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Mobile ultrasonic transducer positioning

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Abstract: For positioning a moving ultrasonic transmitter, most of the existing ultrasonic positioning systems require the use of a bank of correlators to estimate the Doppler shift associated with its movement which require high computational complexity. In this paper, for positioning a moving transmitter, a computationally efficient a Doppler shift estimation and compensation technique is proposed. As the proposed approach has the ability to measure the Doppler shift directly from the received signal, it does not require to use a bank of correlators to estimate the Doppler shift associated with its movement of the transmitter.

1 Introduction

Distance-based ultrasonic positioning systems (UPSs) with multilateration algorithm are used in various types of applications across a wide variety of fields. All UPSs obtain more precise location information when a mobile device (MD) is stationary compared with when it is in motion due to the Doppler effect. Most of the existing systems, e.g. the authors [1, 2] use a bank of correlators to estimate the Doppler shift associated with the movement of the MD. Such kind of technique requires high computation as in it the bank of correlators is created by shifting the frequency of the transmitted signal to different values and then each signal is cross-correlated with the received signal to find the maximum correlation peak which represents the Doppler shift. In this paper, using orthogonal frequency division multiplexing (OFDM) signal, a computationally efficient Doppler shift estimation and compensation technique for positioning a moving transmitter in a complex pendulum model is proposed. The proposed approach has the ability to measure the Doppler shift directly from the received signal, thus, it does not require to use a bank of correlators to estimate the Doppler shift associated with its movement of the transmitter.

2 Ultrasonic mobile transducer positioning

To represent the operation of an MD in an active mobile architecture, consider Fig. 1 in which, a single transmitter ($T$) is moving with velocity $v_T$ in an area deployed with $R_i$ receivers, where $i = 1, 2, \ldots, 9$, and we are interested in positioning it. Let $T$ transmits a signal with the frequency $f_{i,T}$ (which contains multiple frequency components) measured by the receiver $R_i$. As $T$ moves within the coverage area of $R_i$, it is observed that $f_{i,T}$ is Doppler shifted by $\Delta f_{d,i}$ due to the movement associated with $T$. The Doppler shift is the apparent frequency difference between the frequency at which the signal leaves the transmitter ($T$) and that at which it arrives at a receiver ($R_i$) with its amount dependent on the relative motion between them. Now, the frequency shifted signal due to the Doppler shift at $R_i$ is given by

$$s_{R_i}(t) = A_i e^{j2\pi f_{i,T}t} e^{j2\pi \Delta f_{d,i}t} + \hat{r}(t)$$ (1)

where

$$f_{i,T} = f_{i} + \Delta f_{d,i}$$ (2)

In (1), $A_i$ represents the amplitude of the signal received by the $i$th receiver, $\hat{r}(t - t_{i,R})$ is the propagation delay between the transmitter and $i$th receiver, $\hat{r}(t)$ is the additive white Gaussian noise and $t_{i,R}$ is the time-of-flight (TOF) (i.e. the travel time taken by a physical signal to propagate between a transmitter and receiver) which is given by $t_{i,R} = d_i/v_T$, where $d_i$ is the distance between transmitter and $i$th receiver and $v$ the speed of sound.

The standard TOF estimation technique is cross-correlation, in which transmitted and received signals are cross-correlated to produce the maximum value at the time delay. If $S_T$ and $S_{R_i}$ represent the transmitted and received signal (at $i$th receiver), respectively, in frequency domain, the cross-correlation between the transmitted and received signal is [3]

$$c_{i}(t) = \mathcal{F}^{-1}(S_{T}(f_{i})S_{R_{i}}(f_{i}))$$ (3)

where $\mathcal{F}^{-1}$ denotes the inverse Fourier transform and $*$ denotes the complex conjugate.

After estimating the Doppler shift on the received signal and then compensating, the final position of $T$ can be easily calculated using the multilateration algorithm described in [4]. Once the correct position of $T$ is known, the velocity of $T$ ($v_T$) can be calculated by knowing the system update rate (i.e. how many positions of $T$ are calculated per second) given by

$$v_T = \frac{d_T}{t_u}$$ (4)

where $d_T$ represents the distance between two consecutive positions of $T$ and $t_u$ the update rate.

Therefore, to calculate the accurate TOF, in other word, the accurate position of $T$ and its velocity ($v_T$), it is necessary to estimate the Doppler shift at $R_i$ and then compensate. As discussed earlier, to estimate the Doppler shift ($\Delta f_{d,i}$), in most of the existing systems, e.g. [1, 2] a bank of correlators $c_{i}(t)$ is created using (5), where the frequency of the transmitted signal $f_{i,T}$ is shifted to different values and then each signal is cross-correlated with the received signal

$$c_{i}(t) = \mathcal{F}^{-1}(S_{T}(f_{i,T} + \Delta f_{d,i})S_{R_{i}}(f_{i}))$$ (5)
where \( m = 1, \ldots , M \) represents the number of shifting required to obtain the value of \( \Delta f_{{ds}_i} \), at which maximum cross-correlation can be achieved which represents the associate Doppler shift as well as the accurate TOF. Therefore, in existing technique as a bank of correlators is required (according to (8)) to estimate the Doppler shift associated with the transmitter’s movement, it is not computationally efficient. In the following section using OFDM signal, a computationally efficient Doppler shift estimation and compensation technique for positioning \( T \) is proposed. The proposed approach has the ability to measure the Doppler shift directly from the received signal, therefore, it does not require to use a bank of correlators to estimate the Doppler shift associated with the movement of \( T \).

