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Research Article

Research into the Automatic Guidance System for AGVs Used for Logistics Based on Millimeter Wave Radar Imaging

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AGV technology has been increasingly widely used in intelligent warehousing and logistics as well as automatic chemical plants along with the accelerating industrialization and rapid advancement of the design and manufacturing industry in China. This paper elaborates on the characteristics, application scenarios, and values of AGVs used for logistics, compares and analyzes the common automatic guidance modes of the vehicle, and puts forward a design scheme of AGVs used for logistics system based on millimeter wave radar imaging technology from the perspective of enhancing the accuracy of vehicle guidance. In this scheme, millimeter wave radar, array antenna, and BP forward-looking imaging algorithm are used to present high-resolution target images. Then, according to the result of target trace condensation, the travel route is re planned to realize the automatic guidance of AGVs used for logistics. The simulation results show that the design scheme is highly accurate in target detection and imaging resolution, and thus, the scheme is effective and feasible.

1. Introduction

The popularization and application of AGVs (Automatic Guided Vehicles) have entered a new stage with the rapid development of smart factories and intelligent logistics as well as the accelerating modernization of production and logistics.

In 2016, the State Council of China issued the National Plan on Technology and Innovation, emphasizing the importance of conducting further research on the next generation of robot technology and highlighting the policy of industrializing industrial robots, making service-oriented robots become commercial products and the mass application of special robots [1]; in 2017, the Ministry of Science and Technology allocated 600 million yuan to launch the application for key special projects of "intelligent robot"; in December 2021, the Ministry of Industry and Information Technology, together with other eight departments, jointly issued the "14th Five-Year Plan for the Development of Intelligent Manufacturing," which put forward specific requirements for the development direction of the intelligent manufacturing industry and provided strong support for accelerating the construction of an intelligent manufacturing development ecosystem [2]. A number of national support policies have been issued successively, which has also laid a foundation for the development of AGV industry. Whether it is the AGV in the logistics warehousing industry or the AGV in the manufacturing industry, we should not only pay attention to the accuracy of guidance and positioning, the stability of the scheduling system, and the reliability of data collection but also connect the whole cycle of production and manufacturing, so as to lay the foundation for intelligent production. In order to enhance the accuracy of vehicle guidance, this paper proposes a design scheme of AGVs used for logistics system based on millimeter wave radar imaging, which provides a reference for the realization of "black light factor" [3]. This scheme also can meet the needs of AGV trolleys and other high-tech equipment to complete production and storage and repair tasks by themselves according to certain program requirements in the dark without lights.

2. The Application of AGVs Used for Logistics and Its Value

2.1. The Application of AGVs in Logistics. An Automatic Guided Vehicle is an unmanned transport vehicle with an automatic navigation device. It can rely on electromagnetic or optical automatic guidance devices to obtain the external environment information and its own position information and automatically drive along the corresponding path and parking position. It is widely used in storage, manufacturing, logistics, and other industries. It is one of the most effective transportation tools in modern integrated manufacturing system.

An AGV can realize the automatic handling of goods, which not only reduces the human investment and capital cost but also shortens the logistics operation cycle as much as possible, providing guarantee for the efficient automation of production, warehousing, and other links in the smart logistics industry. At present, AGV devices are mainly used in the following fields of the logistics industry:

2.2. Logistics AGV Automation in Manufacturing Production. AGV plays an important role in internal logistics and supply chain logistics. It can automatically complete the warehouse entry and warehouse exit of production materials in each link of the factory, effectively connecting the relationship between feeding and processing, production, and logistics, thus providing a guarantee for reducing resource waste and improving production efficiency. AGVs can automatically track the completion of material carrying tasks, and its route can be automatically and timely adjusted according to the changing production process, making the manufacturing on the production line more convenient and fast.

2.3. AGV Vehicles in Warehousing and Logistics. With the rapid development of automated 3D warehouses, AGV, as an automatic loading, unloading, and material carrying equipment, has been widely used in 3D warehouses. AGV is more intelligent and automatic than the traditional manual forklift truck. When an item is required in a certain stage of the warehousing operation, the operator only needs to input the relevant task instructions to the terminal system of the computer, and AGV can accept and execute the task and move the item to the designated place, which saves a lot of manpower and material resources. With the continuous improvement of the innovation ability of industrial AGV technology, many warehousing logistics companies have started to use AGVs to improve work efficiency. In the future, AGVs will play an increasingly important role in intelligent warehousing.

