SIGNAL PROCESSING ALGORITHMS FOR HIGH-PRECISION NAVIGATION AND GUIDANCE FOR UNDERWATER AUTONOMOUS SENSING SYSTEMS

Daniel Doonan, Chris Utley, and Hua Lee
Imaging Systems Laboratory
Department of Electrical and Computer Engineering
University of California, Santa Barbara
Santa Barbara, California 93106

ABSTRACT

This paper presents an alternative approach to high-precision bearing estimation for navigation and guidance in homing and docking of underwater vehicles. This new technique is significantly simpler than the conventional methods in terms of computation complexity and yet produces results of superior precision and consistency.

KEY WORDS

Polarity estimation, bearing angle, homing and docking, navigation, geolocation.

INTRODUCTION

The key to the successful execution of autonomous imaging and sensing is the time synchronization and geolocation among the units. In particular, geolocation is an extremely challenging task. In underwater environments, the sensing, imaging, and communication signals are all within the acoustic range, which is more constrained in terms of available bandwidth, propagation speed, and serious multi-path interferences. This makes the geolocation a much more challenging and interesting research topic.

Geolocation can be achieved by estimating the relative location with respect to a set of underwater base stations. In three-dimensional underwater geolocation, the objective parameters involved are the range distance and a two-dimensional bearing angle.

Because of the multi-path interferences, the estimation of the polarity of the homing signal has been difficult. This paper introduces a new approach to the estimation of polarity with significantly improved accuracy and computational complexity. The presentation of this paper includes system design, signal analysis, development of processing algorithms, and results from full-scale experiments.

CONVENTIONAL TECHNIQUE FOR BEARING ESTIMATION

As described, one of the key capabilities in mobile autonomous sensing is geolocation for navigation and guidance. This can be achieved by estimating the position of the sensor unit with respect to the underwater base stations. The locations of the underwater base stations are constantly estimated and updated with respect to the interface stations over the ocean surface, which is supported by the GPS systems and microwave mutual reference capability. Thus, the most critical element is the accuracy of a sensor's dynamic estimation of its relative location with respect to the underwater base stations. In three-dimensional underwater geolocation, the objective parameters involved include the range distance and a two-dimensional bearing angle. The focus of this proposed project is the high-precision estimation of the two-dimensional bearing angle for real-time navigation and guidance.

Figure (1) is the three-element transmitter prototype for the base stations. With the three transmission elements, the transmitter sends a sequence of three waveforms. The first, from the top transducer element, is an in-phase reference signal. The second, from the middle transducer element, is a pair of signals with a left-right polarity with 180-degree phase offset for the estimation of the bearing angle in the horizontal direction. Similarly, the third signal from the bottom transducer is with a top-bottom polarity for the estimation of the bearing angle in the vertical direction.