3 Signal design

Let the lower carrier frequency of the OFDM signal be \( f_l \) and the upper carrier frequency be \( f_u \), to maintain orthogonality, the sub-carrier gap must be at minimum \( r_s = (F_c/N) \), where \( F_c \) and \( N \) are the sampling frequency and signal length, respectively. Now the frequency-domain OFDM signal is given by

\[
S_f[n] = \begin{cases} 
A[n]e^{j\omega[n]}, & \text{where } n = \left( \frac{f}{f_s} + 1 \right) + l \\
A[n]e^{-j\theta[n]}, & \text{where } n = \left( N + 1 - \frac{f}{f_s} \right) - l \\
0 & \text{elsewhere}
\end{cases}
\]  

for \( l = 0, 1, \ldots , (f_u - f_l)/r_s \). In this equation, \( A \) and \( \theta \) indicate the amplitude and phase of each carrier, respectively, and \( n \) represents the sample points in the frequency domain. The inverse Fourier transform of \( S_f[n] \) represents the corresponding time-domain signal.

4 Doppler shift estimation and compensation technique

In the proposed method, unlike in the existing Doppler shift estimation method which requires a bank of correlators (described earlier), the Doppler shift is estimated by introducing a pilot carrier, with a significantly increased amplitude compared with those of the other sub-carriers, in the OFDM signal described in earlier section. Then, the Doppler shift is compensated in the received signal to calculate the accurate TOF using cross-correlation technique.

Initially, in (1), one of the operating frequencies is taken as the pilot carrier \( f_p \) (i.e. \( f_p \epsilon \{ f_l, f_u \} \)) that has a higher amplitude than the other sub-carriers (e.g. \( A[n] = 3A[n] \)) and is transmitted from transmitter (Fig. 1). When the transmitter is moved from its initial position, a Doppler shift is introduced in the received signal, resulting in the position of the pilot carrier being shifted from that location during transmission (which can easily be calculated as the pilot carrier \( f_p \) has a higher amplitude than the other sub-carriers). Based on the amount of the shift of the pilot carrier, the Doppler shift is estimated.

Now, if the frequency of the pilot carrier of the transmitted signal is \( f_p \) and, in the received signal, it is changed to \( f_{ds} \) at \( i \)th receiver due to the Doppler shift, the Doppler shift is given by

\[
\Delta f_{ds} = f_p - f_{ds}
\]  

Now using the information of the \( \Delta f_{ds} \) in (5) as follows, we can get the maximum cross-correlation value, hence, the accurate TOF

\[
c_i(t) = \Theta^{-1} (S_T(f_T) + (f_i/f_{ds})\Delta f_{ds}) S_R(f_i)
\]  

Therefore, in the proposed approach, the Doppler shift directly from the received signal, thus, it does not require to use a bank of correlators to estimate the Doppler shift associated with its movement in the transmitter. Now, using the TOF information of each received signal, the position of the transmitter can be calculated using the multilateration algorithm described in [4] at each update rate (i.e. how many positions of the transmitter are calculated per second). Once the correct position of the transmitter is known, the velocity of the transmitter \( v_T \) can be calculated by knowing the system update rate \( (t_u) \) given by \( v_T = d_T/d_u \), where \( d_T \) represents the distance between two consecutive positions of the transmitter.

5 Experimental setup and results

A physical pendulum was used to test the accuracy of the proposed US system when compared with the Vicon system. As the Vicon system offers sub-millimetre accuracy, we consider the results obtained from the Vicon system to be a suitable ground truth.

The experimental setup for the Vicon and proposed systems is shown in Fig. 2. This system uses 10 Bonita cameras with a near infrared (NIR) strobe light attached to each camera. A pendulum assembly was placed in the centre of the Vicon’s field of view so that the markers placed on the pendulum assembly could be viewed by a sufficient number of cameras. Although at least three markers are required for the Vicon system to define an object, we used four markers (each of diameter 12 mm) on the pendulum assembly in an ‘L’ shape, one of which is our desired tracking point (the bottom marker in Fig. 2). The bottom marker was attached to the wooden pendulum ~33 cm from the base which was attached securely to a table. Then the pendulum’s bottom point was manually pulled away from the vertical to ~90°, and then gently released, so
that the pendulum swings in a vertical plane. Data was captured from just before the pendulum started moving with a frame rate of 100 Hz. Image processing was conducted on each camera view to track the desired marker positions in 3D. The NIR strobe is reflected from the markers placed on the pendulum assembly. Each camera was connected to an Ethernet hub which supplies power and exchanges data using a single gigabit ethernet cable. A PC was connected to the same ethernet hub as the cameras and communicates with them using TCP/IP. The camera calibration was performed using a calibration object (known as a wand) containing five active markers in a known geometry. Once the calibration is completed, the origin is set using the wand. A software package called ‘Tracker’ was installed on the computer to extract the camera data and perform the motion computation.

