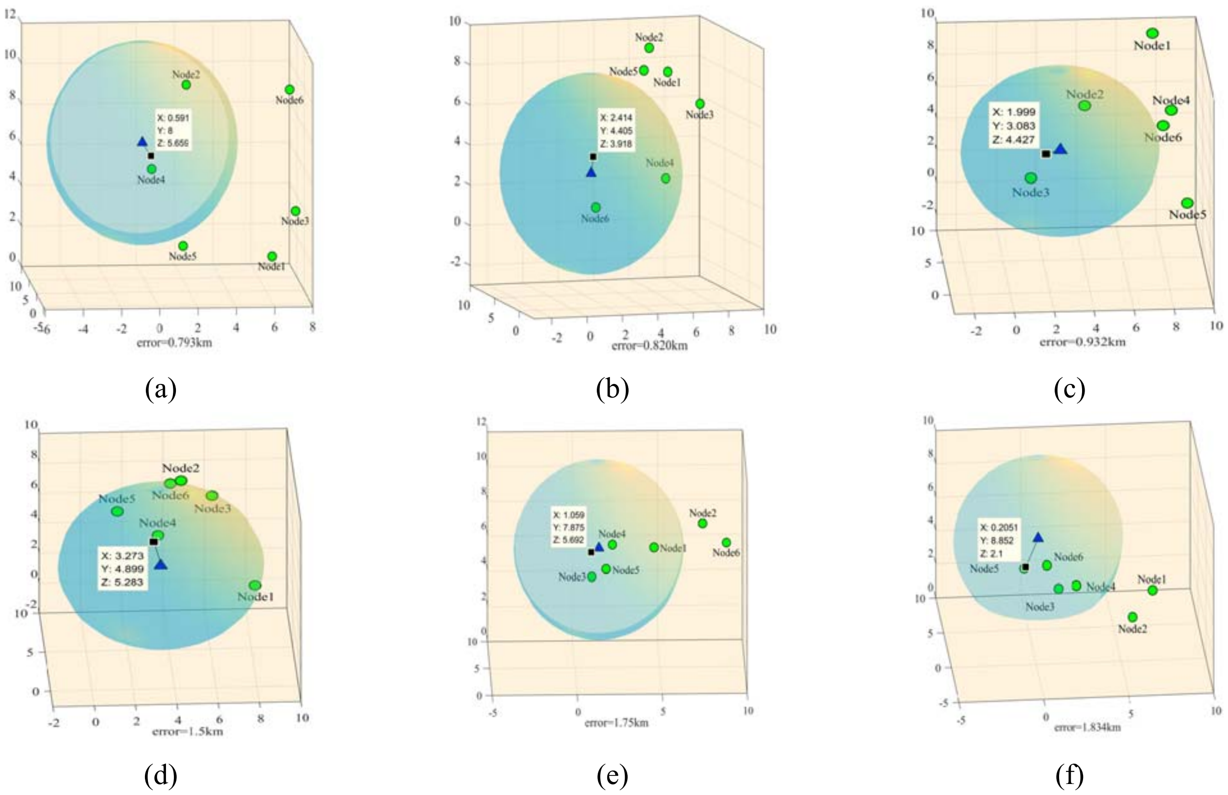
Six beacons	Estimation error	0.793 km	0.82 km	0.932 km	1.5 km	1.75 km	1.834 km
	Running time	0.224 s	0.220 s	0.204 s	0.217 s	0.187 s	0.279 s
Twelve beacons	Estimation error	0.874 km	0.968 km	0.970 km	1.023 km	1.098 km	1.115 km
	Running time	0.222 s	0.222 s	0.221 s	0.218 s	0.221 s	0.232 s
Eighteen beacons	Estimation error	0.331 km	0.641 km	0.698 km	0.882 km	0.902 km	0.982 km
	Running time	0.233 s	0.227 s	0.234 s	0.229 s	0.229 s	0.233 s
Twenty-four beacons	Estimation error	0.187 km	0.441 km	0.643 km	0.645 km	0.721 km	0.794 km
	Running time	0.232 s	0.237 s	0.230 s	0.233 s	0.236 s	0.214 s

