Challenge and Prospect of High-speed Rail Radar Communication Integration Technologies

Shuai. Pan1,2*, De.Han. Zhang1,2, Cong.Tong1,2, and Kai. Feng1,2
1State Key Lab of Advanced Rail Autonomous Operation, Beijing Jiaotong University, Beijing, China
2School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China

Abstract. Radar plays an important role in urban public transit system, so it is of great significance to ensure the safe operation of High-speed rail. Radar communication integration technology has the characteristics of high efficiency and low energy consumption, it can improve communication quality, speed up transmission efficiency and improve detection accuracy. Firstly, this paper introduces the running scene of High-speed rail, and puts forward that radar communication integration technology has a broad application space in High-speed rail. Then it introduces radar communication integration technology and the research status, advantages and development prospects of radar communication integration technology based on linear frequency modulation (LFM). Finally, it is proposed that obstacle detection technology is one of the difficulties to ensure the safe operation of High-speed rail. Radar integration technology can be effectively applied to train obstacle detection, which is an important technical support for improving service quality and speeding up the intelligent construction of High-speed rail in the future.

1. Introduction

High-speed rail is an efficient mode of transportation in which vehicles run on the rails. In the past ten years, High-speed rail has developed rapidly. In recent years, fully automatic driving has become one of the research hotspots in the field of High-speed rail. With a high degree of automation, fully automatic driving greatly reduces the cost of personnel management and training, as well as the cost of train operation and maintenance. The speed and frequency of trains have been greatly increased, increasing passenger capacity. Improve stability and reliability, increase flexibility and reduce energy consumption[1]. In China, Beijing Yanfang Line, Shanghai Line 10, Nanjing Metro Line 7[2] all adopt fully automatic driving operation, Wuhan and other cities are also carrying out the construction of fully automatic driving routes[3].

2. Automatic Driving Framework

As shown in Figure 1 and Table 1, through the description of the application scenarios of fully automatic driving, the linkage logic between the system and user requirements as well as various systems and equipment involved in automatic driving can be further clarified.
3. Lfm-Based Radar Communication Integration Technology

Chirp signal is also called LFM signal. It is often encountered in applications such as radar, sonar, and seismic signals\textsuperscript{[7-8]}. In LFM, the frequency of the modulating signal increases linearly over the pulse duration of the signal, making LFM the most popular radar waveform due to its good range resolution and Doppler sensitivity\textsuperscript{[9]}. LFM is a spread spectrum modulation technique that does not require pseudorandom coding sequences. Since the frequency bandwidth occupied by the chirp signal is much larger than the information bandwidth, a large system processing gain can also be obtained. LFM technology is widely used in radar technology. For example, in radar positioning technology, it can increase the radio frequency pulse width, increase the average transmit power, and increase the communication distance while maintaining sufficient signal spectrum width without reducing the distance resolution of the radar rate. The chirp signal has always been a hot spot in the research of radar communication integration. The research on the integration of radar communication based on LFM has been widely studied by scholars\textsuperscript{[10-12]}. They\textsuperscript{[13-14]} have proposed different schemes to realize the integration of radar communication. They\textsuperscript{[15-16]} studied the radar detection performance and communication performance of the integrated waveform. Most of the literatures are from integrated scheme design and signal processing, integrated signal Doppler frequency offset compensation method and channel estimation method. The integrated system is evaluated and analyzed from the perspectives of communication bit error rate, signal processing calculation amount, spectrum utilization rate and communication rate. For the integration of radar communication using phase modulation for radar waveforms, there are problems such as difficulty in ensuring the orthogonality of integrated signals, inflexible parameter adjustment, and low communication transmission rate\textsuperscript{[17]}. In order to improve the integrated signal communication rate, inspired by the Orthogonal Frequency Division Multi-plexing(OFDM) and 16Quadrature Amplitude Modulation(16QAM) technologies in the field of communication, they\textsuperscript{[18-19]} actively explore OFDM and 16QAM in the field of communication integration.

Li Xiaobo et al\textsuperscript{[20]} designed an integrated chirp signal with coherent frequencies and different initial frequencies. According to the different characteristics of energy accumulation at different sampling points after the integrated signal sequence undergoes p-order Fourier transform, the communication data is modulated on different integrated chirp signals to realize the integration of radar communication. The initial frequency of the Chirp signal is f, and the i-th signal with different initial frequencies of coherence frequency can be expressed as:

\[
X(t) = a_i \cos \left(2\pi f_i t + \pi \mu_i t^2 \right) \quad -\frac{T_s}{2} \leq t \leq \frac{T_s}{2}
\]

In the formula, \(f_i\) is the modulation frequency of the signal; \(T_s\) is the time width of the signal.

