# Sonar Aided High Accuracy Inertial Navigation in a Partially Known Environment

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*Abstract*—**P-SURO II is a hybrid AUV which can be operated in both of ROV and AUV modes [1]. In its AUV mode, the vehicle is supposed to carry out some of underwater missions such as inspection and maintenance of complex underwater structures which are usually difficult to be done by ROV or divers due to the cable system. To complete these missions, the vehicle is required to have high level of autonomy, where high accuracy navigation is the most important and basic requirement. In this paper, we present a high accuracy of hybrid inertial navigation method using image sonar in a water tank environment. Various water tank experimental studies are carried out to investigate the effectiveness of presented hybrid navigation method. Some of practical issues of applying image sonar for inertial navigation aiding are also discussed.**

***Keywords—image sonar; hybrid inertial navigation; autonomy; hybrid AUV.***

## I. INTRODUCTION

Due to its untethered feature and some of being matured underwater technologies, AUV is increasingly considered not only as an inexpensive substitute of ROV but also as a utility player of exploring a new era of subsea applications. Up to date, ROVs and/or divers are typically committed to the inspection and maintenance of underwater structures. However, for some complicated targets such as jacket structures, see Fig. 1, ROVs and divers are difficult to complete detailed inspection and maintenance due to its cable systems. In this case, AUV might be a proper alternative. To carry out its missions, AUVs are generally required to have a high level of autonomy. And high accuracy of underwater navigation is one of the most important and basic requirements.


Fig. 1 Example of an underwater jacket structure.

For P-SURO II hybrid AUV, a kind of DVL-aided SDINS (strap-down inertial navigation system) is designed for its underwater navigation [2]~[4]. Obviously, this kind of inertial navigation system cannot prevent position drift on the tangent plane if there is not any proper external position aiding. On the other hand, GPS is not suitable for being as proper aiding solution, especially in the case of high accurate operation in the deep sea environment, due to both of its relatively long term aiding period and inaccuracy. For acoustic systems [5], such as LBL, USBL, and SBL, also do not work well in the case of operation in the complicated underwater structural environment. Under these considerations, some of alternative position aiding methods, such as pattern recognition (camera, sonar, laser, etc.) based method which can provide vehicle pose (both of position and orientation), are considered for P-SURO II AUV.

In this paper, we present a hybrid inertial navigation system with image sonar aiding in a water tank environment. In practice, it is difficult to get satisfactory sonar measurement because of frequent failure or multipath effect, especially in the cuboid water tank environment. Therefore, it is not easy to provide high accuracy of position and orientation information using sonar based pattern recognition [6]. However, some of experimental studies show that image sonar still can provide relatively high accuracy of aiding information in some cases shown in later. In the study, we use the sonar raw range measurements of multi-beam array instead of image file. Some of interesting practical issues of sonar application are also discussed in the paper. The remainder of this paper is organized as follows. In Section II, we briefly introduce the constructed DVL aided INS, and position and heading aiding method using 2D sonar in a water tank environment is presented in Section III, and some of its experimental results are discussed in Section IV. Finally, in Section V, we summarize the conclusion and also discuss some of future works.

## II. DVL AIDED INS

It is well known that inertial navigation is the process of integrating acceleration and angular rate measured by IMU

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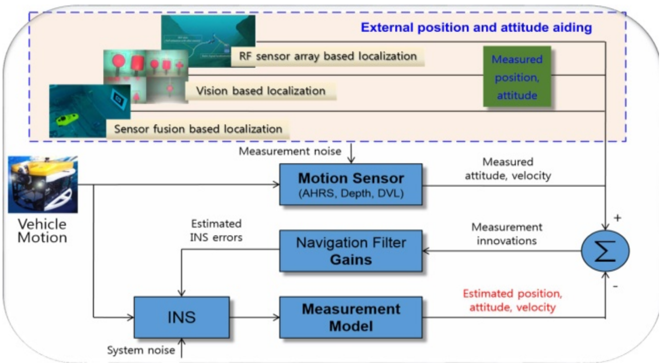

Fig. 2 Hybrid INS designed for P-SURO II AUV.

(Inertial Measurement Unit) over time to calculate velocity and attitude, and further to estimate position. However, because of unknown bias terms in the IMU measurements, pure inertial navigation usually drifts over time. Quite number of methods and corresponding sensors are now available to complement this kind of pure INS drift [3],[7],[8], and DVL is one of the most common and basic equipment of underwater vehicles for both of navigation and control.