2.4. AGV Automatic Sorting in the Express Industry. An AGV sorting robot can continuously sort goods in large quantities, and it can also sort goods 24 hours a day, which effectively reduces the logistics costs. In the sorting process, the AGV robot sends the shelves to the workstation and then returns the shelves to the storage area after the specified goods are unloaded under the guidance of the system. Except for code scanning and packing, the whole order system does not require manual operation. AGVs can be used for accurate, efficient, and fast express sorting, which greatly saves the operation time of all links and improves the efficiency of warehouse management.

2.5. AGV Carrying in Post Office, Wharf, and Other Places. In post offices, wharves, and other places where the volume of goods is uncertain and the carrying distance and process are often changing, the AGV with automatic adjustment function can give full play to its intelligent, flexible, and automatic carrying characteristics, effectively complete the carrying tasks, reduce the use of manpower, and improve the efficiency to a new level. For example, an AGV device cannot only move in any direction in the two-dimensional plane but also includes three combined actions of clamping, pressing and pushing. It can carry nearly 800 kg of goods into the container at a time and automatically stack them for storage, which greatly reduces the labor force, improves work efficiency, and facilitates the port automation.

2.6. The Application Value of AGV Vehicles in Intelligent Logistics. AGV is an indispensable tool in intelligent logistics. Its application value mainly includes the advantages of automatic operation, automatic route optimization, safety, speed, and automatic diagnosis.

2.7. Automatic Operation and Route Optimization. Traditionally, logistics sorting mostly relies on manual work. Under the huge workload and limited time limit, it is easy to make mistakes and cause low efficiency, which has a certain impact on the production value, image, and reputation of the enterprise. After the introduction of AGV, the route can be automatically optimized and the goods can be transported to the destination according to the path specified by the system [4, 5]. This reverse work mode of finding people for goods is both easy and convenient for enterprises.

2.8. Safe, Fast, and Automatic Diagnosis. AGV works faster than man-made vehicles and has certain self-diagnosis function because it is an artificial intelligence product. Therefore, it can also be analyzed and diagnosed automatically in the operation, and once problems occur, they can be solved in time.

2.9. Commands Can Be Received. Different from ordinary carrying equipment, an AGV can receive remote instructions. As long as there is network, wireless or infrared, it can complete the task of instructions, which is very convenient.

2.10. Realize Refined, Flexible, and Information-Based Logistics Management. An AGV can be used in conjunction with modern logistics technology and can realize point-to-point automatic access. In the process of goods carrying and operation, it can ensure fine operation, flexible cooperation, and information processing, so as to make logistics management more intelligent [6–9].

3. Selection of Guidance Ways of AGVs Used for Logistics

Depending on the trolley guidance system, AGVs used for logistics automatically drive along a certain route and complete automatic loading, unloading, and carrying of equipment as well as other operations. Common guidance methods include infrared detection, ultrasonic detection, Lidar detection, trajectory detection, image recognition, and inertial navigation [10]. Different boot technologies have different working principles and applicable scenarios.

3.1. Infrared Acquisition. Pyroelectric elements are often used in this method, which is easy to detect the electrical signal released when the infrared radiation temperature changes, so as to identify the location of the object. The guidance mode is flexible, but it is easily interfered by various heat sources, light sources, part of RF radiation, and other environmental factors. With poor discrimination ability for radial motion, it is not capable of measuring the angle and cannot complete the delicate ranging function.

3.2. Ultrasonic Detection. This method uses the time when the ultrasonic wave meets with different materials after transmitting to detect the actual distance of unknown objects according to the time difference between sending and receiving. It has great advantages in the ranging of moving objects. Generally, the ranging range can reach 100 meters, but it is not accurate.

