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Research of New Concept Sonar—Cognitive Sonar

Xiaohua Li*, Yaan Li, Lin Cui and Wangsheng Liu

College of Marine Engineering, Northwestern Ploytechnical University, Xi'an 710072, China

Abstract: The performance of a sonar system is closely related to the marine environment and the target characteristics. When dealing with the echoes of a traditional active sonar system, the sonar designers often do not take into account the influence of the environmental information and prior knowledge perceived by sonar receivers, making it difficult to obtain desired processing results. Based on the basic principle and key technology of sonar, this paper proposed a cognition-based intelligent sonar system in theory--cognitive sonar. Cognitive sonar is capable of jointly optimizing the transmission waveform and receiver according to the changes of environment so that its detection and identification performance can be significantly improved.
Key words: sonar; cognition; bat echolocation; cognitive sonar
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1 Introduction

Underwater acoustics is a vast discipline, as it offers a means of observation in muddy and turbid water where optical methods are ineffective (light waves and radio waves propagation quickly attenuates in the ocean, so the transmission distance is very limited and it cannot satisfy human ocean activities). Therefore, it is of potential importance in underwater sensing and communication, data transmission, target detection, location, identification, and navigation (Urick, 1983). The past three decades have seen a growing interest in underwater acoustic technology and advances are occurring in many areas. Outstanding sources of information on these advances are contained in the Ocean Conference Proceedings and the IEEE Journal of Oceanic Engineering (JOE).

Sonar is a technique that uses sound propagation to navigate, communicate with, or detect other vessels. It may be used as a means of acoustic location and of measurement of the echo characteristics of "targets" in the water (Waite, 2002). It plays an important role not only in underwater communication, navigation, and anti-submarine warfare, but also in marine development and utilization. In many respects, underwater acoustics and sonar signal processing are intrinsically connected.

Besides hardware and software features, the performance of sonar systems is also closely related to its marine working environment, target characteristics, and designer's subjective cognition on target characteristics. From the view of communication theory, owing to the spatial-time-varying characteristics of an underwater acoustic channel, the marine environment is actually a spatial-time-varying random filter between the transmission system and receiving sensor-array. A traditional sonar system can stay at the best state based on the ideal theory of an optimum receiver only in the marine environment (such as the underwater acoustic channel, background noise, and reverberation characteristics) meeting ideal conditions; if not, its performance will drop rapidly.

In terms of target characteristics, with the development of techniques for underwater ship noise elimination and submarine stealth, it's difficult to enhance the ability of target detection and localization at a low signal-to-noise ratio (SNR) as well as propose higher requirements for the sonar operator's ability of judging targets correctly.

High-speed communication in the underwater acoustic channel is challenging due to limited bandwidth, extended multi-path, refractive properties of the medium, severe fading, rapid time-variation, and large Doppler shifts (Chitre *et al*., 2008). In order to guarantee the best matching between the complicated marine environment and sonar systems, scientists are searching for a new underwater acoustic system structure which can bring the marine environment and the target characteristics into the overall structure of the system. This is the prototype of cognitive sonar.

Cognitive sonar is a new concept which has been derived from the rapid development of cognitive radio (Mitola *et al*., 1999; Haykin, 2005a) and cognitive radar (Haykin, 2006a; Haykin, 2006b) in recent years. By means of automatically perceiving the marine environment, especially the underwater acoustic channel parameters, cognitive sonar is capable of sensing the underwater acoustic channel's spatial-time-varying characteristics and establishing a complex spatial-time-varying mathematical model to track underwater target dynamically. Meanwhile, by the use of

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***Corresponding author Email:** lxhxy2009@163.com

target features and prior marine environmental knowledge, cognitive sonar constantly adjusts its parameters and operating system, which allows the sonar to always stay under the best working state. It is capable of intelligently interacting with its environment by both adapting to transmissions and receiving functions in the light of contextual awareness and expert reasoning.

Based on the analysis of the existing sonar systems, and inspired by the pioneer work of cognitive radar, a new concept of intellectual sonar system is proposed. It embodies the marine environment, target characteristics, and the sonar designers' prior knowledge, and brings feedback to the system to change sonar system's working condition in a timely manner. Therefore, cognitive sonar in theory is a highly intelligent system.