Constructed hybrid INS for P-SURO II AUV is shown in Fig. 2. As shown in the figure, various underwater localization methods are now being considered to provide position and attitude aiding. In general, IMU measures the accelerations and rotation angular rates relative to the inertial space along the platform frame. Therefore, it is convenient to describe the navigation mechanisms using local geodetic or tangent plane frame [9],[10] with navigation state vector as $S=[\lambda,\Phi,h,v_N, v_E,v_D,\phi,\theta,\psi]^T$. Here, $(\lambda,\Phi,h)$ denotes the vehicle's position (latitude, longitude, height), and $(v_N,v_E,v_D)$ is velocity and $(\phi,\theta,\psi)$ denotes the vehicle attitude (roll, pitch, yaw). Instead of direct estimation of $S$, we usually estimate its error terms $\delta S$ through proper filter design. For its detailed navigation equations and geodetic error dynamics, also for the details of inertial sensor specifications, refer to [4]. Here we briefly introduce the navigation filter design as follows.

### A. System Model

According to the geodetic error dynamics [4], filter system equations can be expressed as following

$$\dot{X}(t)=F(t)X(t)+G(t)w(t)\,, \tag{1}$$

where $X=[\delta\lambda,\delta\Phi,\delta h,\delta v_N,\delta v_E,\delta v_D,\varepsilon_N,\varepsilon_E,\varepsilon_D,b_{au},b_{av},b_{aw},b_p, b_q,b_r]^T$ with $(\varepsilon_N,\varepsilon_E,\varepsilon_D)$ rotation matrix error vector, $(b_{au}, b_{av},b_{aw})$ and $(b_p,b_q,b_r)$ bias vectors in each of accelerometer and gyro measurements. For detailed construction of system matrix $F(t)$ and noise gain matrix terms $G(t)$, refer to [4]. For the bias terms in the sensor measurements such as bias component in the DVL output, we do not include them in the state vector. In practice, these terms are difficult to be properly estimated due to its insufficient dynamics.

### B. Measurement Model

For P-SURO II AUV, besides IMU sensor, three additional motion sensors, each of depth sensor, AHRS, and DVL, are mounted on the platform to provide navigation sources. As aforementioned, during the filter design, we ignore the bias terms in the sensor measurements. Therefore, unlike to the previous works [4], sensor measurements error equations can be expressed as following

$$\hat{h}-h^m=\delta h+v_h\,, \tag{2}$$

$$\begin{bmatrix}\hat{v}_N\\ \hat{v}_E\\ \hat{v}_D\end{bmatrix}-\begin{bmatrix}v_N^m\\ v_E^m\\ v_D^m\end{bmatrix}=\begin{bmatrix}\delta v_N\\ \delta v_E\\ \delta v_D\end{bmatrix}-P\hat{C}_b^n\begin{bmatrix}u^m\\ v^m\\ w^m\end{bmatrix}-\hat{C}_b^n v_v\,, \tag{3}$$

$$\begin{bmatrix}\hat{\phi}\\ \hat{\theta}\\ \hat{\psi}\end{bmatrix}-\begin{bmatrix}\phi^m\\ \theta^m\\ \psi^m\end{bmatrix}=\begin{bmatrix}\varepsilon_N\\ \varepsilon_E\\ \varepsilon_D\end{bmatrix}+v_\varphi\,, \tag{4}$$

where superscript $m$ denotes sensor measurements, $P=\rho\times$ with $\rho=[\varepsilon_N,\varepsilon_E,\varepsilon_D]^T$, and $v_h,v_v$, and $v_\varphi$ indicates white noise terms in the corresponding sensor measurement.

Using (2)~(4), we can get the following measurement error equation

$$Y(t)=C(t)X(t)+H(t)v(t)\,, \tag{5}$$

where $v=[v_h^T,v_v^T,v_\varphi^T]^T\sim N(0,R)$.

The AHRS sensor used by P-SURO II AUV is a MEMS based IMU with onboard three axes of magnetometers to get reference true north. However, this kind of heading sensor does not work well in the indoor environment, especially in the similar case of KIRO water tank which is located in the basement of a steel structural building. Consequently, only six, not seven, measurement equations are available to construct the filter in the water tank environment.

As aforementioned, this kind of navigation filter cannot prevent position drift on the tangent plane. To complement this drift, some of external position aiding schemes should be integrated with INS. In this paper, we attempt to use an image sonar, which was originally designed for obstacle detection and avoidance, to provide position and heading aid in a water tank environment.