3.3. Lidar Detection. This method detects the position, speed, and other characteristics of the target by emitting a beam, which has good environmental adaptability and stable detection performance, but has high requirements for the band. At present, slam (Simultaneous Localization and Mapping) laser navigation is widely used. It takes the columns and walls in the warehouse as the positioning reference to realize the positioning guidance function.

3.4. Trajectory Detection. This method completes the guidance by identifying the track line through the photosensitive sensor, and its advantages are high sensitivity and stable function; the defect is that it can only drive on a fixed route. Besides, with weak anti-interference ability, it is easily affected by environmental factors such as different light sources and has high requirements for the working environment.

3.5. Image Recognition. This method is a new detection technology developed based on artificial intelligence technology. The recognition accuracy is unstable and is easily affected by light, weather, and other environments. For example, Amazon's Kiva robot can also scan the QR code based on the AGV on-board camera to obtain the accurate position coordinates of the goods through the QR code guidance method, so as to realize the automatic tracking.

3.6. Inertial Navigation Technology. The principle of this method is realized through the interactive communication between the gyroscope and the ground positioning block. The gyroscope can calculate the azimuth and other specific position information of the current vehicle in combination with the information fed back by the ground positioning block, compare it with the known ground route, and constantly adjust the travel angle and route of the AGV to realize the automatic tracking. This method has accurate positioning, high flexibility, and wide market application value.

In view of the above characteristics, this paper proposes a scheme of AGVs used for logistics automatic guidance system based on millimeter wave radar imaging technology. Through the millimeter wave radar with the band of 30-300 GHz, the near target point information can be accurately obtained. At the same time, combined with array antenna imaging technology and BP (Back Project) forward-looking imaging algorithm, the microwave image environment can be dynamically obtained in real time, providing accurate guarantee for the automatic guidance and positioning of AGVs used for logistics and laying the foundation for intelligent production.

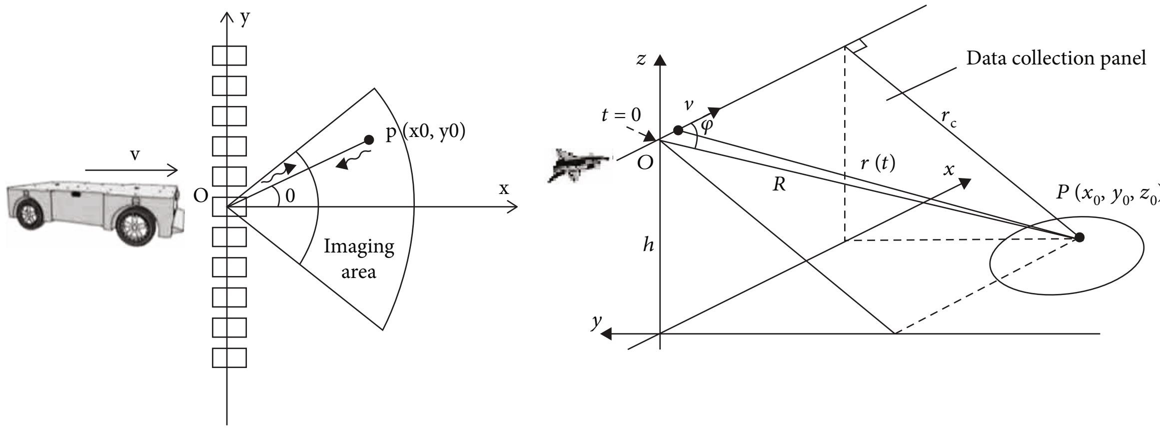
4. Millimeter Wave Radar Imaging Technology

4.1. Principle of Millimeter Wave Radar. Millimeter wave radar refers to a radar operating in the millimeter wave band of 30-300 GHz. By measuring the time difference and phase difference between the received and generated magnetic wave signals of the radar antenna, the specific information such as the azimuth, altitude, angle, and speed of the target can be calculated [11, 12]. Because of its strong recognition ability and high anti-jamming performance, it has become an indispensable means for target recognition, ranging, and velocity measurement.