Table 1 shows that different number of beacons will result in different localization errors for the estimated of the measured objects. As the number of beacons increases, the positioning error estimated by the measurement object gradually decreases. This indicates that the localization error is proportional to the number of beacons. When the number of beacons is 6, the minimum localization error of the measured object is 0.793 km. When the number of beacons is 12, the minimum localization error of the measured object is 0.874 km. When the number of beacons is 18, the minimum localization error of the measured object is 0.331 km. When the number of beacons is 24, the minimum localization error of the measured object is 0.187 km. The time required to run the results is independent of the number of beacons.

4.1.2 Analysis of Weighted Centroid Location

In the seabed measuring 10 km × 10 km × 10 km, six beacons are randomly deployed. Each beacon is used to scan a distance of 5 km to measure the intensity of the sound signal of the object from the beacon.

As shown in Figure 6, the six beacons are used to detect the target. Positioning errors are 0.793 km, 0.82 km, 0.932 km, 1.5 km, 1.75 km and 1.834 km, respectively. The six localization errors differ greatly, which suggests that the localization errors are closely related to the location and density of beacons deployed. Since the measurements and beacons are deployed randomly, the program is implemented differently each time. The simulation diagram indicates the nearest beacon to the real-time location of the target. Table 2 is derived from Figure 6.



(Beacon ▲ Target Position ■ Estimate Position)

Figure 6. Three-dimensional positioning results

Table 2. Estimated positional error of beacon judgment with large weight

Figure 6	Closest beacon to the measurement	Estimated position of the measured object	Position of the measuring object	Estimation error
a	2^{nd}, 4^{th}	(0.591 km, 8 km, 5.659 km)	(0.172 km, 8.291 km, 6.266 km)	0.793 km
b	4^{th}, 6^{th}	(2.414 km, 4.405 km, 3.918 km)	(2.277 km, 4.357 km, 3.111 km)	0.82 km
c	2^{nd}, 3^{rd}	(1.999 km, 3.083 km, 4.427 km)	(2.684km, 2.581km, 4.81km)	0.932 km
d	1^{st}, 3^{rd}, 4^{th}, 5^{th}, 6^{th}	(3.273 km, 4.899 km, 5.283 km)	(3.6 km, 4.542 km, 3.864 km)	1.5 km
e	1^{st}, 3^{rd}, 4^{th}, 5^{th}	(1.059 km, 7.875 km, 5.692 km)	(1.536 km, 9.535 km, 5.409 km)	1.75 km
f	3^{rd}, 4^{th}, 5^{th}, 6^{th}	(0.205 km, 8.852 km, 2.1 km)	(1.017 km, 9.954 km, 3.321 km)	1.834 km

As shown in Table 2, the proximity of the beacon node to the measured object determines the effect on its positional coordinates. Thus, the positional accuracy is improved based on this intrinsic relationship. As shown in Table 2, the position of the measured object in Figure 6(a) is (0.172 km, 8.291 km, 6.266 km), the estimated position of the measured object is (0.591 km, 8 km, 5.659 km). The 2nd and 4th beacon is the closest to the real-time location of the measured object. The deviation between the position obtained by the weighted centroid location algorithm and the real position of the measured object is 0.793 km.

The weighted centroid location algorithm can approximate the real location as much as possible, although the location information is not consistent with the real-time location of the target. Thus, the positioning error can be reduced below a reasonable threshold. However, this type of location algorithm is often associated with a large error during the estimated of the specific location. At the same time, the deviation between the location and the real location of the target depends on the deployment density of the beacon. Thus, positioning accuracy was improved at the cost of the deployment density of the beacon. In order to minimize the error, we used the least square algorithm for ranging location and the weighted centroid algorithm for non-ranging location to develop a comparative experiment.

