Distance estimation for hopping-frequency-coding-based continuous wave

YoungKwang Seo, Geun-Ho Park, Wan-Jin Kim and Hyoung-Nam Kim

Abstract. A distance estimation method for hopping-frequency-coding (HFC)-based continuous wave (CW) is proposed herein. It is important to frequently update the distance estimate of a near-field underwater vehicle, robust to the time delay, Doppler effect, and volume reverberation. Frequency hopping ensures a high estimation accuracy of the wideband signal without being influenced by the Doppler effect, and also allows the receiver to update the target information at each frequency-hopping instance. The proposed algorithm, which is the initial algorithm for HFC-based CW, focuses on the update period of the estimates and real-time implementation rather than the optimization of estimation accuracy. To achieve this goal, the proposed method exploits multiple Doppler correlators, a difference moving average filter, and four thresholds. The update period is inversely related to the hopping frequency, which is directly proportional to the Doppler frequency. As the target or transceiver moves at a high speed, the frequency-hopping period can be reduced, and the proposed algorithm can update the target information more frequently.

Keywords: AUV, near-range SONAR, frequency hopping, real-time processing

1. Introduction

As autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) have been widely used, the related technologies have also been actively developed. One of these techniques, the near-range sonar, is indispensable for preventing dangerous collisions with objects approaching rapidly [1–3]. These collisions can occur when the AUV or UUV moves at a high speed or when an unidentified object approaches rapidly as shown in Fig. 1. To prevent these kinds of collisions, a near-range sonar is required to satisfy the following three constraints: First, the distance estimate can be updated regardless of the reflected signal’s delay. Next, the estimate should not be influenced by the Doppler effect, and finally, the information should be stably estimated even in a high-level reverberation environment caused by continuous wave (CW) transmission.

Frequency-modulated continuous wave (FMCW) is a representative technology for various short-range applications, such as proximity fuse, collision avoidance radar, and level measurement radar [4–8]. These FMCW radars transmit a high-frequency signal to a target and use the received time-delayed signal to generate a beat-signal with low frequency. This beat signal is a sine wave in the time domain, and its frequency is directly related to the distance of the target.

However, two problems occur in applying the FMCW technique to the near-range underwater sonar system, which moves very fast. The first problem
is that it can no longer exploit the beat signals and related estimation methods because of the Doppler effect, which is approximately 200,000 times larger than that of the radar system. The second problem is that it cannot take advantage of the FMCW that has an accuracy proportional to the bandwidth and time-frequency slope. This is because the delay time in the sonar system, in units of milliseconds, is much longer than that of a radar, and the sonar system has to use only the limited bandwidth because of the reverberation [9].

To robustly estimate the information of a high-speed underwater vehicle, a new signal model and its corresponding algorithm for distance estimation, which should be designed in consideration of each other, are required. Basically, they must be very robust to the Doppler effect and can update the estimates more frequently than the delay time. In [10], the hopping-frequency-coding (HFC)-based CW was introduced without its corresponding estimation algorithm. Frequency hopping ensures a high estimation accuracy of the wideband signal without being influenced by the Doppler effect, and also allows the receiver to update the target information at each frequency-hopping instance. We herein propose a distance estimation method that is the initial algorithm for an HFC-based CW, and focuses on the update period of the estimates and real-time implementation rather than the optimization of the estimation accuracy. In underwater environments where the target or transceiver is moving at a high speed, frequent updating of the target’s information in real time is critical to monitor the target continuously.

The proposed method is composed of three steps: First, the frequency of the received HFC signal is estimated with a number of Doppler correlators. Next, a difference moving average filter is applied to the estimated frequency sequence to generate a signal that has non-zero values of the hopping frequencies at the time of each frequency hopping and zero values at other instants. Finally, the frequency-hopping point is detected based on the four pre-determined thresholds and then the detected hopping frequency is classified into five cases, of which four cases indicate the four hopping frequencies and one case is the non-hopping frequency. Finally, the target distance is calculated from the difference between the frequency-hopping times in the transmitted HFC and the received HFC.