4.2. Millimeter Wave Radar Imaging Technology. Because the resolution of millimeter wave radar is not high and the resolution of objects without distance difference in the same plane is not strong, a linear array antenna can be introduced into the radar to build a system working mechanism of multiple transmitter and multiple receiver, so as to greatly improve the horizontal resolution of the system and obtain well-focused images. This technology is called millimeter wave radar imaging technology.

In order to realize forward-looking imaging, it is only necessary to place a uniformly distributed array antenna (y) along the vertical driving direction in the plane (x) parallel to the ground in the vehicle to realize the scene imaging in the area directly in front of the vehicle, as shown in Figure 1(a). The array antenna continuously transmits continuous radar signals to the outside during traveling. When encountering a position object, the signal will be reflected. The reflected echo signal contains the detailed position information of the target and is received by the array antenna of the radar. After corresponding signal processing and imaging algorithms such as Fourier transform, accurate target image information can be obtained.

The equivalent linear array imaging model is transformed into a geometric model, as shown in Figure 1(b), where the X axis is the driving direction of AGVs used for logistics, which is called the distance direction in imaging; the direction perpendicular to the X axis is the Y axis, i.e., the square direction. The height of the array from the ground is h. The carrier moves at the speed v. The antenna transmits coherent pulses at equal intervals T_{PRT}. These transmitted pulses are sent by antenna array element which is lined by $\Delta x = v \cdot T_{\text{PRT}}$. The coordinates of point target P in xoy plane are $P(x_0, y_0)$. Millimeter wave radar imaging



(a) Imaging diagram

(b) Equivalent linear array imaging geometric model

FIGURE 1: Radar imaging antenna array and imaging model.

technology involves two important parameters: range resolution and azimuth resolution.

4.3. Range Resolution. According to the theory of ambiguity function, the radar range resolution ρ_r is determined by the radar signal bandwidth B_r [13], and

$$\rho_r = \frac{c}{2B_r}, \tag{1}$$

where c is the light speed. The wider the signal bandwidth is, the better the target image resolution is.

4.4. Azimuth Resolution. The high azimuth resolution is obtained by compressing the azimuth chirp signal generated by Doppler Effect, and the key of radar imaging technology is to greatly improve the azimuth resolution. According to the geometric relationship, the distance function between radar and point target $P(x_0, y_0)$ is

$$r(t) = \sqrt{{r_c}^2 + (vt - x_0)^2}. \tag{2}$$

By analyzing the phase generated by distance, it can be concluded that the azimuth instantaneous frequency (or frequency process) is

$$f_a(t) = f_{dc} + k_a t^2 |t| \le \frac{T_a}{2}, \tag{3}$$

where the Doppler center frequency is $f_{dc} = 2v \cdot \cos(\phi)/\lambda$ and the azimuth direction modulation frequency is $k_a = -2 v^2 \sin^2\phi/\lambda r_c$.

Azimuth bandwidth B_a of radar echo signal can be expressed as

$$B_a = |k_a T_a| = \frac{2v^2 \sin^2(\phi)}{\lambda \cdot r_c} \cdot T_a. \tag{4}$$

Thus, the azimuth resolution obtain is

$$\rho_a = \frac{v}{B_a}. \tag{5}$$

5. Automatic Guidance Design of AGVs Used for Logistics Based on Millimeter Wave Radar Imaging

The key factor for AGVs used for logistics to realize high-precision automatic guidance and positioning is the accurate collection of environmental data by sensors, although the visual camera has high resolution. However, due to the use of optical band electromagnetic wave, it has poor penetrability and diffraction and is easily affected by ambient light, especially in the "black light factory." In addition, it is more susceptible to weather when used in outdoor environment. Millimeter wave imaging radar is less affected by natural factors and has higher resolution [14]; it can realize the accurate detection and collection of all-weather and all-weather environmental data around the vehicle and has become the preferred technology for automatic guidance of AGVs. Therefore, this paper proposes a scheme of AGVs used for logistics automatic guidance system based on millimeter wave radar imaging technology. The guidance process is shown in Figure 2.