2 Traditional sonar information processing and underwater acoustic modeling

2.1 The working principles of sonar

The word "sonar" is an acronym for sound navigation and ranging, and can be thought of as a kind of underwater radar, using sound instead of radio waves to interrogate its surroundings. Its primary purpose is to detect or characterize (estimate position, velocity, and identity) submerged, floating, or buried objects. According to its working principles, sonar can be divided into active sonar and passive sonar (Yuan, 2010), which are distinguished, respectively, by the presence and absence of a transmitter.

Active sonar is also called echo sonar and works on the basis of the principle of echolocation. As shown in Fig.1, the transducer array, transmitter, receiver, transceiver switching device, displayer, timing center, and controller make up the basic parts of active sonar.

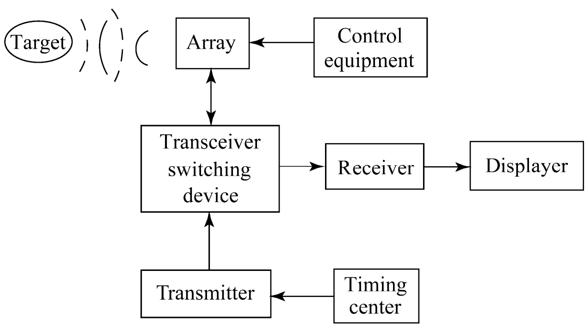

Fig.1 Block diagram of active sonar

Active sonar creates a pulse of sound, and then listens for reflections (echo) of the pulse. This pulse of sound is generally created electronically by using a sonar projector consisting of a signal generator, power amplifier, and electro-acoustic transducer/array. The transmitter "illuminates" the target and active sonar determines the target distance, direction, speed, and other motion parameters by receiving target reflected echoes. The target distance can be calculated in the light of the time delay between the echo signal and the transmitted signal. The target direction can be recognized with the normal wave direction, while the target radial velocity can be inferred by the frequency shift between the echo signal and the transmitted signal. In addition, the target shape, size, nature, and state of motion can be recognized by virtue of the echo amplitude, phase, and its variation. Active sonar is used for detecting icebergs, reefs, wrecks, surface ships, and hidden underwater navigation submarines. It can detect silent targets and measure their direction and range. However, the active pulse is more vulnerable to interception of the enemy in combat situations.

The working principle of active sonar can be expressed by an active sonar equation in which there are two performance limitations: environmental noise and reverberation. In general, one of them will dominate, so the two effects can be considered separately.

A typical active sonar equation with environmental noise is as follows:

$$\mathrm{SL}-2\mathrm{TL}+\mathrm{TS}-(\mathrm{NL}-\mathrm{DI})=\mathrm{DT}$$

where SL is the source level, TL is the transmission loss (or propagation loss), TS is the target strength, NL is the noise level, DI is the directivity index of the array (an approximation to the array gain), and DT is the detection threshold.

In reverberation dominated conditions, we have

$$\mathrm{SL}-2\mathrm{TL}+\mathrm{TS}-\mathrm{RL}=\mathrm{DT}$$

where RL is the reverberation level received by the hydrophone and the other terms are as before.

Passive sonar is also known as noise sonar. As shown in Fig.2, receiving transducer arrays detect targets by receiving noise or signals emitted by the target. Passive sonar is mainly composed of the transducer arrays, receiver, displayer, and beam-former.

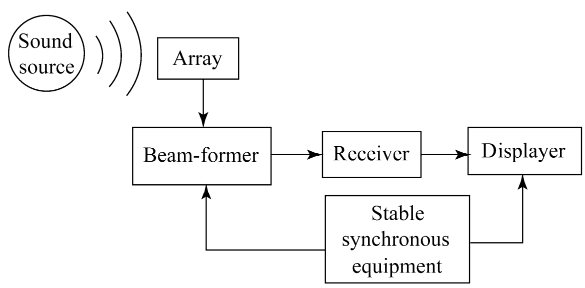

Fig.2 Block diagram of passive Sonar

Passive sonar listens without transmitting. It detects targets by receiving radiation noise from an underwater target such as a ship and signals of other sonar equipment. It is often employed in military settings. It is also used in scientific applications, for example, detecting fish for studies in various aquatic environments. Although it is good for hiding itself and identifying targets, it cannot detect static silent targets. Passive sonar itself has no reverberation and its noise mainly comes from self-noise and environmental noise. Unlike active sonar, only one way of propagation is involved. Meanwhile, passive sonar doesn't have a target strength TS. The equation for determining the performance of passive sonar is:

$$SL - TL - (NL - DI) = DT$$

Most modern sonar works in an integrated active-passive sonar style. In order to hide itself, sonar usually works in a passive way at alert state. Once the target appears, sonar usually works in an active way so as to get the precise target location and other characteristic parameters of the target. The integrated active-passive sonar can effectively protect itself and detect underwater targets, as well as estimate target motion parameters accurately.

2.2 Underwater acoustic modeling

Underwater acoustic modeling (Paul, 2003) mainly researches acoustic production, emission, transmission, and reception in the ocean, and it is one of the main studies on underwater acoustics, closely related to sonar system design and performance analysis. In addition, acoustic modeling is also used to train staff to understand the marine environment and judge enemy targets. Underwater acoustic models are now routinely used to forecast acoustic conditions for planning at-sea experiments, designing optimized sonar systems, and predicting sonar performance at sea. Modeling provides an efficient means by which to analyze the acoustic environment and to estimate the performance of existing sonar in different areas and seasons.

Underwater acoustic modeling includes marine environment models, basic acoustic models, and sonar performance models. Environment models are mainly used to describe the boundary conditions and volumetric effects of the sea environment. Such models include the sound speed, absorption coefficient, surface and bottom reflection loss, and bottom and volume backscattering strengths. A basic acoustic model is mainly comprised of transmission loss, noise, and reverberation models. Sonar performance models are composed of marine environment models, basic acoustic models, and appropriate signal processing models for solving specific sonar-application problems such as submarine detection, mine hunting, and underwater communications.

In recent years, the use of sonar has shifted from open-ocean operations to shallow-water scenarios, while sonar systems were originally designed for the operation in deep-sea environments and seldom worked optimally in the coastal regions. Shallow-water geometries make the boundary interactions more prominent, which diminishes acoustic energy through scattering and also complicates the detection and localization of objects due to multi-path propagation. In addition, the unique boundary reverberation and interfering noises in coastal regions also bring great difficulties to underwater target detection and localization.

At present, some naval countries have been studying the new generation of environmental adaptive sonar in view of sonar detecting in shallow-water scenarios. Environmental adaptation is accomplished by measuring marine environmental parameters in real time and using an environmental feedback loop, thus keeping an optimal performance.

The other important content of underwater acoustic modeling is inverse acoustic sensing of the ocean. This inverse method combines direct physical measurements with theoretical models of underwater acoustics and acquires ocean acoustic information. The main goal of inverse acoustic sensing of the ocean is to estimate related underwater acoustic fields from the limited physical measurements by using the theoretical models as guides.

3 Cognition and its application

3.1 The concept of cognition

According to the Oxford Dictionary, cognition is "knowing, perceiving, or conceiving as an act." The term cognition refers to a faculty for the processing of information, applying knowledge, and changing preferences. Another view of cognition is described as an interdisciplinary study of the general principles of intelligence through a synthetic methodology termed learning by understanding (Pheifer and Scheier, 2001). For psychology or philosophy, the concept of cognition is closely related to abstract concepts such as the mind and intelligence. It is used to refer to the mental functions, mental processes (thoughts), and states of intelligent entities (humans, human organizations, highly autonomous machines). From a large systemic perspective, cognition is considered to be closely related to the social and human organizational functions and constraints.

Cognition describes people's ideas and perspectives on the things around them, and cognitive processing includes knowledge, perception, inference, and response. Knowledge includes knowledge acquisition, learning, expression, and storage. Perception consists of monitoring, perceiving, and adapting to the surrounding environment. Inference includes modeling of uncertainties, robust processing, statistical decisions, and Bayesian inference. Response includes control, optimizing, tracking, and detection.

