Micro-motion Target Detection Based on Wall Envelope Alignment in Through-the-wall Ultra-wideband Radar

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Abstract— Change Detection techniques are used to detect moving targets and mitigate the heavy clutter caused by strong reflections from stationary targets in through-the-wall radar. However the jitter of antenna platform results in phase distortion of scattered radar signal and decreased the performance of micro-motion target detection. This paper proposes an antenna platform jitter compensation method based on wall envelope alignment, aiming to detect micro-motion targets behind wall. Firstly, the antenna platform jitter model is established, then wall envelope alignment is applied to compensate antenna jitter in range direction and the jitter effect in cross direction is evaluated. Simulation and experimental results demonstrate that the proposed approach can compensate antenna platform jitter, eliminate the stationary clutter and detect micro-motion targets correctly and effectively.

1. INTRODUCTION

The detection of human targets behind obstacle has become a keen research topic in recent years and is highly desired in military and civil applications [1]. The jitter of through-the-wall (TTW) ultra-wideband (UWB) radar antenna platform caused by working engine wobble or environmental factors such as wind blowing, results in stationary targets position change in different data frames. Although the change is tiny, the residual energy of stationary targets after change detection [2] is much greater than that of moving targets, particularly of micro-motion human targets due to the low reflectivity of human and high signal attenuation of wall.

The error caused by antenna platform jitter includes antenna tilt error and translation error, and the former can be ignored due to the large beam angle of UWB radar. Literature [3] points out that when the jitter extension is less than a quarter of wavelength, the jitter in a frame time for stepped frequency continuous wave (SFCW) radar can be ignored. Besides, the jitter frequency is inferior to frame frequency, so it is reasonable that the platform was assumed to be unchanged during a frame time, and the jitter compensation is only performed between different frames.

Antenna platform jitter compensation, including envelope alignment and phase compensation, are widely investigated in inverse synthetic aperture radar (ISAR), where the antenna is fixed and target movement is decomposed into the rotation motion and translation motion. Envelope alignment methods, such as dominant scattering point method, envelope cross-correlation method and minimum entropy method [4], are aimed to eliminate the target dislocation relative to radar antenna. However, the received signal of different frame cannot be perfectly aligned because of the target moving, so the envelope cross-correlation method and the minimum entropy method can't achieve the optimal results. Dominant scattering point method is especially significant if there exists a stable and strong dominant scattering center. The envelope alignment of antenna jitter in TTW is distinct from that in ISAR in the following aspects: firstly, only the range direction jitter is considered in ISAR, while in TTW, the jitter in cross direction and in range direction are both required to compensate. Secondly, there is no dominant scattering center but a strong plane reflection of the wall in TTW, so the jitter in range direction can be compensated by the front surface of the wall who has the maximum amplitude in every frame data. However, the jitter in cross direction can't be compensated properly.

This paper proposes an antenna platform jitter compensation method based on wall envelope alignment. The remainder of this paper is organized as follows: in Section 2, the antenna platform jitter model is established. In Section 3, envelope alignment is applied to compensate antenna jitter and the jitter effect in cross direction is evaluated. Simulation and experiments are performed in Section 4. Section 5 gives the conclusion and acknowledge of this paper.

2. ANTENNA PLATFORM JITTER MODEL

A dual mode antenna with a transmitter and a receiver is applied to explore human target behind wall, as shown in Figure 1. The front surface of the wall is set to be X axis, and Y axis is perpendicular to X axis, the standard Cartesian coordinate system is established in the plane of the antenna. When m_1 and m_2 frame signals are acquired, the antenna platform is located at $A\,(x,\,y)$ and $A'\,(x+\Delta x, y+\Delta y)$, respectively. The jitter misregistration in X axis and Y axis are donated as Δx and Δy. A human target is located at $H\,(x_t,\,y_t)$ behind the wall, d and ε are the thickness and dielectric constant of the wall. To simplify the analysis, only the reflection of front surface of the wall and the human target are considered.