## III. Sonar Based Position and Heading Aiding

P900-130 BlueView sonar [11] is mounted in front of the vehicle for the purpose of obstacle detection and avoidance. The sonar consists of total of 834 beams with 0.18° of beam spacing. Each beam width is 1° x 20°. As aforementioned, it is usually difficult to get satisfactory results using sonar sensor. However, in some cases such as operation in the KIRO water tank, which is a 12(L)x8(W)x6(D)m dimension of cuboid, we can get some of useful aiding information from sonar raw measurements. Consider the case where the vehicle is moving around on the horizontal plane in the tank. Using profile image acquired by sonar raw measurement (in this paper, we use the range raw measurements from multi-beam array in each of sonar ping instead of image data), it is easy to calculate the sonar head position and heading, from which further can get

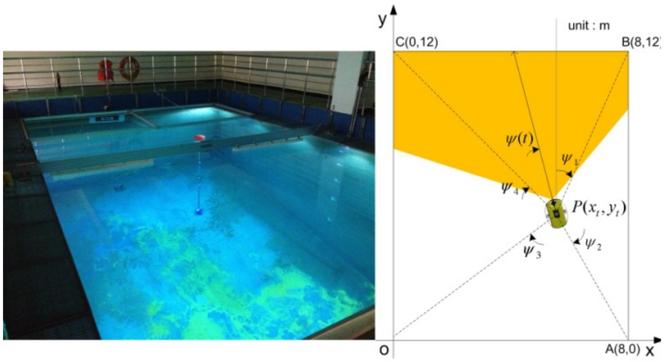


Fig. 3 Water tank navigation frame.

the vehicle's position and heading.

### A. *Water Tank Navigation Frame*

Water tank frame is shown in Fig. 3, where y axis is along side with the tank length and correspondents to the north axis in NED reference frame, while x axis correspondents to the east axis. The azimuth of y axis is 70.45°.

After receiving a ping of raw range measurements, first the vehicle calculates four angles of $\psi_1 \sim \psi_4$ using its current position $P(x_t, y_t)$, see Fig. 3. By comparing these angles with its current heading, the vehicle can determine which tank wall(s) it is now confronting. Then, using image profile, see Fig. 4, acquired by sonar measurement, vehicle can calculate its heading and/or position.

### B. *Heading and Position Calculation*

Consider Fig. 4, where Y' axis is along side with the sonar head heading. If we know the information of line $l_2$, in other word, know the parameters $a_2$ and $b_2$, then we can get

$$l_{OP_2} = \frac{b_2}{a_2}\sin[\arctan(a_2)], \quad (6)$$

$$\angle Ob_2P_2 = \frac{\pi}{2} + \arctan(a_2). \quad (7)$$

If we further know the point B in Fig. 4 correspondents to the corner B in Fig. 3 as mentioned before by comparing vehicle heading with $\psi_1 \sim \psi_4$, then we can determine that

$$\psi_t = \frac{\pi}{2} + \arctan(a_2), \quad x_t = 8 - \frac{b_2}{a_2}\sin[\arctan(a_2)]. \quad (8)$$

Similarly, using $l_1$, we also can calculate the following information

$$\psi_t = \arctan(a_1), \quad y_t = 12 - \frac{b_1}{a_1}\sin[\arctan(a_1)]. \quad (9)$$

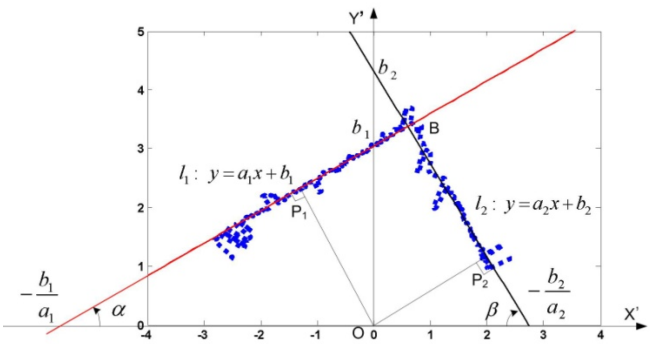


Fig. 4 Calculation of sonar head heading and position using sonar profile image.