From the perspective of the information theory, cognition is about how people obtain information and respond to the surroundings based on the cognitive information processing. Cognitive information (CI) (Wang, 2007; Wang, 2002) has been described as a new discipline that studies the natural intelligence and internal information processing mechanisms of the brain, as well as processes involved in perception and cognition. It has been recognized that CI has led to the design and implementation of future generation computers, known as cognitive computers, that are capable of thinking and feeling (Wang, 2006). The famous international signal processing expert Simon Haykin noted that CI processing mainly consists of three sections (Haykin, 2005b): (1) being aware of its surrounding environment; (2) using understanding-by-building to learn through interactions with the environment and other means; (3) adapting its internal states to statistical variations in input stimuli by making corresponding changes in adjustable system parameters in real time with specific objectives as determined by the application of interest.

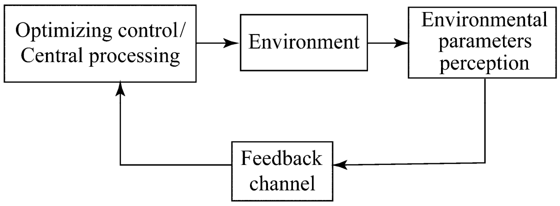

Fig.3 Block diagram of cognitive cycle

The cognitive information processing model can be simplified as a two-level structure of an "environmental parameter perception and optimization control" (Figure 3). Perception is comprised of information collection, information organization, and information explanation. Also, it can be regarded as the original information collection and initial handling. The optimization control is similar to the central processing of the brain. It includes information processing, information extraction, learning, and optimization. As a significant part of cognition, the feedback channel delivers important system information in a timely manner to the central processing. In return, the central processing compensates and corrects system parameters to make the system performance optimal.

3.2 Application of cognition

In recent years, international information sciences have attracted much interest in cognitive science and intelligent information processing. Many famous journals have put forward papers based on perception and cognitive intelligent signal processing theory. Cognition theory not only provides a new theory for development of artificial intelligence and a new generation of intelligent computers, but also can be used in radar systems, sonar systems, vehicle navigation, robot control systems, and disease diagnosis.

At present, the cognition theory has been successfully used in the fields of wireless data communication; cognitive radio and cognitive radar can be taken as good examples. Cognitive radio (CR) is an intelligent technology of increasing spectrum utilization, which can change its transmitter parameters based on interaction with the environment in which it operates. It becomes a promising approach to increase spectrum efficiency, the importance of which is dynamic spectrum allocation. It also makes network terminals more flexible; the key to share the spectrum is sensing it reliably.

In view of the inadequacy of conventional radar signal processing, Simon Haykin in the Adaptive Systems Laboratory at McMaster University in Canada put forward the concept of "Radar vision" (Haykin, 2003; Haykin, 1990) in 1989 and cognitive radar in 2003 at the IEEE International Radar Conference. The cognitive radar system embodies three fundamental ingredients: adequate attention given to learning from the environment through experience, adjustment of the transmission signal in an intelligent manner, and feedback from the receiver to the transmitter which makes this adjustment possible. Considering the adaptive match between the transmitter&receiver system and the environment, cognitive radar is more adaptive to modern increasingly complex battlefield environments. Domestic and foreign scholars have carried out a wide range of research in the field of cognitive radar.

Cognitive radio and cognitive radar are examples of closed-loop feedback control wireless systems. Both share two features (Haykin, 2007): (1) Scene analysis which enables the radio or radar receiver to sense its surrounding environment on a continuous basis and thereby learn from it. (2) A feedback channel which connects the receiver to the transmitter and thereby makes the transmitter adapt itself to the environment by virtue of the information passed on to it by the receiver.

With the rapid development of modern physics technology, information technology, and computer technology, cognitive research has important scientific significance and broad application prospects.