This paper is organized as follows: In Section 2, the FMCW sonar problem is described. The proposed HFC-based CW is introduced in Section 3, and the proposed distance estimation algorithm is presented in Section 4. In Section 5, the simulation results are presented, and finally the conclusion of this paper is drawn in Section 6.

2. FMCW radar and FMCW sonar

This section presents the primary principle of an FMCW radar, and the problems of an FMCW sonar with frequency and phase evaluations.

2.1. FMCW with frequency and phase evaluations

In the FMCW radar, a typical method can achieve a high estimation accuracy of the distance measurement using the frequency and phase of the beat signal. One advantage of the FMCW radar system is that the in-phase and quadrature (IQ) receiver is not required to calculate the phase, thus keeping the overall costs of the radar system low. The instantaneous frequency of the FMCW is given by

\[ f_T(t) = f_0 + m_T t, \]

where \( m_T \) is the chirp rate and is defined as \( m_T = B/T \), with bandwidth \( B \), and sweep time \( T \). A reflected signal from a target at distance \( r \) has a time delay \( \tau = 2r/c \), where \( c \) is the light velocity. Thus, the received signal is a delayed version of the transmitted signal as shown in Fig. 2. If the transmitted and received signals are mixed and low-pass filtered, this results in a beat signal \( s_b(t) \) which has two low frequencies called the up-beat frequency \( f_{ub} \) and down-beat frequency \( f_{db} \) as shown in Fig. 2. In an FMCW radar system, the target is located sufficient close such that \( T \) is much larger than \( \tau \). Therefore, the beat signal with the value of \( f_{db} \) has a much
longer interval than that with the value of $f_{udb}$, and the frequency $f_{db}$ is represented by

$$f_{db} = \frac{B\tau}{T}. \quad (2)$$

Accordingly, the phase of $f_{db}$ is given by

$$\varphi_{db} = 2\pi f_0 \tau. \quad (3)$$

It is noteworthy that $f_{db}$ and $\varphi_{db}$ are directly proportional to the distance, and thus the measurement accuracy depends on the accurate estimation of $f_{db}$ and $\varphi_{db}$. Once their accurate estimates are obtained, the distance estimation accuracy can be achieved by estimation methods using both $f_{db}$ and $\varphi_{db}$, such as the chirp z-transform (CZT) algorithm [11, 12].

2.2. FMCW sonar problem

When the FMCW radar technique is applied to the underwater sonar system for the distance and velocity estimation of a high-speed underwater vehicle, some problems occur that are fundamentally caused by the speed difference between sound and light, i.e., the Doppler effect of underwater sonar is approximately 200,000 times larger than that of the radar.

In the underwater sonar system, it is no longer valid to assume that the variation in the signal length and bandwidth is negligibly small. This means that the length of the FMCW signal reflected from the high-speed underwater vehicle is contracted and the bandwidth is increased as shown in Fig. 3. Consequently, the values of the up-beat and down-beat frequencies are no longer constant as in Fig. 2. Therefore, it is difficult to estimate the distance and velocity of a target using the discrete Fourier transform (DFT) or fast Fourier transform (FFT)-based algorithms because the estimates of $f_{db}$ and $\varphi_{db}$ of $s_b(t)$ obtained by these algorithms are not constant.

Another problem is that $\tau$ is not sufficiently smaller than $T$. Even though the target is located sufficiently close, a considerably long $\tau$ occurs because the speed of sound is not as fast as the speed of light. Thus, it is not acceptable that only the down-beat frequency signal exists. The down-beat frequency $f_{db}$ changes continuously according to the distance of the target. In addition, if the information of the target needs to be updated more frequently than that of $\tau$, the sweep time $T$ cannot be used long enough.

Because of the high Doppler effect and the long delay time in the underwater sonar, it is difficult to utilize the existing FMCW radar technology in estimating the information of a high-speed underwater vehicle. Therefore, a new transmission and reception method suitable for underwater sonar is required, especially in the near range.

3. HFC-based CW

The HFC-based CW is designed to allow the receiver to frequently update the distance estimate by considering the following three points.