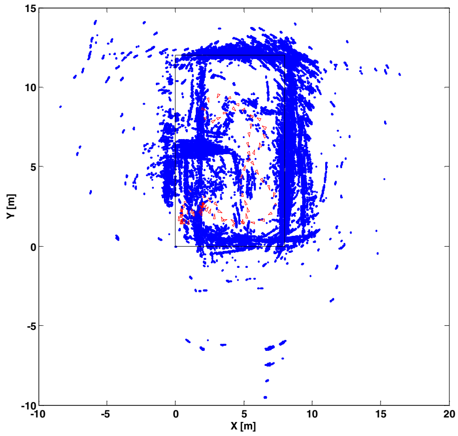


Fig. 5 Example of sonar raw measurements during a water tank test.

### C. *Some of Practical Remarks*

*1)* As aforementioned, in practice it is not easy to get satisfactory results using sonar raw measurements. Fig. 5 shows the sonar raw measurements while vehicle move around the tank, where red triangles indicate vehicle trajectory. Therefore, pre-filtering of sonar raw data is a very important step for further data handling. In this paper, we pre-filter the sonar raw data as follows. For each beam of given ping data, we can easily predict the range measurement corresponding to the beam by using beam bearing information and vehicle's current heading and position. And fortunately, through various experimental water tank tests, we have found that this kind of prediction is very accurate. If the difference between the beam raw measurement and this predicted one exceed certain threshold, then we discard this beam raw measurement.

*2)* Consider Fig. 4. If there are insufficient (filtered) sonar measurements corresponding to certain tank wall, for instance, there are too small amount of sonar data corresponding to the tank wall $BP_2$, then acquired $l_2$ might not provide accurate wall information. Therefore, calculated heading and position information also could include significant errors. In this paper, we calculate the vehicle's heading and position only when the raw measurements number corresponding to the same tank wall exceeds certain threshold, which is another design parameter in the navigation.

## IV. Experimental Studies

To demonstrate the effectiveness of presented sonar aided high accuracy of inertial navigation system, we carried out

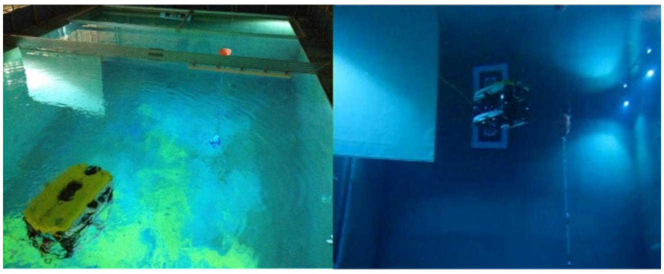

Fig. 6 Water tank experimental tests for raw data acquisition.

various water tank experimental tests. In each of tests, we saved all of sensor raw measurements, which were further used to analysis the presented navigation algorithm performance using MATLAB post processing. In the tests, the vehicle was operated in its ROV mode and moved around the tank in a certain pattern by operator.

### *A. Raw Measurements Acquisition*

At first, the vehicle was located in a previously known point with its heading direct to the y axis. With start command, the vehicle took auto depth keeping motion of 1.5m depth rate, while its horizontal motion was controlled by operator using joystick. After several times of move around the tank, the vehicle rose to the surface and relocated to the initial point by operator with the same heading.

There is a white blinds rolling down on the left center, see Fig. 6. This blinds and the upper right orange colored ball were taken as obstacles for the vehicle to detect. Image sonar was directly connected to the surface unit computer where all of sonar raw measurements were recorded, while other sensor raw measurements were saved on the onboard navigation computer.

### *B. Experimental Results*

Experimental results are shown in Fig. 7~9, where the test lasted about 9 minutes. Fig. 7 shows the DR (Dead-reckoning) result. Here the DR is constructed using DVL output and AHRS heading measurement. As aforementioned, due to significant magnetic field distortion in the water tank, AHRS cannot output proper heading value. However, in the tests, we complemented the each of AHRS heading outputs using its initial output $\psi_0$. In other word, we subtract $\psi_0$ from each of after then AHRS heading outputs. Therefore, we can conclude that the inaccuracy in Fig. 7 does not caused by the incorrect AHRS output, but by the fact that AHRS sensor used for P-SURO II AUV does not correctly estimate the vehicle's heading changes.

DVL aided INS result is shown in Fig. 8, which looks much better than the one in Fig. 7. The positin drift is about 3m after 9 minutes. Compared to some of its previous field tests results in both of river and outdoor water tank [1],[4], the result in the indoor water tank environment is much better. This, to the authors knowledge, might be caused by the fact that the vehicle took much more dynamic motion in the indoor environment compare to the case of field tests. And this kind of dynamic activities can (significantly) increase the system observability, which can further increase the navigation filter's estimation performance.