SFCW radar is applied with frequency from f_0 to f_P at a step Δf. T is the pulse interval time and N is the total frequency number, $f_p = f_0 + (N-1)\Delta f$, and $f_c = (f_0 + f_p)/2$ is the center frequency of SFCW. The transmitter signal $s(t)$ is expressed as

$$s\,(t) = \sum_{n=0}^{N-1} \text{rect}\left(\frac{t-(n+1/2)\,T}{T}\right) \exp\left[j2\pi\,(f_0 + n\Delta f)\,t\right] \tag{1}$$

where t is the fast time. Neglecting the transmitting loss, the received signal $s_r(t)$ is described as

$$\begin{aligned} s_r\,(t) =& \sum_{n=0}^{N-1} \text{rect}\left(\frac{t-(n+1/2)\,T-\tau_w}{T}\right)\rho_w \exp\left[j2\pi\,(f_0 + n\Delta f)\,(t-\tau_w)\right] \\ &+\sum_{n=0}^{N-1} \text{rect}\left(\frac{t-(n+1/2)\,T-\tau_h}{T}\right)\rho_h \exp\left[j2\pi\,(f_0 + n\Delta f)\,(t-\tau_h)\right] \end{aligned} \tag{2}$$

where ρ_w and ρ_h are the reflectivity. $\tau_w = 2r/c$ and $\tau_h = 2R_h/c$ are time delay, c is the speed of light in free space, and r is the range between antenna and the front surface of the wall. R_h is the equivalent distance from A to H according to literature [5], R_h is described as

$$R_h = r_2 + D\left(\sqrt{\varepsilon - \sin^2\theta} - \cos\theta\right) \tag{3}$$

where θ is the incidence angle, r_2 is the direct distance from A to H. After mixing, filtering and sampling with T interval, $s_r(t)$ is expressed as

$$s_r(m,n) = \rho_w \exp[-j2\pi(f_0 + n\Delta f)\tau_w(m,n)] + \rho_h \exp\ [-j2\pi(f_0+n\Delta f)\tau_h(m,n)] \tag{4}$$

where $\tau_w(m,n) = \tau_w((m-1)NT + nT)$, $\tau_h(m,n) = \tau_h((m-1)NT + nT)$, $m = 1,\,2,\,\ldots,\,M$ is the slow-time index, $n = 0,\,1,\,\ldots,\,N-1$ is frequency index. High resolution range profiles are achieved by performing the inverse fast Fourier transform (IFFT) of (4), the HRRP of m frame is expressed as

$$\begin{aligned} S\,(m,k) =& \rho_w \exp[-j2\pi f_0\tau_w] \exp[j\pi(N-1)(k/N - \Delta f\tau_w)] \frac{\sin\left[\pi\,(k - N\Delta f\tau_w)\right]}{\sin\left[\pi\,(k/N - \Delta f\tau_w)\right]} \\ &+\rho_h \exp\left[-j2\pi f_0\tau_h\right] \exp[j\pi(N-1)(k/N - \Delta f\tau_h] \frac{\sin\left[\pi\left[k - N\Delta f\tau_h\right]\right]}{\sin\left[\pi\,(k/N - \Delta f\tau_h)\right]} \end{aligned} \tag{5}$$

where $k = 0,\,1,\,2,\,\ldots,\,N-1$ is the range cell index, and $S(m,k)$ is the slow-time range map.

3. ENVELOPE ALIGNMENT

According to (5), there are two peak positions for ever frame of $S(m,k)$, corresponding to the front surface of the wall and human target, and the maximum amplitude of $S(m,k)$ in m_1 and m_2 frames are located at $k_1 = \Delta f\tau_{w1}$ and $k_2 = \Delta f\tau_{w2}$, respectively. So the misregistration is described as

$$k_1 - k_2 = \Delta f\,(\tau_{w1} - \tau_{w2}) = \frac{2\Delta f\Delta y}{c} \tag{6}$$

thus, the misregistration of m_1 and m_2 frames in range direction is

$$\Delta y = \frac{(k_1 - k_2)\,c}{\Delta f} \tag{7}$$

the antenna platform jitter in range direction can be compensated properly by (7). As a result of the plane reflection of the wall, the antenna jitter in cross direction which is parallel to the wall front surface has no influence on the scattered wall signal.

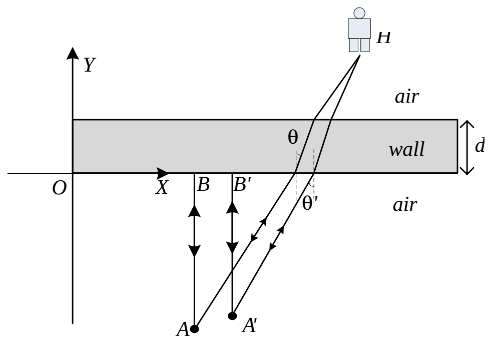

Figure 1: The scenario of human targets behind wall.