Through the array antenna installed in front of the vehicle, AGVs used for logistics send out electromagnetic waves. When encountering the surrounding obstacles or vehicles, the reflected signal is received by the antenna, and the electromagnetic wave is sent to the signal processing module for radar imaging processing. At the same time, the target is automatically detected to obtain the information about the environment around the vehicle and the location of the obstacles. Then, according to the result of target trace condensation, the travel route is replanned to realize the automatic guidance of AGVs used for logistics. The specific process is described as follows.

5.1. Radar Imaging. Radar imaging is realized by the BP back projection algorithm in the imaging model; that is, the target point information is scanned by continuously

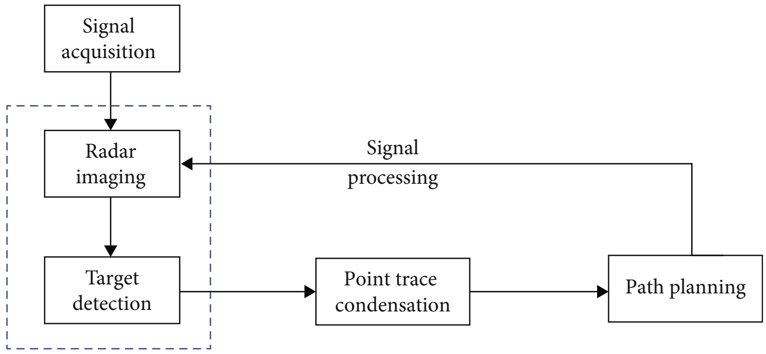


Figure 2: Diagram of automatic guidance of AGC vehicles used for logistics.

transmitting electromagnetic wave signals from the radar. After acquiring the echo signals returned at different azimuth times, coherent accumulation is used to distinguish the imaging points in the range dimension. On this basis, interpolation is used to complete the pulse compression in the azimuth dimension and finally form the target image.

5.2. Target Detection. MIMO (Multiple-Input Multiple-Output) radar is used to transmit and receive multiple signal beams, and the target characteristics are intensively analyzed through multi-channel echo signals, which effectively improves the clutter suppression ability. The slow target detection can better obtain accurate target slant distance, speed, and angle, which lays a foundation for improving system performance and enhancing the accuracy of target recognition and detection [15].

5.3. Point Trace Condensation. According to the radar imaging and target detection results, the range, azimuth, intensity, and speed of obstacles and moving targets relative to AGVs used for logistics are extracted. However, at this time, the target information contains false targets or repeated targets, so it is necessary to perform point trace condensation on the targets, that is, to eliminate the repeated targets and false targets and to focus on the face targets or volume targets. Through data preprocessing, effective target information is finally obtained for subsequent path planning of AGVs used for logistics.

5.4. Path Planning. According to the target point information obtained after signal processing, the distance from the target object is calculated in the grid environment in combination with particle swarm optimization evolutionary algorithm to solve the azimuth, angle, and velocity data of AGV. At the same time, the updated position information is sent to signal processing, and then the distance, speed, and other information of the target point are updated according to the millimeter wave radar imaging and target detection results at the next time, so as to complete the re planning of the AGVs used for logistics path until the optimal path is found [16–19].

Table 1: Simulation parameters.