4.2 Ranging Location Algorithm

4.2.1 Experimental Setup

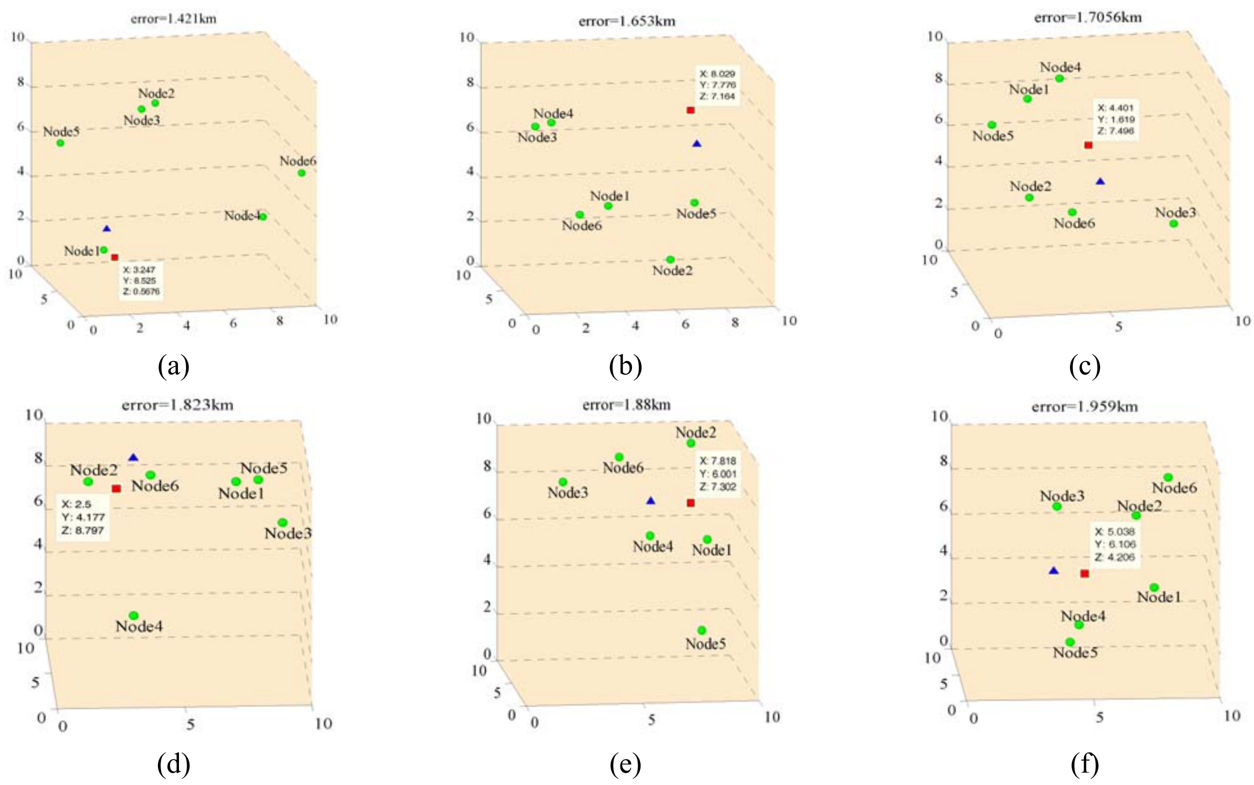
In the seabed measuring 10 km × 10 km × 10 km, six beacons are randomly deployed. The beacon is used to measure the distance between the beacon and the measured object using sensors.

4.2.2 Results Analysis

Based on MATLAB simulation, the location error is calculated using the least square algorithm, as shown in Figure 7. Figure 7 shows that the location of the measured object is A (2.851 km, 8.277 km, 1.91 km), and the estimated location of the measured object is B (3.247 km, 8.525 km, 0.5676 km). As shown in Figure 7, the deviation between the estimated position obtained by the least square localization algorithm and the real position of the measured object is 1.421 km. Table 3 is summarized from the simulation results in Figure 7.