4 Bat echolocation mechanism and cognitive sonar

4.1 The mechanism of bat echolocation

Bat echolocation is a complex and highly evolved physical process. It’s a perceptual system where ultrasonic sounds are emitted specifically to produce echoes. By comparing the outgoing pulse with the returning echoes, the brain and auditory nervous system can produce detailed images of the bat's surroundings. This allows bats to detect, localize, and even classify their prey in complete darkness. The bat gathers information about its local environment and then adjusts the parameters of the next call as well as changing its position to ensure that it extracts the right or the best information to continue and then complete its task as successfully as possible.

Bats emit ultrasonic pulses and listen to the echoes to obtain range and texture information about the target, and change the design of the emitted pulse flexibly depending on their tasks and surrounding environments. They are divided into two groups, CF-FM (constant frequency – frequency modulation) and FM bats, according to the design of the frequency structure in the echolocation pulse (Hagino *et al.*, 2007). CF-FM bats emit CF-FM type pulse consisting of CF and narrow FM components. On the other hand, FM bats are generally reported to utilize only broadband FM component.

To clearly distinguish returning information, bats must be able to separate their calls from the echoes they received. They are also capable of estimating their prey's range according to the delay of the returning echoes. The Doppler shift of the returning echoes yields information relating to the motion and location of the bat's prey. These bats must deal with changes in the Doppler shift due to changes of their flight speed.

According to the position and state of a target, bats adapt different ultrasonic pulse frequencies and waveforms to search, track, and capture targets in the hunting process. At the search stage, bats use low frequency and long duration acoustic waves to search targets. Once targets appear, they switch to higher frequency and shorter waves to distinguish targets and estimate their direction and flight speed. Once the target is determined, bats start to change acoustic frequency and waveform to capture the target. At this time, bats focus on the target's precise location and movement rules and features. Inspired by a bat's echolocation mechanism, scientists have developed various echolocation devices; for example, radar and sonar are now widely used.

In short, a bat echolocation system is very plastic in that the parameters of the transmitted sound bursts can be changed considerably in different phases of the target pursuit sequence. It is therefore justifiable to view the bat echolocation system as physical proof of cognitive sonar.

4.2 The structure of cognitive sonar

The idea of cognitive sonar originated from both Simon's cognitive radar and the bat echolocation system. Figure 4 depicts its general principles.

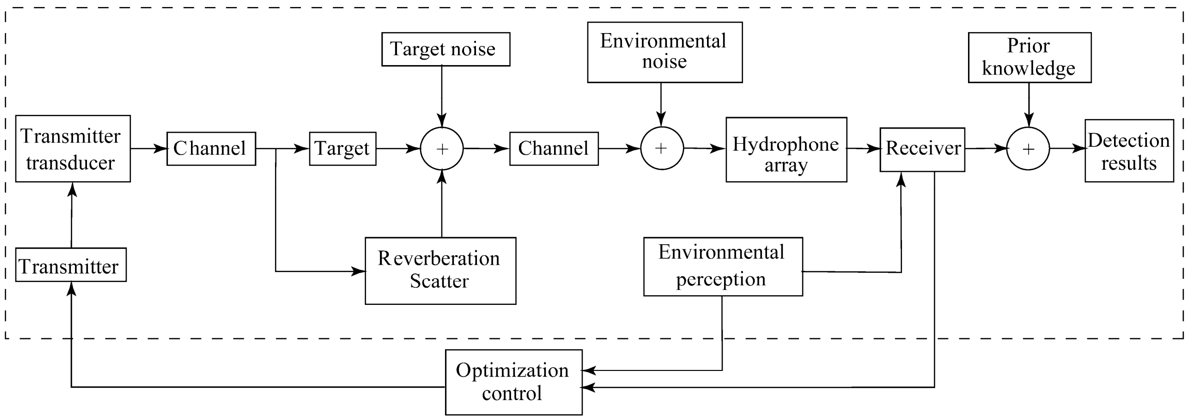

Fig.4 Block diagram of cognitive sonar

There is a feedback loop, namely an optimization control, between the transmitter and receiver. The transmitter, environment/target, and receiver formed a dynamic closed loop system and the transmission waveform and receiver can be jointly optimized according to the change of the environment, which distinguishes itself from adaptive sonar which only optimizes the receiver. Traditional sonar is an open loop system. Sonar designers developed a transmitting waveform in light of the knowledge of sonar's working environment, performance requirements, and prior knowledge on targets. The sonar receiver would achieve specific detection function by receiving and processing echoes from targets, reverberations, and noises. Sonar operators would finally determine whether targets exist or not according to the results of a sonar receiver, prior knowledge of target characteristics, and the sonar operators' subjective judgment (actually, the sonar operators' subjective judgment has great influence on detection result).