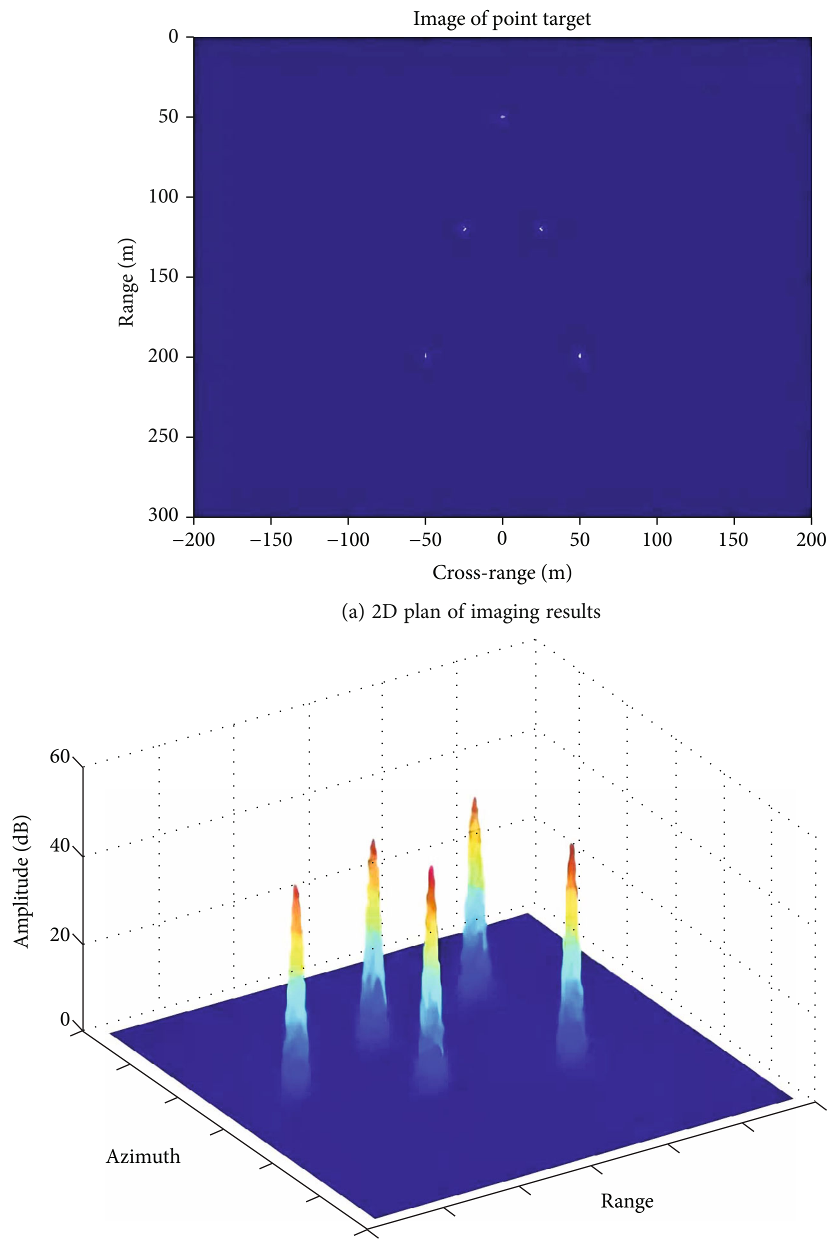
Parameter	Value
Center frequency	35 GHz
Signal bandwidth	500 MHz
Beam azimuth angle	20°

6. Millimeter Wave Radar Imaging Algorithm and Simulation Analysis

6.1. BP Imaging Processing Flow. The remarkable feature of BP imaging algorithm is that it has high accuracy, has no special requirements for radar track, and can be realized by straight-line track or circular track. It is especially suitable for the case of large motion error, and both strip mode and spotlight mode are applicable. It is an imaging algorithm with superior performance. The basic principle of this algorithm in the AGVs used for logistics automatic guidance system is to project the radar echo data back to each pixel of the imaging area, then coherently stack the echoes at each pixel, and finally obtain the image of the object imaging area. The specific steps of algorithm implementation are described as follows.

6.2. Range Pulse Compression. It can be seen from the analysis in Section 2.2 that the range resolution is inversely proportional to the bandwidth of the transmitted signal. The wider the bandwidth, the smaller the resolvable size, indicating the higher the resolution performance. Radar imaging uses this principle to transmit a large bandwidth LFM signal and uses the matched filtering method to realize pulse compression, so as to obtain a higher range resolution and improve the efficiency of AGV automatic guidance.

6.3. Range Interpolation. The range compressed data is interpolated to further subdivide the range resolution unit. Generally, the interpolation can be realized by frequency domain processing technology; that is, after the data is transformed to the range frequency domain by FFT (Fourier Transform), the data tail is filled with zero, and then the IFFT (Inverse Fourier Transform) processing is performed to change it back to the time domain to realize the range interpolation.



