UNDERWATER NAVIGATION METHOD BASED ON SIDE-SCAN SONAR IMAGES

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1 Introduction

Underwater navigation is a critical technique for underwater platforms in both civil and military missions. In order to make autonomous underwater vehicle (AUV) capable of time-extensive submerged operations, navigation methods using geophysical characteristics have been proposed recently as a supplementary means to the inertial navigation system (INS) [1]. For an AUV equipped with side-scan sonars, image processing techniques can be applied for its navigation system.

Side-scan sonar images can provide a clear view of the sea floor in 2D with a relative higher resolution than multi-beam bathymetry sonar [2]. This equipment is often be employed for buried-object detection [3], seafloor sediments classification [4] and ocean environment monitoring [5] etc. Similar to the concept of terrain aided navigation [6], this paper investigated the possibility of using side-scan sonar and proper image analysis methods in the matching process of underwater positioning.

The remainder of this article describes the bispectrum of images and presents the simulation results about its robustness of rotation in underwater application.

2 Bispectrum of side-scan sonar images

2.1 High-order Cumulant

The theory of high-order statistics is developed from the theory of second order statistics (e.g. correlation function and power spectrum). It can reflect the phase information of signal which is absence in the theory of second order statistics. Benefit from this, high-order statistics can be employed to deal with non-minimum phase systems. Many applications based on this theory can now be found in the research of signal processing for radar, sonar, communication and fault diagnosis.

Let *x* be a random variable and *f(x)* is its probability density function (PDF). The characteristic function of *x*, $\Phi(\omega)$, is define as the integration presented in (1).

$$\Phi(\omega) = \int_{-\infty}^{\infty} f(\mathrm{x})\,\mathrm{e}^{j\omega x}\,dx \tag{1}$$

In other words, the PDF of *x* equals to the Fourier transform (FT) of *f(x)*. $\Phi(\omega)$ is also called the first characteristic function of *x*.

Then, the second characteristic function of *x*, $\Psi(\omega)$, is defined as (2).

$$\Psi(\omega) = \ln[\Phi(\omega)] \tag{2}$$

Value of the *k* order derivative of $\Phi(\omega)$ at the origin, m_k, is the *k* order moment of *x* as shown in (3).

$$m_k = \Phi^{(k)}(\omega)\,|_{\omega=0} = E[x^k] = \int_{-\infty}^{\infty} x^k f(x)dx \tag{3}$$

Value of the *k* order derivative of $\Psi(\omega)$ at the origin, c_k, is the *k* order cumulant of *x* as shown in (4).

$$c_k = \Psi^{(k)}(\omega)\,|_{\omega=0} \tag{4}$$

Further, assume *x* obeys a Gaussian distribution $N(0,\sigma^2)$. Then the PDF of *x* will be like (5).

$$f(\mathrm{x}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}} \tag{5}$$

The first and second characteristic functions of *x* will then be (6) and (7) respectively.

$$\Phi(\omega) = \mathrm{e}^{-\frac{\sigma^2\omega^2}{2}} \tag{6}$$

$$\Psi(\omega) = \ln[\Phi(\omega)] = -\frac{\sigma^2\omega^2}{2} \tag{7}$$

Now every cumulant of *x* is available that is shown in (8).

$$\begin{cases} c_1 = 0 \\ c_2 = \sigma^2 \\ c_k = 0 \quad (k \geq 3) \end{cases} \tag{8}$$

As a result, high-order cumulant is capable of restraining the effect of Gaussian noise.

2.2 Bispectrum

As shown in 2.1, to any Gaussian process, its high-order cumulant is always zero while its high-order moment is not. This explains why high-order cumulant and its spectrum are more often used in scientific researches. Theoretically, high-order cumulant is able to restrain Gaussian colored noise completely. Spectrum of high-order cumulant is named high-order spectrum (HOS). Among them, three order and four order HOS, called bispectrum and trispectrum separately, are used most frequently. To reduce the computation cost, this paper selected the bispectrum of side-scan sonar images as the characteristic used in the following matching process.