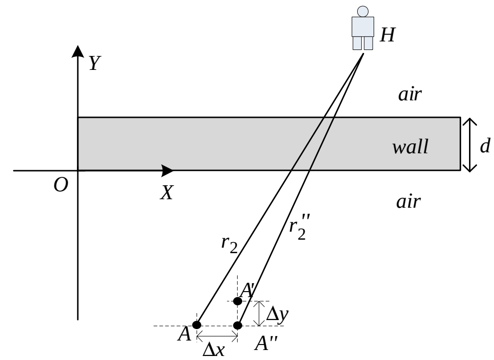

Figure 2: The scenario after envelope alignment in range direction.

After the alignment in range direction the antenna is located at $A''(x + \Delta x, y)$, as depicts in Figure 2. Δx is the antenna jitter misregistration in cross direction. Denote

$$R''_h = r''_2 + D\left(\sqrt{\varepsilon - \sin^2\theta''} - \cos\theta''\right), \quad R'_h = r'_2 + D\left(\sqrt{\varepsilon - \sin^2\theta'} - \cos\theta'\right) \tag{8}$$

where R''_h and r''_2 are the equivalent and direct range between A'' and H, R'_h and r'_2 are the equivalent and direct range between A' and H. θ'' and θ' are the incidence angle, respectively. Considering $r''_2 \gg \Delta x$, $r_2 \gg \Delta x$, $\theta'' \approx \theta' \approx \theta$, the range misregistration of m_1 and m_2 frames after envelope alignment is

$$R_h - R''_h \approx r_2 - r''_2 \approx \frac{(\Delta x)^2}{2r_2} = \frac{\Delta x}{2r_2}\Delta x \approx 0 \tag{9}$$

When the range between the target and the antenna is 10m, the antenna jitter in cross direction is 0.2 m. The misregistration after jitter compensation in range direction is about 2 mm by (9). Therefore, the antenna jitter in cross direction can be ignored when the jitter in range direction is compensated.

4. SIMULATION AND EXPERIMENTAL RESULTS

Simulation and experimental results are used to validate the proposed method in this section. A dual mode antenna located at (0, 0) is set to be random jitter both in range direction and in cross direction. Two targets are concerned: a stationary target located at (0, 8 m), and a harmonic motion target located at (0, 10 m) with amplitude 1.5 cm and frequency 0.3 Hz. SFCW is used at frequency from 1.0 GHz to 3 GHz with 2 MHz frequency steps. The signal-to-noise-ratio (SNR) of radar echo is set to be −5 dB mixed with additional white gauss noise.

Figures 3(a) and 3(b) depict the raw slow-time range map and its antenna jitter compensation results based on the envelope alignment of the stationary target. In order to improve the accuracy of alignment, only the first frame is regarded as a reference. MTI is performed by average canceller to eliminate stationary clutter of every range cell, followed by accumulation of different frame data to aggrandize the micro-motion target.

The antenna platform jitter in range direction is simulated firstly, and the jitter extension is set to be 1 cm, 2 cm, 5 cm, 10 cm and 15 cm, respectively. The accumulation results before and after envelope alignment are depicted in Figure 3(c) and Figure 3(d). The residual energy of stationary target is greater than that of micro-motion target before the compensation is performed. The residual energy of stationary is approach to zero, and the micro-motion is outstanding after jitter compensation, because of the alignment in the stationary position. The SNR of accumulated data decreases along with the antenna jitter extension increases from 1 cm to 15 cm. However, when the maximum jitter in range direction is 15 cm, the proposed method can also eliminate the effect of antenna jitter correctly.

Figure 3(e) and Figure 3(f) depict the effect of antenna jitter in cross direction. The extension in range dimension is set to be 10 cm, and the jitter extension in cross direction is set to be 1 cm, 2 cm, 5 cm, 10 cm, 15 cm, respectively. After envelope alignment in range dimension, there is no significant distinction when the jitter extension varies from 1 cm to 15 cm, so the jitter in cross alignment can be ignored.