Table 3. Estimated positional error of beacon judgment with large weight

Figure 7	Closest beacon to the measurement	Estimated position of the measured object	Position of the measuring object	Estimation error
a	1^{st}	(3.247km, 8.525km, 0.568km)	(2.851km, 8.277km, 1.91km)	1.421km
b	1^{st}, 3^{rd}, 4^{th}, 5^{th}, 6^{th}	(8.029km, 7.776km, 7.164km)	(8.318km, 8.103km, 5.57km)	1.653km
c	1^{st}, 2^{nd}, 4^{th}, 5^{th}, 6^{th}	(4.401km, 1.619km, 7.496km)	(4.82km, 1.206km, 5.895km)	1.7056km
d	2^{nd}, 6^{th}	(2.5km, 4.177km, 8.797km)	(3.225km, 5.523km, 9.791km)	1.823km
e	1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 6^{th}	(7.818km, 6.001km, 7.302km)	(6.201km, 6.954km, 7.202km)	1.88km
f	1^{st}, 2^{nd}, 3^{rd}, 4^{th}	(5.038km, 6.106km, 4.206km)	(3.912km, 7.691km, 3.968km)	1.959km



(Beacon Target Position Estimate Position)

Figure 7. Three-dimensional positioning simulation

In Table 2 and Table 3, the closest beacons to the measured objects are obtained from the weighted centroid localization algorithm in the non-ranging location (Figure 6) and the least square localization algorithm in the ranging location (Figure 7), respectively. Compared with the least square localization algorithm, the weighted centroid localization algorithm can intuitively determine the nearest beacon of the true location of the measured object. Selection of the most appropriate beacon for the real-time location analysis of the distance of the measured object can reduce the positional error of the measured object.

4.3 Comparison of Algorithms

Positioning accuracy is the D-value between the estimated of position (usually coordinates) and its real location. Table 4 shows the comparison among the advantages and disadvantages of the non-ranging location algorithm and the ranging location algorithm.

Table 4. Comparison of location algorithms

beacon/m	category	Location Algorithms	minimum error	maximum error	average error	positioning accuracy
m=6	non-ranging	centroid	0.876km	2.33km	1.412km	low
		Weighted centroid	0.793km	1.834km	1.272km	high
	ranging	least square	1.421km	1.959km	1.740km	low

5 Conclusion

Innovation. The traditional centroid location algorithm is based on connectivity and does not require distance information. However, the information received by the known nodes is not of the same size. When the variance of each node is large, the accuracy of positioning will become very low. The weighted centroid location algorithm adopted in this study has a low computational complexity, and therefore, resolves the issue. The unknown node only relies on the received beacon node to determine the location, without interaction between adjacent nodes.

The target location algorithm is one of the strategies to acquire the target position. Based on the observations, the most reasonable positioning algorithm can be combined with the characteristics of the application field to improve the results. The advantages of the non-ranging location algorithm include low-energy consumption, low hardware cost, strong anti-measurement noise capability and simple implementation; however, it has a low localization accuracy. The high range of positioning accuracy and hardware requirements effectively reduce positioning errors and enhances positioning accuracy. The positioning accuracy of the weighted centroid localization algorithm depends on the location of the beacon node and the beacon node received by the unknown node. Sparse beacon nodes result in large positioning errors.

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Biographies

Biyuan Yao is currently pursuing her Ph.D. degree in School of Computer Science and Engineering, South China University of Technology, Guangzhou, China. Her research interests include applications of image processing and pattern recognition, communication and graph theory with applications.

Xinghui Cao is an Associate Professor of Laboratory of Deep-sea Information Technology at Institute of Deep-sea Science and Engineering. Her research interests include bottom interacting acoustics, sonar design and positioning.

Binjian Shen is a Researcher of Laboratory of Deep-sea Information Technology at Institute of Deep-sea Science and Engineering. His research interests include acoustics, underwater positioning and signal processing.

Guiqing Li currently works at the School of Computer Science and Engineering, South China University of Technology, Guangzhou, China. His research interests focus on fields related to Computer Graphics such as digital geometry processing, dynamic geometry processing, and image and video processing.

Jianhua Yin is Professor of Hainan University, MS supervisor. His research interests include graph theory with applications.