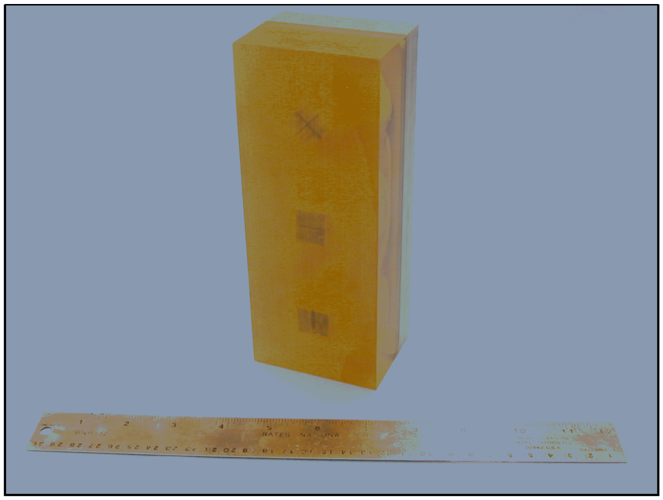

Figure (1): Three-element transmitter of the guidance system

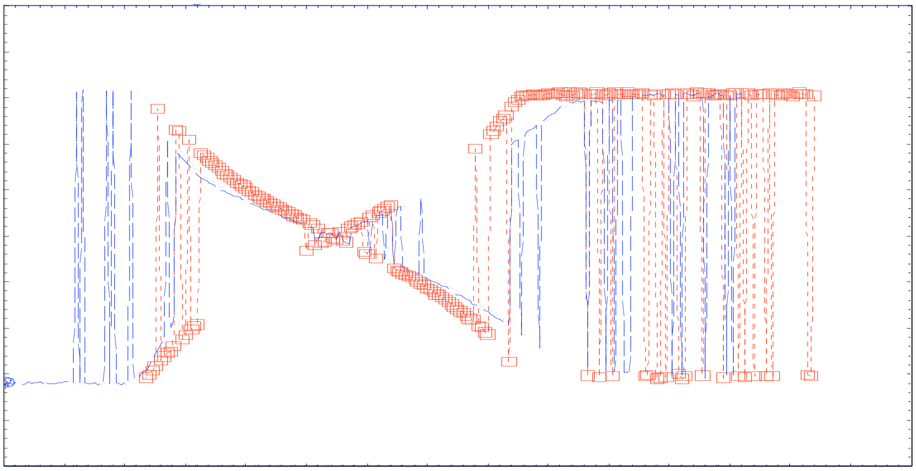

Figure (2): Bearing-angle estimation with polarity errors

As shown in Figure (1), the prototype transmission array consists of three transducer elements. At the top of the array, the square transducer element is designed to transmit the full reference signal *s(t),* which is used as the calibration waveform for bearing-angle estimation as well as the estimation of the range distance. The second transducer, in the middle, consists of two rectangular sub-elements, separated by a small gap. The two transducer elements are transmitting the same waveform *s(t)*, but with different polarities. The signal detected by a sensor unit can be written in the form of,

$$r_x(t) = \underline{+} [s(t) - s(t - \Delta t)]$$

The time difference _*t* is directly governed by the off-axis bearing angle. Larger bearing angles produce larger time delay Δt. When the sensor is moving along the central axis, the time delay term is zero, which results in a full cancellation and the received waveform is zero. This means the beam pattern gives a null along the central axis.

This technique is theoretically sound. The fundamental concept is to identify the bearing angle through the accurate estimate of the time differential in the received signal. Yet, in practice, there are serious challenges. When the bearing angle is large, the received signal becomes weak due to the nature of the beam pattern. If the bearing angle is small, *s(t)* and $s(t - \Delta t)$ start to overlap and cancel each other. The accuracy of the estimation of the bearing angle becomes increasingly difficult due to the decreased signal-to-noise ratio, especially in serious multi-path environment, which is common in underwater acoustic propagation. The conventional approach is to estimate the time differential by identifying the peak magnitude of the received signal *r(t)* and then the phase term at the peak, which indicates the polarity of the transmitted signal. Ideally, the estimate of the bearing angle is a monotonically increasing function. Figure (2) shows the result of the bearing angle estimation experiment with the conventional method. The horizontal axis is the bearing angle and the vertical axis is the estimate. The ideal result is a monotonically increasing function. As it can be seen, accuracy of the estimates was limited and the estimation of the polarity of the signal is particularly challenging.

ALTERNATIVE APPROACH

Therefore, it is highly important and desirable to design and develop high-precision signal processing algorithms for accurate geolocation. The main objective of the polarity method is to accurately estimate the bearing angle of the source of the transmitted signals. Because the range distance can be determined through time delay estimation, the accurate estimation of the bearing angles will effectively complete the geolocation process, in the three-dimensional polar coordinate system, which is the key to underwater navigation and guidance.

As described, the conventional technique conducts the estimation process based on the maximum of the received signal. That implies the entire result of the estimation process lies on one single data point. Noise and multi-path interferences can introduce serious errors. To optimize the accuracy of bearing-angle estimation, an alternative procedure is proposed. Prior to the estimation procedure, we first (a) decode the received signal and down shift it to the base band, (b) remove the negative sideband to obtain the single-sideband version, and (c) integrate the single-sideband signal.

The combined transmitted signal can be represented alternatively in the form of a convolution of the designated waveform with two impulses with temporal offset,

$$r(t) = s(t) \ast [\pm(\_(t) - \_(t-\_t))]$$

After demodulation and matched filtering, the signal is in the form of

$$\_(t) = a_{ss}(t) \ast [\pm(\_(t) - \_(t - \_t))]$$

where $a_{ss}(t)$ is the auto-correlation of $s(t)$. Then it can be seen that the most critical element for the polarity estimation is the second term of the equation. If we integrate the signal, it becomes

$$\_{}_{1}(t) = a_{ss}(t) \ast [\pm g(t)]$$

where the gate function $g(t)$ is

$$g(t) = u(t) - u(t - \_t)$$

For positive polarity, the auto-correlation function $a_{ss}(t)$ will be convolving with $+g(t)$ and $-g(t)$ for negative polarity. Since $g(t)$ is non-negative and the point-like auto-correlation $a_{ss}(t)$ is real and even, the results of the integral gives an accurate estimate of the polarity. In addition, the duration of the gate function is governed by _*t*, which is directly related to *dsin_*, where *d* is the separation of the transducer elements and _ is the bearing angle. Thus, the magnitude of the subsequent integration produces the estimate of the bearing.