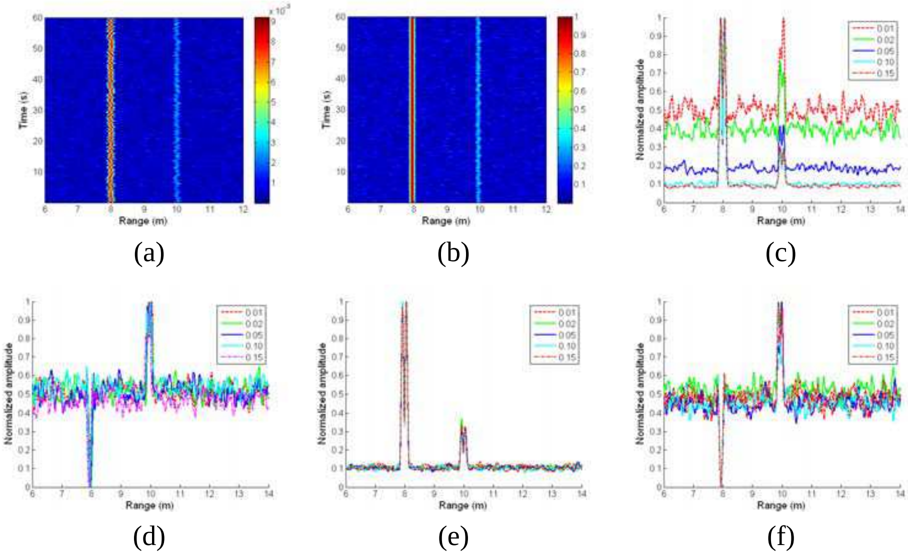

Figure 3: (a) The slow-time range map before jitter compensation; (b) the slow-time range map after jitter compensation; (c) accumulation results before envelope alignment; (d) accumulation results after envelope alignment; (e) accumulation results before envelope alignment; (f) accumulation results after envelope alignment.

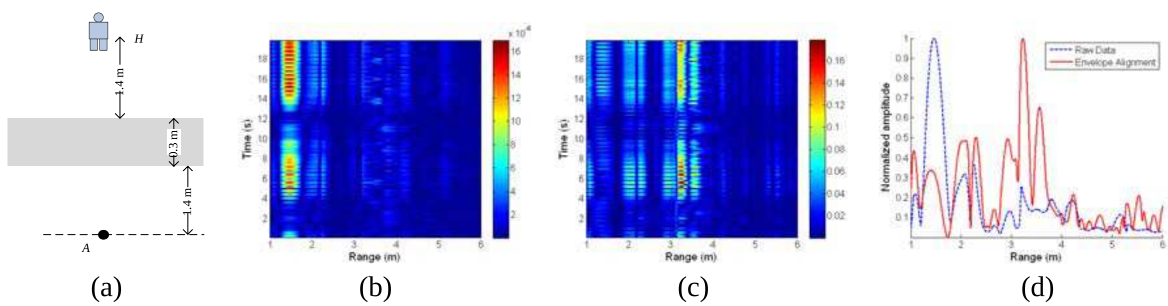

Figure 4: (a) The scenario of the experiment; (b) the slow-time range map before jitter compensation; (c) the slow-time range map after jitter compensation; (d) accumulation results.

A UWB TTW radar system is set up to test the proposed method. The antenna is on a handcart with an eletrodynamic vibrator providing the jitter of the platform, and the range between the antenna location and the front surface of the concrete wall is 1.4 m, the wall thickness 30 cm, a human stands at 1.4 m behind the wall, as depicted in Figure 4(a). SFCW radar is applied at frequency from 2.0 GHz to 2.6 GHz with 4 MHz frequency steps. The raw slow-time range map and jitter compensation results are depicted in Figure 4(b) and Figure 4(c), respectively, and the accumulation data is shown in Figure 4(d). In Figure 4(b), the residual of the stationary wall after change detection is dominant due to the antenna jitter. After wall envelope alignment, the wall residual is mitigated and the micro-motion target is prominent. Besides, the human target is located at 3.4 m in the aligned range profile, but the direct range from antenna to the human is 3.1 m. this is because when transmitting signal penetrates through the wall, the free space assumption is no longer applicable. If the thickness d and dielectric constant ε are prior known, the targets range can be compensated to the real position correctly [5].

5. CONCLUSION

The antenna platform jitter results in phase distortion of scattered radar signal and decreased the performance of micro-motion target detection. The residual energy of stationary targets is much greater than that of micro-motion targets after change detection. Antenna jitter compensation based on wall envelope alignment is performed to detect micro-motion targets. Simulation and experimental results demonstrate that the proposed method can compensate antenna jitter in range direction correctly, and the cross-direction can be ignored, and the front surface of the wall is a stable characteristic to compensate the antenna jitter.

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