In a traditional sonar framework, the transmitted sonar waveforms are fixed and the environmental information and processing results perceived by a sonar receiver do not completely affect the sonar transmitter system. There is very little provision for "learning" over time, feedback to the transmitter, or the integration of exogenous environmental information sources that can provide significant benefits. This kind of sonar system architecture has dominated sonar research and application.

People usually idealize environmental conditions when designing traditional sonar. For example, the stochastic signals are simplified as ergodic processes, nonstationary backgrounds are considered to be stationary, and uncertain factors such as signal the multi-path effect, interference fluctuation, and boundary effect are not taken into account. Thus there is great difference between measurement results and the practical results. Although an optimal processing system relative to transmission waveform and prior knowledge has been set up, the fixed transmission waveform and the complicated dynamic space spectrum make the computation burden large and processing results unsatisfying. In this condition, the new concept of "cognitive sonar" which adaptively matches the transmitter and receiver with the environment can greatly improve sonar's performance.

Cognitive sonar is a kind of intelligent sonar which has certain reasoning and learning functions based on knowledge theory. In order to make sonar system cognitive, sonar transmitter must constantly learn from the environment and intelligently use the receiver information extracted from the monitored target.

Based on Fig.4, there are three major differences between cognitive sonar and traditional sonar: (1) By learning about its working environment and target information, cognitive sonar can continually update the receiver with relevant information on the environment and, correspondingly, adaptively adjust the transmitter. (2) The transmitter illuminates the environment in an intelligent manner, taking into account such practical matters as the size of the target and its range, and consequently, adjusting the transmission waveforms in an effective and robust manner. (3) Unlike traditional sonar, the whole cognitive sonar system constitutes a dynamic closed feedback loop encompassing the transmitter, environment, and receiver.

4 Signal processing of cognitive sonar

Figure 5 depicts the cognitive sonar signal processing diagram applied to active and active-passive sonar systems.
The dashed frame is the part of the receiver, and the working process of the closed-loop system is similar to the traditional sonar. The difference is that cognitive sonar adds feedback from the receiver to transmitter, the sonar operator's prior knowledge on the marine environment, and target characteristics. Although the process of target detection is not explicitly stated in Fig.5, it is a necessary part of the Bayesian target-tracker which combines the functions of detector and tracker together for a better performance.

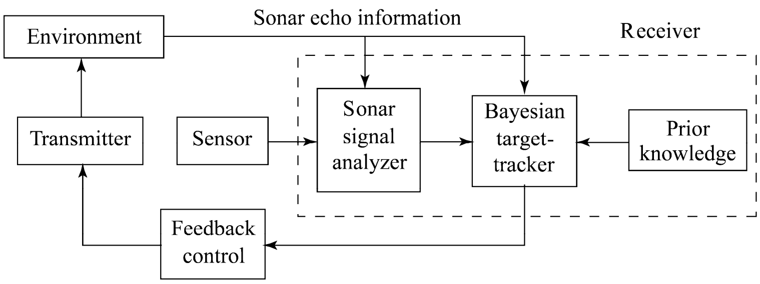

Fig.5 Block diagram of cognitive sonar signal processing

The cycle begins with the transmitter illuminating the environment. Once the cognitive sonar system comes into operation, the system would become closely related to its surrounding environment in the sense that the environment has a strong and continuous influence on the sonar echo information. The sonar echo information produced by the marine environment is entered into two functional blocks: the sonar signal analyzer and Bayesian target-tracker. The sonar signal analyzer would perceive sonar echo information and other relevant environmental information, and send it to Bayesian target-tracker. The tracker finds the possible existent targets and forms tracks on a continuing time, on the basis of the relevant information provided by the sonar signal analyzer and prior knowledge. The transmitter, in turn, illuminates the surrounding environment in real-time by virtue of the decisions on possible targets made by the receiver, and dynamically adjusts sonar system's working state, changes the transmission waveform, and sends it to the receiver. The cycle is then repeated over and over again until the sonar works optimally.