For performance evaluation purposes, the new method is applied to several data sets obtained form full-scale field tests. Multi-path interferences exist in these data sets and the conventional technique was unable to accurately estimate the signal polarity. Typically, the bearing angles of these data sets range from -30 to 30 degrees. To isolate the polarity estimation problem, the range distance was kept constant. As previously described, the received signals were first down shifted to the base band. The left-side band was removed to convert it to the single-side band version. A matched filter of *s(t)* was then applied to produce the time-delay profile. Subsequently, a double-integral procedure was applied to obtain the estimates of the polarity a well as the separation of signal pair. Figure (3) shows the results obtained by the new algorithm. The polarity estimation achieved 100% accuracy rate with a very high-degree of consistency. The estimation of the bearing also showed significant potential. With simple calibration procedure based on the beam patterns, this method can be fully implemented as a standard bearing estimation technique, not only for the accuracy of the estimation, but also the simplicity of the procedure for real-time processing.

CONCLUSION

In this paper, a simple algorithm was presented for the accurate estimation of the polarity of the transmitted signal for the underwater homing and docking systems. This new technique was successfully tested with several field-test data sets, which the conventional failed to achieve accurate estimation of the polarity. With extensions and modifications, for the accuracy and simplicity, this new technique can be implemented for real-time three-dimensional underwater navigation and guidance.

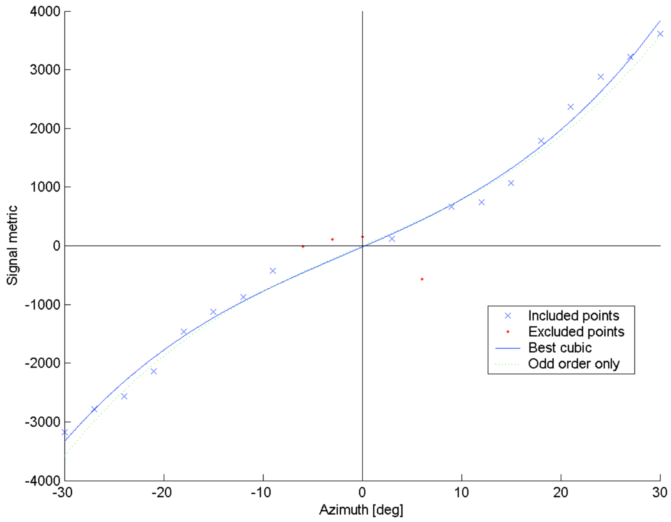

Figure (3): Results of polarity estimation by using the new method

ACKNOWLEDGMENT

This project is supported by Sonatech through the UC MICRO Program.

REFERENCES

(1) H. Lee and G. Wade, *Imaging Technology.* New York, New York: IEEE Press, 1986.
(2) A. S. C. Wright, "The wide swath, deep towed seamarc," *Oceans 88, pp.* 323-328, 1988.
(3) C. D. Loggins, "Advanced sonar imaging techniques," *Advanced Techniques in the Processing of Active Sensor Data,* 1987.
(4) J. T. Christoff, C. D. Loggins, and E. L. Pipkin, "Measurement of the temporal phase stability of the medium," *Journal of the Acoustical Society of America,* vol. 71, no. 6, pp. 1606-1607, 1982.
(5) J. C. Kirk, "Motion compensation for synthetic aperture radar," *IEEE Transactions on Aerospace and Electronic Systems, vol.* AES- 11, no. 3, 1975.
(6) B. L. Douglas and H. Lee, "Synthetic aperture active sonar imaging," *Proceedings of the 1992 International Conference on Acoustics, Speech, and Signal Processing,* vol. 3, pp. 37-40, 1992.
(7) J. C. Curlander and R. N. McDonough, *Synthetic Aperture Radar.* New York, New York: John Wiley & Sons, 1991.
(8) H. Lee and G. Wade, *Modern Acoustical Imaging*, IEEE Press, New York, 1986.
(9) C. Dorme and M. Fink, “Matched Filter Imaging Through Inhomogeneous Media,” *Acoustical Imaging*, Vol. 22, Plenum Press, pp. 1-8, 1996.