- It can update the distance estimate regardless of the delay time of the reflected signal.
- It should not be influenced by the Doppler effect.
- The receiver can detect the frequency hopping in the reverberation environment.

The HFC-based CW hops within three frequencies of $f_c - f_B$, $f_c$, $f_c + f_B$, and the hopping frequency of $\pm f_B$ or $\pm 2f_B$ is determined by the code $c_{T1}$ as presented in Fig. 4. The reason for allocating and
Corrected Proof

Y.K. Seo et al. / Distance estimation for hopping-frequency-coding-based continuous wave

Fig. 4. An example of the HFC based continuous wave.

utilizing \( cT,l \) is that the receiver can obtain the transmission time \( nT,l \) of each frequency hopping from the code sequence. The HFC signal should satisfy the following two constraints to be applied in the near-range underwater environments.

First, the target information can be normally estimated only when the received frequency band is separated from the volume reverberation. In this case, the hopping frequency \( f_B \) should be less than one-half of the Doppler frequency \( f_D \):

\[
f_B < \frac{f_D}{2}.
\] (4)

Second, the hopping period \( T_c \) should be sufficiently long to detect the frequency hopping stably at the receiver, and is a parameter that determines the length of the Doppler correlators. The hopping period \( T_c \) is set as follows considering \( f_B \) and the delay time \( \tau \):

\[
T_{\text{min}} < T_c, \quad \text{for } T_{\text{min}} = \max \left\{ \frac{1}{f_B}, \frac{\tau}{3} \right\}.
\] (5)

4. Distance estimation for HFC-based CW

The proposed algorithm is composed of three steps, and can be summarized as a block diagram as shown in Fig. 5. First, the instant frequency of the received HFC–based CW is estimated using a number of Doppler correlators. Next, a difference moving average filter is applied to the estimated frequency sequence to generate a signal that has the value of each hopping frequency at the frequency hopping instance, and zero at other times. Finally, the proposed algorithm exploits four thresholds to detect the time of the frequency hopping, and to classify five cases that are composed of the four hopping frequencies and a non-hopping frequency.

4.1. Filter bank - doppler correlators

The received-signal frequency is estimated through the filter bank composed of the Doppler correlators. The frequency range of the Doppler correlators should satisfy the range in Equation (6), which is set in consideration of the \( a \ priori \) Doppler effect in Equation (4).

\[
\text{Detection of the hopping-time & Classification of the hopping-frequency}
\]

\[
\begin{align*}
n_{R,j} & \quad f_{R,j} \\
   & \quad c_{R,j}
\end{align*}
\]

\( n \): discrete time index
\( \hat{f}(n) \): estimated frequency of the received signal \( r(n) \)
\( f_m(n) \): output of the difference moving average filter \( h_d(n) \)
\( n_{R,j} \): time index of \( l^{th} \) frequency hopping
\( f_{R,j} \): \( l^{th} \) hopping-frequency
\( c_{R,j} \): \( l^{th} \) code of received HFC based CW

Fig. 5. Block diagram of the proposed algorithm.
where $\alpha$ is a scaling parameter of the maximum frequency of the Doppler correlators.

A basic purpose of the Doppler correlator is to estimate the frequency of the received signal and to assist in estimating the frequency-hopping time in the following process. Hence, the operation period of the Doppler correlators is set to include both the previous period and the following period based on the hopping time of the received signal as follows:

$$\kappa T_c \leq T_{\text{cov}} < 2\kappa T_c,$$

where $\kappa$ is the Doppler ratio and is defined as follows

$$\kappa = \frac{f_c}{f_c + f_D}.$$

The output of the filter bank is a sequence of the estimated frequency $f_m(n)$, which could be updated with a sampling interval or much longer interval, and is applied to estimate the Doppler frequency.