The sonar signal analyzer provides the receiver with information on the environment, which is of critical importance to the decisions made by the receiver on possible targets of interest. There are two sources of information-bearing signals: (1) sonar echo information, which is derived from the sonar's own transmitted signals; (2) other relevant information on the environment (such as water temperature, salinity, and pressure) which is gathered by sensors on the water.

The Bayesian target-tracker is the main component of a cognitive sonar system. The Bayesian method takes unknown parameters as random variables and uses prior probability and currently observed information to calculate posteriori probability. It coordinates the priori information and current information and is suitable for dealing with nonlinear and non-Gaussian system state estimation. By adjusting certain parameters in the transmitted signal in response to the probabilistic decisions made by the Bayesian tracker on the environment under surveillance, the whole sonar system can be made to be adaptive.

In terms of underwater target tracking, a Bayesian tracking model was built by studying the statistical characteristics of background noise and target signal probability distribution, and the target signal dynamic tracking was realized by continuously observing the background noise and recursively calculating the target signal probability distribution.

For a Bayesian target tracking problem of a linear Gaussian model, the Kalman filter (Kalman, 1960; Rhodes, 1971) gives an optimal solution under the maximum a posteriori probability criterion. There is no perfect solution for general nonlinear non-Gaussian models, and all kinds of existing nonlinear filtering methods such as the extended Kalman filter (Julier and Uhlmann, 1997; Villares and Vazquez, 2004), unscented Kalman filter (Julier and Uhlmann, 2004; Li and Wei, 2007), and particle filter (Doucet and Godsill, 2000; Arulampalam *et al*., 2002) can give approximate optimal solutions.

Methods of tracking targets (especially a maneuvering target) quickly, accurately, and reliably is always the main research content of underwater target tracking technology in complicated marine environments. Cognitive sonar can keep the system at the best working state and thus improve target detection capability, in that it can match the marine environment optimally, bring the marine environment into the overall structure of the sonar system, and adjust the sonar system's working parameters and operating mode.

Cognitive sonar whose advantages have been demonstrated by Monte Carlo simulations have been proposed for harbor and maritime surveillance applications (Wenhua *et al*., 2009). Additionally, the results reported by Wenhua Li and Genshe Chen attested the effectiveness of the cognitive sonar.

Prior knowledge (such as Geographic Information Systems and the clutter model database) and online learning of environments (such as sonar system bias and jamming) are both utilized to improve the detection performance of cognitive sonar. It has been proven that through cognition processing and space-time-waveform adaptive processing, cognitive sonar has many superior advantages over conventional sonar.

6 Prospects and challenges

In the future, sonar will play an increasingly important role in ocean information warfare. New ideas and technologies should be put forward to realize great leaps in development of sonar technique, taking towed linear array, variable depth sonar, passive ranging sonar, and long passive distance localization techniques as a good example. Cognitive sonar gives innovative ideas to high-performance sonar systems in theory. However, it is in the exploration stage and how to apply it in practice is still a challenge. Further research is needed and the new results will be reported in later papers.

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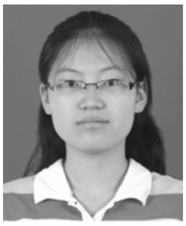
Xiaohua Li was born in 1986. He is presently a PhD candidate for acoustics at College of Marine Engineering, Northwestern Ploytechnical University. His current research interests include Underwater Acoustic Signal and Information Processing and target tracking.

Yaan Li was born in 1961. He is a professor and a PhD supervisor at Northwestern Polytechnical University. His research interests are focused on acoustic signal and information processing, nonlinear dynamic modeling and information extraction.



Lin Cui was born in 1984. She is a PhD. of Northwestern Polytechnical University. She is currently working with underwater signal processing. Her main research is robust array beamforming techniques.

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