In the US setup shown in Fig. 2, a Piezotite MA40S4S transmitter was placed at a known offset from the bottom Vicon marker, and nine Piezotite MA40S4R receivers were placed on a plane. Since ultrasonic waves are pressure waves, they lead extensive fluctuations in the sound intensity near the source due to the constructive and destructive wave interference which is known as the near field. Therefore, we placed the transmitter beyond the near field where the ultrasonic beam is more uniform which is called the far field. The separation between the pendulum assembly (i.e. transmitter) and receiver plane was ~100 cm which is far beyond the near field.

Both the transmitter and receivers operate in a narrow band of frequencies centred ~40 kHz. The transmitted OFDM signal contains 20 orthogonal frequency components ranging from 36.2 kHz ($f_1$) to 44 kHz ($f_6$) with intervals of 400 Hz ($2f_1$) and its duration is 10 ms ($N = 10,000$ in sample). Note that to estimate the Doppler shift associated with the movement of the transmitter, one of the operating frequencies in the OFDM signal was taken as the pilot carrier ($f_6 = 40.2$ kHz) that amplitude was three times higher than the other sub-carriers. During data capture of the Vicon system, the transmitter was continuously transmitting the OFDM signals with a separation of 10 ms between two successive signal bursts. Both the transmitted and received signals were captured by a measurement computing USB-1604 data acquisition module with a sampling rate of 1 M sample/s (i.e. $F_s = 1$ MHz).

For each transmission, the 3D position of the transmitter was calculated using the multilateration algorithm. During the calculation of the 3D positions of the moving transmitter, the Doppler shift was estimated using (7) and then compensated using (8). Note that as the sound velocity depends on temperature, to measure the room temperature a digital thermometer was used and the corresponding velocity was measured. The measured temperature ($\phi$) was 23°C and its corresponding velocity ($v$) was calculated as 345.10 m/s using the formula $v = (331.3 + 0.64) \phi$ m/s. Since the effect of humidity on the speed of sound is much smaller than for temperature, the effect of humidity on sound velocity was assumed to be negligible. Note that as the measurements were taken over a short period of time, the effects of variations in temperature and humidity on the sound’s velocity were assumed to be negligible. Therefore, the sound velocity was assumed to be constant during the experiments.

Although the data was simultaneously captured for both the US and Vicon systems, it was not possible to place the tracking marker at exactly the same position as the transmitter during experimentation as it would have blocked transmission of the US signal. Hence, it was placed at a known offset from the transmitter which was then compensated for during later processing. As the Vicon system provided coordinates with respect to its origin (calculated using the wand) and the US system with respect to the location of the central receiver ($R_1$), a method for transforming the former to the latter was required. To accurately achieve this transformation, three additional markers were used (as at least three markers are required for the Vicon system to define an object), one of which was placed at a known offset from the position of $R_1$ and its coordinates were also calculated using the Vicon system (Fig. 2). The known offset was compensated for during later processing. Now, if the tracked marker’s coordinates after compensation are $((x_{11}, y_{11}, z_{11}), \ldots, (x_{1n}, y_{1n}, z_{1n}))$ and the coordinates, after compensation, of the marker placed beside $R_1$ are $((x_1, y_1, z_0), \ldots, (x_n, y_n, z_0))$, the transformed Vicon coordinates will be $((x_{11} - x_1, y_{11} - y_1, z_{11} - z_0), \ldots, (x_{1n} - x_1, y_{1n} - y_1, z_{1n} - z_0))$. The markers’ height is also compensated for during this transformation. As the Vicon system and the US system might start sampling at different times, and they sample at every 10 and 20 ms, respectively, a method for synchronising the two sets of data was required. To achieve this, multiple data were captured for both systems simultaneously and checked manually for the sample when the pendulum began moving. The set of data where both systems captured data closest to the time when the pendulum movement began was chosen for analysis.

Two different experiments were conducted to evaluate our proposed method. In the first, the pendulum assembly was placed approximately parallel to the receiver plane and, in the second, at an angle of $\pm 45^\circ$ to the receiver plane. The trajectories obtained using the proposed method and the Vicon system shown in Figs. 3a and b. To demonstrate the performance of the proposed Doppler effects compensation, Figs. 3c and d show the absolute location errors (calculated using the Euclidean distance between true and estimated positions) with respect to the velocity of the transmitter from the two experiments using the proposed method. These plots show significant improvement in location errors between after the Doppler shift compensation (mean absolute error (MAE) for the first and second experiments was 3.71 and 3.47 mm, respectively) and before the Doppler shift compensation (MAE for the first and second experiments was 6.11 and 5.99 mm, respectively).

6 Conclusion

Here, a novel Doppler shift estimation and compensation technique is proposed for positioning a moving ultrasonic transmitter which is computationally efficient as it does not require a bank of correlators to estimate and compensate the Doppler shift associated with the transmitter’s movement. Experimental results show that the
accuracy of the proposed system is acceptable for high-accuracy applications.

7 References