### 4.2. Difference moving average filter

To calculate the difference of the adjacent frequency $f_m(n)$ of the estimated frequency $\hat{f}(n)$, the difference moving average filter is utilized at the second step and is defined as follows:

$$h_d(n) = \begin{cases} 
1/2N, & \text{for } 0 \leq n < N \\
-1/2N, & \text{for } N \leq n < 2N
\end{cases},$$

In Equation (9), the total length of $h_d(n)$ is $2N$. If the HFC signal is generated by satisfying the constraints of Equations (4-5), $f_B$ can be obtained even if $N=1$. The output $f_m(n)$ is zero in the interval where frequency hopping does not occur, and it becomes the hopping frequency $\pm f_B$ or $\pm 2f_B$ at the time of frequency hopping as described in Fig. 6. The difference moving averaging filter has to generate a signal with values of the hopping frequency at the time when frequency hopping occurs.

### 4.3. Detection and classification of the hopping frequencies

In this step, the detection of the frequency-hopping time $n_{R,i}$ and the classification of the four hopping frequencies, are performed simultaneously using four thresholds: $z_1, z_2, -z_1, -z_2$ as depicted in Fig. 6. These thresholds divide the frequency range of $f_m(n)$ into five intervals composed of four sections for the frequency hopping and one section for the non-hopping. Table 1 summarizes the divided frequency intervals and their corresponding hopping frequencies. In the receiver, frequency hopping is detected at each detected time $n_{R,i}$ with a regular interval $\kappa T_c$.
Table 1

<table>
<thead>
<tr>
<th>Frequency interval</th>
<th>Detection results</th>
<th>Hopping frequency Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>( z_2 \leq f_m(n) )</td>
<td>o</td>
<td>+2f_B</td>
</tr>
<tr>
<td>( z_1 &lt; f_m(n) &lt; z_2 )</td>
<td>o</td>
<td>+f_B</td>
</tr>
<tr>
<td>( -z_1 &lt; f_m(n) &lt; z_1 )</td>
<td>x</td>
<td>0</td>
</tr>
<tr>
<td>( -z_2 &lt; f_m(n) \leq -z_1 )</td>
<td>o</td>
<td>-f_B</td>
</tr>
<tr>
<td>( f_m(n) \leq -z_2 )</td>
<td>o</td>
<td>-2f_B</td>
</tr>
</tbody>
</table>

4.4. Distance estimation

The proposed algorithm can estimate the distance and the Doppler effect using \( c_{T,I} \) and \( n_{T,I} \) of the transmitted HFC signal and \( c_{R,I} \) and \( n_{R,I} \) of the received HFC signal. If the sequentially obtained \( c_{R,I} \) are equal to \( c_{T,I} \), it means that the target is approaching normally from the initial distance. The distance estimate \( \hat{d}(n) \) is obtained at each time \( n = n_{R,I} \) as follows

\[
\hat{d}(n) = \frac{(n_{R,I} - n_{T,I}) c}{2}, \quad \text{for } n = n_{R,I},
\]

where \( c \) represents the speed of sound.

5. Simulations

A simulation was performed to evaluate the proposed estimation algorithm for the HFC-based CW in the volume reverberation environments, and compared with the distance estimation accuracy of a sine pulse. The sine pulse was selected for performance comparison because the HFC-based signal can be considered as a case where interference signals exist before and after the sine pulse.

5.1. Generation of reverberation signal

In an active sonar, the closer the distance between the target and the receiver, the larger the influence of the volume reverberation. As the transmitted signal is a CW, the near-range sonar for the HFC-based CW is greatly affected by the volume reverberation.

In the simulation, we used the reverberant channel of the linear filter model with two assumptions [13]. The first assumption is that the scatter density in the unit volume is sufficiently high and uniformly distributed. This means that the reverberant channel has a scattering coefficient at all times. The second assumption is that the secondary reflection does not occur after the first reflection. Based on these two assumptions, we implemented the reverberant channel with the scattering coefficients at all times as follows

\[
h_r(n) = \beta \alpha(n) \omega_r(n),
\]

\[
\alpha(n) = -20 \log (0.5 \cdot c \cdot T_s \cdot n),
\]

where \( \beta \) is the scaling factor for changing the reverberation level, \( \alpha(n) \) is the damping factor according to the distance, \( T_s \) is the sampling interval, \( |\omega_r(n)| \) and \( R_{\omega_r}(n) \) follow the normal distribution and the uniform distribution, respectively. The reverberation power decreases by \( -20 \text{ dB} \) when the distance is increased by 10 times. The volume reverberation \( w(n) \) was generated by the convolution product of \( h_r(n) \) and the transmitted signal \( x(n) \) as follows:

\[
w(n) = \sum_{k=1}^{N} x(n) h_r(k - n).
\]