Features: coherent frequency \(\mu_i t^2\), different initial frequency \(f_i\). Radar sweeps exist at the same time as communication data.

Li Xiaobo et al\textsuperscript{[20]} proposed an integrated radar communication waveform design based on FMChirp signal, which modulates the communication sub-carriers of positive and negative frequencies to a set of quasi-orthogonal chirp composite signals, and modulates the binary data sequence \(b(t) \in \{-1, 1\} 0 \leq t \leq T_s\) to the chirp signal \(s_i(t)\), that is:
among them, the signal \( s_i(t) s_i(t) \) is the carrier frequency \( f_i \) and the modulation frequency is the chirp signal of \( \mu \).

The integrated signal of radar communication can be expressed as:

\[
f(t) = \sum_{i=0}^{N-1} \text{rect}(t/T)(b_i(t))^{i+1} \exp\left(j2\pi\left(f_0 + i\omega f\right)t + (-1)^i j\pi\mu t^2\right)
\]  

(3)

Among them, when \( i \) is an even number, it is the communication subcarrier \( \left(b_i(t)\right)^{i+1} = b_i(t) \), and the modulation frequency is positive; when \( i \) is an odd number, it is the radar subcarrier \( \left(b_i(t)\right)^{i+1} = 1 \), and the modulation frequency is negative.

Theoretical analysis and simulation results show that the integrated radar communication system based on Frequency Modulated (FM) chirp signal has a good detection effect for vulgar targets under the condition that the multi-carrier spectrum overlap rate is 20%, and has low bit error characteristics. The goal is to ensure the detection performance by reducing the communication spectral efficiency. Zhou Yu et al.\[23]\ proposed an integrated radar communication signal in which the main and sub-carrier chirp signals are superimposed. The chirp signal generated by N-bit symbol mapping realizes the communication function of the sub-carrier, and the main carrier with fixed frequency modulation realizes the radar function. And all sub-carrier frequencies are designed to be smaller than the main carrier frequency to obtain good Doppler robustness, high spectrum utilization and radar resolution. Yang Yunfei et al.\[22]\ designed and implemented a communication demodulation processing scheme based on the integrated signal of continuous phase modulation and linear frequency modulation (CPM-LFM). The simulation results show that the demodulation of communication symbols can be realized under the additive white Gaussian noise. When the input signal-to-noise ratio is greater than 13.5dB, the output bit error rate can be reduced to below 10^-4. Zhao Yuzhen et al.\[23]\ proposed an integrated radar communication waveform design and processing scheme based on OFDM-chirp. The system uses blank guard intervals to replace traditional cyclic prefixes to reduce inter-carrier interference (ICI) and inter-symbol interference (ISI). Avoid false targets and improve energy utilization. In addition, channel estimation and Doppler frequency shift compensation are designed using the prior information of radar transmit signals, which can effectively combat multipath effects and Doppler frequency offsets and improve spectrum utilization. Liu Bingfan et al.\[24]\ proposed a method to map the communication information to the chirp transmission signals of different initial frequencies by changing the initial frequency of the transmitted signal of each transmitting element of the OFDM-LFM-MIMO radar. Compared with other radar integration methods, this scheme realizes omnidirectional communication and omnidirectional beam coverage. Zhang et al.\[25]\ proposed an integrated improved waveform design based on a continuous phase modulation waveform (CPM) with a constant envelope and a linear frequency modulation (LFM) signal. Through the mapping codebook at the beginning and end of the communication symbol sequence, the spectrum of the integrated waveform after loading the communication information is limited to the original bandwidth of the LFM. Avoid severe interference that exists outside the bandwidth, degrading the communication and radar performance of the integrated system. Simulations show that the improved integrated waveform and the integrated waveform without interference maintain the same good bit error rate performance even in the presence of strong interference outside the original bandwidth of the radar system. The all-in-one signal achieves a resolution comparable to that of LFM radar, and at the same time, \( h \)-CPM-LFM has better communication performance than traditional signals.

LFM signal is widely used in radar field, LFM signal can be expressed as:

\[
S_LFM(t) = A \exp\left(j2\pi f_0 t + \pi \mu t^2\right)
\]  

(4)

\( A=1 \), the chirp frequency modulation rate \( \mu = B/T_s \), and the integrated radar communication signal obtained by modulation \( h \)-CPM of the modulation information to the LFM can be expressed as:

\[
S(t) = \sum_{i=0}^{N-1} \text{rect}\left(\frac{t - iT_s}{T_s}\right) \exp\left(j2\pi\left(f_0 + \frac{\mu}{2} t^2\right)\right) \times \exp\left(j2\pi \hat{h}\left(\sum_{i=N-L-1}^{N-1} b_i \frac{t}{2LT_s} + \sum_{i=0}^{N-L-1} b_i \frac{t}{2}\right)\right)
\]  

(5)

\[
\text{rect}(x) = \begin{cases} 1, & 0 < x < 1 \\ 0, & \text{others} \end{cases}
\]  

(6)

This scheme has the same bit error rate as the 16QAM signal. Compared with BPSK-LFM and MSK-LFM modulation methods, the 16QAM-LFM radar communication integration scheme has significantly improved signal spectrum utilization, and has lower computational complexity than OFDM-LFM. However, the Doppler error tolerance of the 16QAM-LFM integrated signal decreases, which weakens the detection performance of high-speed maneuvering targets.