(a) 2D plan of imaging results

(b) 3D plan of imaging results

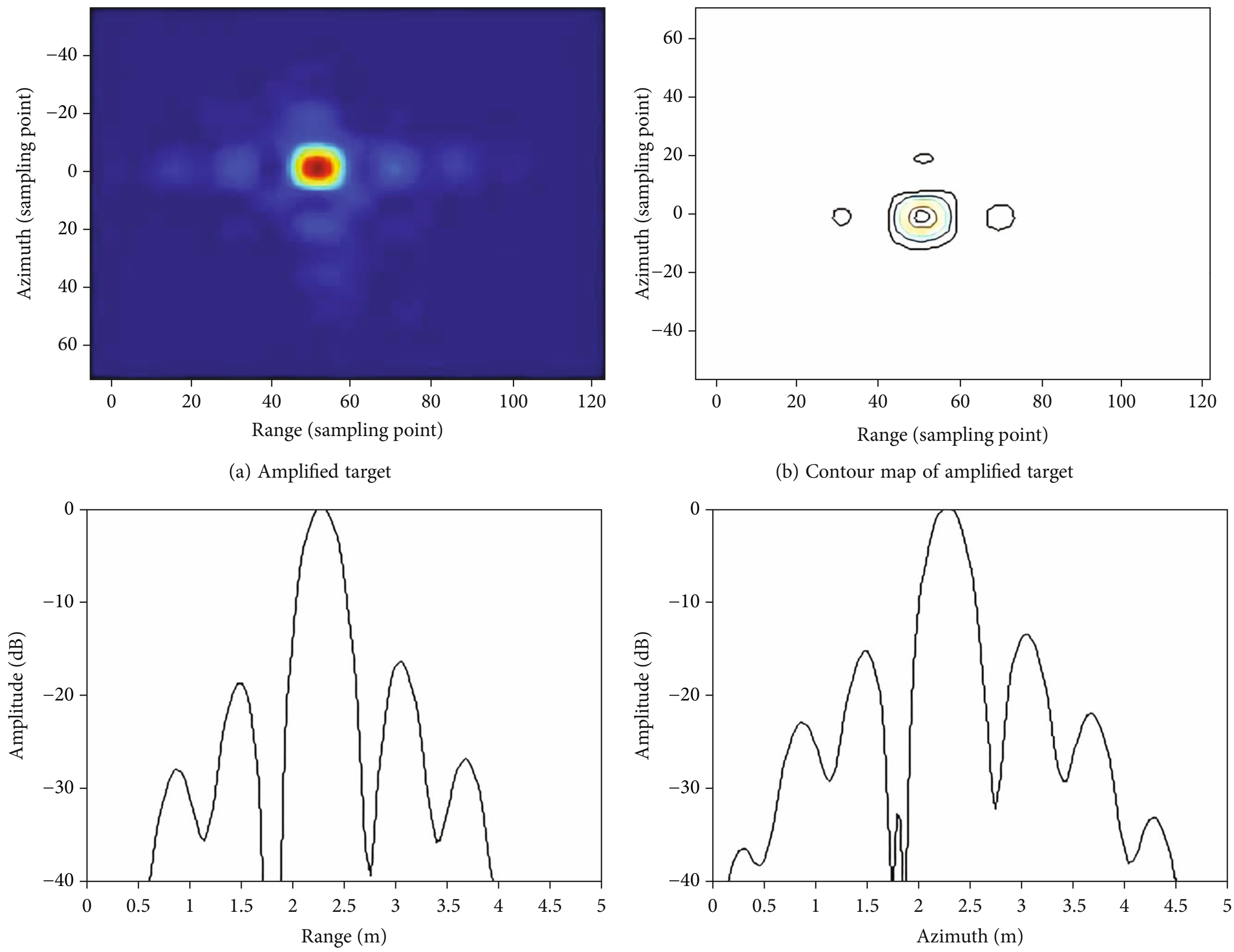
FIGURE 3: Point target imaging results.

6.4. Meshing. The imaging area is divided into grids and the coordinates of each grid point are obtained. This step is to prepare for backward projection processing. Each pixel in the final SAR (Synthetic Aperture Radar) image represents a grid.