Assume *k* order cumulant, $c_{kx}(\tau_1,\tau_2,\cdots,\tau_{k-1})$, is absolute summable ($\tau_{k-1}$ is the time delay between x_{k-1} and x_k), then the corresponding *k* order spectrum is defined as its *k*-1 dimensional Fourier transform presented in (9).

$$S_{kx}(f_1, f_2, \cdots, f_{k-1}) = \sum_{\tau_1=-\infty}^{\infty} \cdots \sum_{\tau_{k-1}=-\infty}^{\infty} c_{kx}(\tau_1, \tau_2, \cdots, \tau_{k-1}) \exp[-j2\pi(f_1\tau_1 + f_2\tau_2 + \cdots + f_{k-1}\tau_{k-1})] \tag{9}$$

Specifically, when $k = 3$, the definition of bispectrum is available in (10).

$$B_x(f_1, f_2) = \sum_{\tau_1=-\infty}^{\infty} \sum_{\tau_2=-\infty}^{\infty} c_{3x}(\tau_1, \tau_2) e^{-j2\pi(f_1\tau_1 + f_2\tau_2)} \tag{10}$$

3 Estimation steps

The method that using bispectrum of side-scan sonar images for underwater navigation can be divided into the following steps:

Step1: A side-scan sonar image of a sea bottom is read as the reference map, such as Figure 1a. Size of the image should be determined by the requirement of resolution and confidence level of the certain task.

Step2: Get an real-time side-scan sonar image of the bottom, such as the region in the yellow dotted lines in Figure 1a. Calculate its bispectrum by (10).

Step3: Using the bispectrum from step 2 as an template (window) to scan the reference map for a match. Calculate the similarity between the bispectrums of the real-time image and the local area at each scanning point.

Step4: After completing the map scanning, the point that has the biggest similarity (such as the central point of the red region in Figure 1a) will be considered as the position estimation of the underwater platform.

4 Simulation results

Simulations were done in Matlab 2012a platform to investigate the performance of the proposed method. Two side-scan sonar images taken from different sorts of sea bottom were used as reference maps. It was assumed that necessary pre-processing to these images were completed as enhancement and the related methods will not be described in this paper.

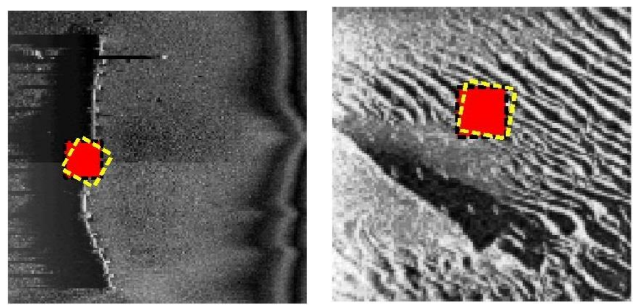
A local area of the reference map was picked out to synthesize the real-time image collected by a side-scan sonar installed on an autonomous underwater vehicle (AUV). Position of the AUV was assumed at the central point of this real-time image. Gaussian noise (signal to noise ratio is 10dB) was added to the real-time images in order to simulate the interference signal slipped into the sonar. The searching step is 2 pixels/move. Mean square deviation (MSD) was chosen as the tool to evaluate the similarity between the bispectrums of the real-time image and the map.

Figure 1 shows the matching results using different rotation of real-time images. Although the real-time images have direction differences against the reference map, the estimated regions (red) keep locating close to the true position (yellow). Horizontal and vertical errors in pixels are (2, 1) and (1, 1) in Figure 1(a) and Figure 1(b) respectively. This result shows good robustness of rotation.

5 Conclusion

Bispectrum of side-scan sonar images was investigated in this paper for its performance in underwater navigation. Bispectrum of synthesized side-scan sonar image was calculated as a template in the matching processing. Simulation results show that the proposed method has good robustness of image rotation.

To find a balance of the calculation time and the estimation reliability, more tests are needed before using this method in actual applications. Side-scan sonar images from sea trial will be processed with this method and a general regulation of template selection can be expected.



(a) (b)

Figure 1: Matching results with rotation in Gaussian noise background. (a) Rotation = 30 °. (b) Rotation = 10 °.

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