Linear Frequency Modulation (LFM) signals are widely used. On the one hand, as a spread spectrum signal with a large time-bandwidth product, LFM signal is widely used in various information systems. As a mature low-probability-of-interception radar signal,
LFM signal is widely used in radars of various systems. Widely. Based on the mature and reliable LFM signal application, many scholars have done a lot of research on the integration of radar communication in this direction. When the communication signals of different modulations are loaded on the radar wave, the integration of radar communication is realized, and the radar detection and communication are realized at the same time. In the increasingly severe train operation environment, the integration of radar communication can have a major application in the detection of train obstacles, reduce the risk of train operation, and improve the safety factor of the train during operation. The integration of radar communication can play an important role in reducing the volume of safety detection and information communication equipment and reducing operating costs.

4. Recent Applications of Radar Communication Integration Technology

With the rapid development of High-speed rail, the railway mileage and operation speed are constantly improving, the coverage of railway is constantly increasing, and the geological environment is becoming more and more complex, and the railway safety guarantee is also facing major challenges. At present, the security risks caused by the invasion of foreign bodies along the railway line are serious, which is the main cause of casualties caused by railway traffic accidents. The occurrence of geological disasters along the railway line will also cause serious security risks to train operation.

On January 2, 2019, when a passenger train in Denmark was running on the Great Belt Bridge, a freight train in front was affected by strong wind and the goods were dumped on the railway tracks. The passenger car couldn't brake enough to hit the goods, and the accident caused 6 deaths and 16 injuries. It was the most serious railway accident in Denmark in the past 30 years. On April 2, 2021, the No.408 train of Taiwan Railway "Taroko" collided with the engineering vehicle that slipped near the tunnel when it was running to the Daqingshui Tunnel in Hualien County, causing the train to derail. The accident killed 50 people and injured 146 people. On June 27th, 2022, an Amtrak train from Los Angeles to Chicago with 255 people on board derailed after colliding with a truck near Mendon, Missouri. At least 3 people were killed and 50 injured. On June 8, 2022, an Iranian train was going from the eastern city of Tabas to Yazd. The train collided with an excavator and derailed. There were 430 people on board. Six carriages were damaged and 17 people were killed in the accident.

In the process of railway running, due to the fast speed of trains, obstacles usually can't be braked in time, resulting in great accidents and casualties. Therefore, it is very important to detect foreign bodies in time and respond quickly. Common obstacle detection methods include key position monitoring, track detection and real-time train detection.

Figure 2. Obstacle detection process diagram

The train obstacle detection system mainly collects information about obstacles on the road ahead through various sensors, such as laser radar, infrared and millimeter wave radar, and transmits the data to the control processing system for processing. Different levels of warning are issued according to different types and distances of obstacles. The detection process is shown in Figure 2. At present, the obstacle detection system is inefficient, costly and time-consuming. The detection and perception function of radar can respond to, automatically detect and give early warning to disasters along the train line all day long, and the radar imaging function can play an important role in the study and judgment of the site situation of the address disaster. Radar communication integration technology can meet the detection and transmission functions of obstacle detection at the same time, and provide high-resolution obstacle detection results by expanding the detection range of radar. At the same time, communication technology realizes low delay transmission and real-time detection and transmission of conditions around the train, which greatly guarantees the safety of train operation. It is of great significance to apply radar communication integration technology to train obstacle detection in the future research.

5. Conclusions

At present, there are still some problems in the application of radar communication integration. Such as security and privacy issues. In the process of radar and communication integration, radar and communication spectrum are shared, which makes the privacy information contained in the communication spectrum have the risk of disclosure, and the radar detection waveform containing communication information can be intercepted. The theory of communication and perception integration is lacking. In order to describe the performance indicators and system functions of communication and perception integration, it is necessary to develop the theoretical research of communication and perception integration to unify the mathematical model of the two. For example, the relationship between detection probability, error probability and mean square error is still unclear, so it is necessary to further consider the performance index based on the actual use of radar, and further reveal its relationship with communication system theory.

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References