6.5. Backward Projection. Calculate the distance R_{ij} between the radar and each grid point at each azimuth time (the time when the pulse is transmitted) and the two-way delay based on starting distance ($t_{ij} = 2 * R_{ij}/c$). Then in the data collected at the current azimuth time, conduct back projection t according to$_{ij}$; i.e., find the data with distance equivalent to R_{ij}. These data are received by the grid point at this time.

6.6. Coherent Superposition. The back projection data at each azimuth time is phase compensated, and the compensated data becomes the same phase, where the phase compensation factor is exp $(j * 4 * \pi * R_{ij}/\lambda)$. At this time, the data vectors after phase compensation are added to realize the coherent superposition of the data, traverse all grid points, and finally get the SAR image of the whole imaging scene.

6.7. Simulation Verification. The reliability of BP imaging algorithm under millimeter wave radar imaging model is simulated and verified by MATLAB simulation software. In the simulation, five point targets within the range are selected for simulation imaging. The coordinates of point targets are P1 (50, 0), P2 (120, -25), P3 (120, 25), P4 (200,



(a) Amplified target

(b) Contour map of amplified target

(c) Distance section

(d) Direction section

Figure 4: Analysis diagram of point target P1.

Table 2: Performance analysis of point target P1.

	Integral sidelobe ratio (dB)	Peak sidelobe ratio (dB)	Resolution (m)
Distance	-11.87	-13.53	0.31
Direction	-11.63	-13.49	0.32

-50), and P5 (200, 50). The simulation sets the signal center frequency as 35 GHz, the bandwidth as 500 MHz, and the azimuth angle of the beam as 20 degrees. The main simulation parameters are shown as Table 1.

The imaging diagram of the five point targets is shown in Figure 3. From the two-dimensional plan of the imaging results in Figure 3(a) and the three-dimensional diagram in Figure 3(b), it can be seen that the five target points have obtained good focusing imaging.

In order to evaluate the quality of the acquired image, the P1 target is further enlarged and analyzed, and the enlarged results, contour map, and profile along the distance and azimuth of the P1 image are obtained, respectively, as shown in Figure 4. It can be seen from the imaging results of point targets and the enlarged figure that the simulated targets have achieved good focusing after BP imaging processing. In the enlarged figure, the internal structure of main lobe and side lobe can be clearly seen, and the side lobes are orderly arranged in the horizontal and vertical directions [20]. The range profile and azimuth profile are similar to Sinc pulse function, and the imaging resolution is high.

The imaging parameters such as integral sidelobe ratio are obtained from the range profile and azimuth profile of P1 point, and the image quality index is shown in Table 2. It can be seen from the data in the table that the imaging resolution, peak sidelobe ratio, and integral sidelobe ratio are consistent with the theoretical analysis.

The above analysis shows that the BP imaging algorithm under the millimeter wave radar imaging model can obtain a good two-dimensional high-resolution image; i.e., millimeter wave imaging technology can be better applied to AGVs used for logistics design, with accurate positioning and high imaging resolution.

7. Conclusion

This paper designs an automatic guidance scheme for AGVs used for logistics based on millimeter wave radar imaging technology. In terms of hardware, the millimeter wave radar imaging model composed of millimeter wave radar and array antenna is used to achieve accurate target positioning; In terms of algorithm, the BP forward-looking imaging algorithm is used to focus high-resolution images and jointly complete the high-precision positioning function of AGVs used for logistics. The whole system completes the accurate measurement of the object position through the above millimeter wave imaging technology and then replans the travel route according to the result of the condensation of the target point trace, continuously updates the distance, speed and other information of the target point, and completes the re planning of the AGVs used for logistics path until the optimal path is found. Simulation experiments of MATLAB show that the design scheme has high imaging resolution and strong reliability and can overcome the disadvantages of conventional AGVs used for logistics, such as high cost, long cycle, and inflexible route. At the same time, it can be applied to more complex environments such as "black light factory" or outdoor. The experimental verification of this design scheme will be the research focus in the next stage. The experimental verification of this design scheme will serve as the research foundation of next stage for the construction of AGVs system, the optimization algorithm of path selection, and the development of AGV system simulation software.

Data Availability

No data were used to support this study.

Conflicts of Interest

The author declares that there is no conflict of interest in this paper.

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