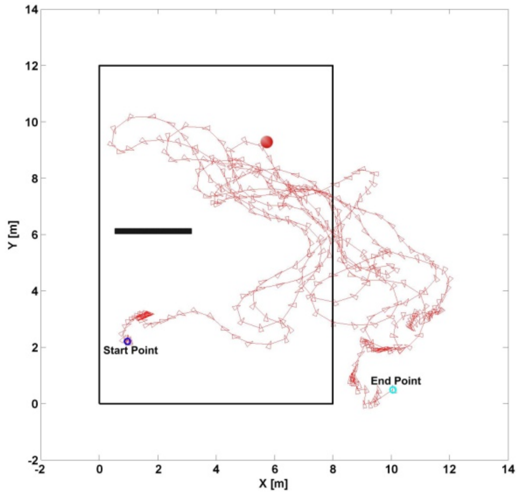


Fig. 7 DR navigation result.

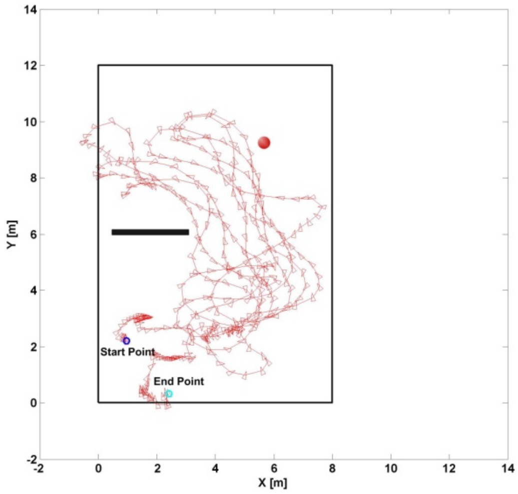


Fig. 8 DVL aided INS navigation result.

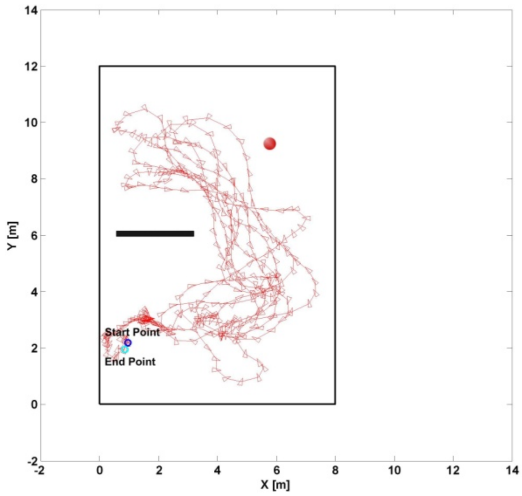


Fig. 9 Sonar aided hybrid INS navigation result.

Fig. 9 shows the result of presented sonar aided INS. Obviously, it is much better than the one of DVL aided INS. In the KIRO water tank environment, there is not any tracking system can provide vehicle's reference position. Therefore, it is difficult to make absolute comparison of these navigation results. However, according to the authors observation throughtout the water tank tests, we found that the trajectory shown in Fig. 9 is mostly similar to the true one.

Consequently, we can conclude that presented sonar aided hybrid INS can work well in some cases such as navigation in the KIRO cuboid water tank environment.

### *C. Some of Practical Remarks*

During the various experiments, we happened to make close contact with the sonar device, and found there are some of interesting phenomena caused by the sonar.

*1)* Fig. 10 shows the sonar raw measurements in one of tests. From this figure, we can see that left side of sonar data (shown as two colored ellipses) are much more noisy than the right ones. In fact, there are two acrylic windows on the left side tank wall. However, the authors are still doubtful if the left center located rolling blinds cause this kind of noisy sonar raw measurements.

2) The sonar device has total of 834 beams with 417 beam array in each of left and right sides. During the tests, however, authors found that horizontal profile images acquired each by left and right side of beam array are different, see Fig. 11.