The volume reverberation for the CW is maintained at a constant level as shown in Fig. 7, and the level of the reflected signal gradually increases as the distance decreases. In the far distance, the reverberation signal has a much higher level than the reflected signal as shown in Fig. 8. However, as the distance decreases, the level of the reflected signal increases as shown in Figs. 7–9.

Essentially, if the hopping frequency is applied while satisfying Equation (4), the frequency bands of the reverberation signal and the reflected signal can be distinguished. Then, the hopping frequency detection and the distance estimation are possible even in a case where the level of the reflected signal is sufficiently low as shown in Fig. 8.

![Fig. 7. Level of the reverberation signal and the reflected signal.](image)
5.2. Distance estimation of a high-speed underwater vehicle

Two simulations were conducted, and the parameters related to the simulations are summarized in Table 2.

The first simulation was to compare the distance estimation performance between the HFC-based CW and a sine pulse according to the signal-to-reverberation ratio (SRR). The other simulation showed the cumulative number of the estimates and the estimation accuracy according to the frequency-hopping period and the distance where the SRR is 0 dB at 12.5 m as depicted in Fig. 7.

The first simulation shows the cumulative number of the estimates as shown in Fig. 10; the root mean squares error (RMSE) of the distance estimation presented in Fig. 11 is when $T_c$ is set to 20 ms, 10 ms, and 5 ms, respectively. The estimation accuracy is inversely proportional to the update period.

As the distance becomes smaller, the SRR increases.

---

**Table 2**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values or variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>$f_c$</td>
</tr>
<tr>
<td>Sampling frequency $f_s$</td>
<td>$10f_c$</td>
</tr>
<tr>
<td>Hopping frequency $f_h$</td>
<td>$0.03f_c$</td>
</tr>
<tr>
<td>Hopping period $T_c$</td>
<td>$2 \cdot 10^2/f_c$</td>
</tr>
<tr>
<td>Doppler frequency $f_D$</td>
<td>$0.065f_c$</td>
</tr>
<tr>
<td>Length of correlators</td>
<td>$T_c/0.065$</td>
</tr>
<tr>
<td>Initial target distance</td>
<td>$100 m$</td>
</tr>
<tr>
<td>Length of the codeword</td>
<td>$5$</td>
</tr>
<tr>
<td>Length of $h_d(n)$</td>
<td>$4$</td>
</tr>
<tr>
<td>Iterations</td>
<td>2000</td>
</tr>
</tbody>
</table>
Subsequently, the distance estimate can be updated frequently with a shorter $T_c$.

In the second simulation scenario, the sine pulse is hardly affected by the reverberation and obviously shows a greater performance compared to the proposed algorithm as described in Fig. 12. Because the HFC signal is a CW and has a wider bandwidth, it is affected more by the reverberation. However, the proposed algorithm has RMSE in centimeters under 0-dB SRR, and it is not considered highly inconvenient in practical applications.

6. Conclusions

We proposed a distance estimation algorithm for an HFC-based CW. As the purpose of the HFC signal is to frequently update the distance estimate, the proposed method had focused on the update period of the estimates and real-time implementation rather than the optimization of the estimation accuracy. Our simulation results show that as the distance becomes smaller, the distance estimate can be updated more frequently. In terms of estimation accuracy, it can be used in near-range applications but is not yet optimized. Future research will be performed to design a new algorithm that is more flexible to set the hopping frequency and the hopping interval, and achieves the optimal performance in distance estimation.

Acknowledgments

This work was supported by the Agency for Defense Development, South Korea, under Grant UD150002DD, 2015.

References