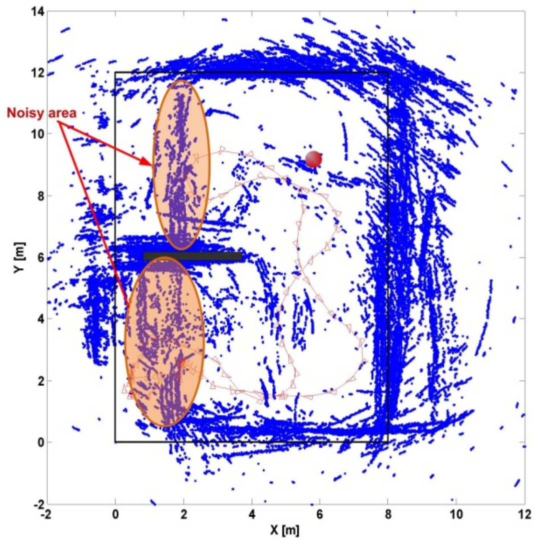


Fig. 10 Sonar raw measurements in a complicated environment.

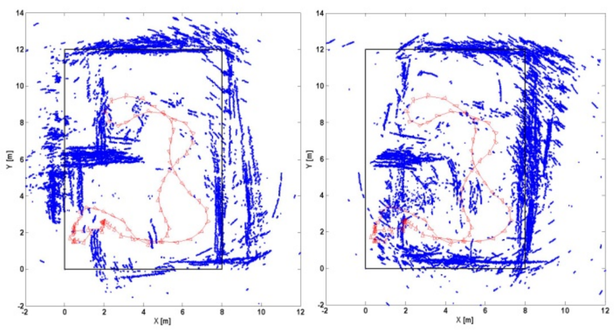

Fig. 11 Comparison of profile images acquired each by left and right side beam array of sonar device.

Besides above mentioned phenomena, some other features of sonar device also should be carefully investigated in order for the efficient practical usage in our future works.

## V. CONCLUSION

In this paper, we've presented a sonar aided hybrid INS for a vehicle operating in a kind of cuboid water tank environment. Under the assumption that the water tank dimension is known *in priori*, 2D sonar can provide accurate position and heading aid to an inertial navigation system. Various experimental studies in the water tank tests shows that presented sonar aided INS works well in the water tank environment. In fact, if there are some of structural patterns in the vehicle's operating environment such that sonar device can detect and further can determine sonar head position and/or heading, then the sonar aided INS method presented in this paper can be applicable, no matter what kind of underwater environment it is.

As aforementioned, the image sonar mounted on the P-SURO II AUV is for the purpose of obstacle avoidance. Therefore, how to efficiently and robustly detect the obstacle(s) using noisy sonar raw measurement is one of our main focuses in the near future.


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## REFERENCES


[1] J. H. Li, M. J. Lee, S. H. Park, J. G. Kim, J. T. Kim, J. H. Suh, "Development of P-SURO II Hybrid AUV and its Experimental Study," *in Proc. of MTS/IEEE Oceans'13 Bergen*, Norway, June, 2013.

[2] D. H. Titterton and J. L. Weston, *Strapdown inertial navigation technology*. Peter Peregrinus Ltd., London, UK, 1997.

[3] L. L. Witcomb, D. Yoerger, H. Singh, "Advances in Doppler-based navigation of underwater robotic vehicles," *in Proc. of IEEE ICRA*, pp. 399-406, 1999.

[4] J. H. Li, M. J. Lee, J. G. Kim, S. K. Park, S. H. Park, J. H. Suh, "Guidance and Control of P-SURO II Hybrid AUV," *in Proc. of MTS/IEEE Oceans'12 Yeosu*, Korea, May, 2012.

[5] P. H. Milne, *Underwater Acoustic Positioning Systems*. Gulf Publishing Company, 1983.

[6] D. Nad, N. Miskovic, V. Djapic, Z. Vukic, "Sonar Aided Navigation and Control of Small UUVs," *in Proc. of 19th Mediterranean on Control and Automation*, Corfu, Greece, June, 2011, pp. 418-423.

[7] M. B. Larsen, "High performance doppler-inertial navigation experimental results," *in Proc. of 2000 Oceans IEEE/MTS*, 2000, pp. 1449-1456.

[8] P. M. Lee, B. H. Jun, K. H. Kim, J. H. Lee, T. Aoki, T. Hyakudome, "Simulation of an Inertial Acoustic Navigation System with Range Aiding for an Autonomous Underwater Vehicle," *IEEE Journal of Oceanic Engineering*, vol. 32, pp. 327-345, 2007.

[9] J. Farrell and M. Barth, *The Global Positioning System and Inertial Navigation*. McGraw-Hill, 1998.

[10] D. H. Titterton and J. L. Weston, *Strapdown inertial navigation technology*. Peter Peregrinus Ltd., London, UK, 1997.

[11] http://www.blueview.com/products/2d-imaging-sonar/p900-series-deepwater/.