






Research Article

Detection of Illegal Movement in Radioactive Material Transportation Security Systems

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Received 30 December 2020; Revised 14 May 2021; Accepted 28 August 2021; Published 10 September 2021

Academic Editor: Michel Giot

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The loss and theft of radioactive material in transport can be attributed to the illegal movement. In order to distinguish it from the movement caused by the turbulence of the transportation vehicle, this paper proposes the criterion of “illegal movement” as the movement of radioactive materials outside the transportation compartment. Since the interior of the compartment is generally a metal environment, this paper proposes wireless signal strength data as a sensing method. The wireless signal strength data is filtered and converted into distance data. We construct a spatial triangle perpendicular to the top and sides of the compartment based on the distance data. When the radioactive material is inside the compartment, the angle between its corresponding point and the top plane of the compartment is less than 90°. Once it moves out of the compartment, the angle will be greater than 90°. Based on this, a sensing method of “illegal movement” based on spatial triangles is proposed. The simulation research shows that the scheme proposed in this paper is feasible.

1. Introduction

The transportation of radioactive material is characterized by long path, complex road condition, and limited response power [1]. In addition, the security of radioactive materials during transportation is more fragile than during storage [2]. Loss of radioactive material during transportation occurred in several countries in the last decade. For example, a package containing two A424-9 Ir-192 industrial radiographic sealed sources was lost during transportation on October 9, 2020. Tracking indicates the last known package location was a common carrier hub in Memphis, TN [3]. IAEA guidance document on transport security-No.9 G was published in July 2020 [4], in which the per package approach for specifying the transport security level is applied. It points out the requirements for the detection of illegal movements. The security system should provide detection of any unauthorized removal of the package at basic transport

security level, provide detection of any attempted unauthorized removal of the package at enhanced transport security level, and provide immediate detection of any attempted unauthorized removal of the package at additional security measures.

Since the transport security level can be determined according to the package, we believe that it is necessary to decentralize security measures to the package, not only just the conveyances of transportation. As one of the implementation methods, giving the radioactive material “self-security intelligence” [5, 6] (adding intelligent electronic device to the radioactive material container), detect its illegal approach and illegal movement through the connection between a single package (security device) or multiple packages (security device) of radioactive material. We proposed a new vehicle transportation security system based on self-security intelligence functions in literature [1]. This article [1] is mainly aimed at the passive problem of the

security system during the transportation of radioactive materials and proposes the theory of self-security intelligence, that is, to realize perception, decision-making, and response on the radioactive materials themselves (containers), and put forward the implementation plan on the transportation vehicle. The biggest innovation of this article is to put forward a security concept different from traditional transportation security and propose active protection for the original passive protection.

This article and article [7] both focus on the loss and theft of radioactive materials during transportation. The detection distance of the two follows the order from far to near, and the detection time is from long to short (if the same communication method is used). Based on the illegal movement detection method of failure detection [7], when the individual self-security security device installed on the radioactive material container is fixedly connected to the container itself, it can be considered that the movement of the individual self-security security device is the movement of the radioactive material (specific fixed connection technology not discussed here). When the radioactive material and the transportation compartment can maintain a communication link, regardless of the damage of the device itself, the distance between the two is not far. When the distance between the radioactive material and the transport carriage is too far, causing the communication between the two to be interrupted, the failure detection method can be used to detect at this time.

The detection distance threshold set in this paper is on the side wall of the carriage. Considering the error, it can be detected only by a certain distance beyond the side wall of the carriage. At this time, there is still a considerable distance from the communication failure, so the detection distance is shorter than the article [7], and the alarm time is shorter.

2. Analysis of Illegal Movement Behavior

The Regulations on the Road Transportation of Radioactive Materials promulgated by China in 2016 (revised edition) stipulates the requirements for transport vehicles [8]. The approved load of 1 ton or less is a van (as shown in Figures 1 and 2) or a closed truck.

According to Security of Radioactive Material in Transport published by IAEA in 2020 [4], the illegal movement detection functions of the security system are as in Table 1.

Radioactive material (container) will leave the compartment after being stolen or lost, that is, move outside of the compartment. The destruction of the radioactive material (container) will also destroy the self-security device on it. As a result, the self-security device cannot feel its position from the compartment. It can also be considered that it has moved to an infinite distance, also out of the compartment. All of the above movements can be regarded as “illegal movements.” During normal road transportation, as shown in Figures 2 and 3, uneven roads cause bumps, and the radioactive materials container will have a certain degree of displacement in the compartment. But this is normal movement. Illegal movement is abnormal movement. In



FIGURE 1: Radioactive material carrier 1.



FIGURE 2: Radioactive material carrier 2.

order to distinguish it from normal movement, “illegal movement” here is defined as moving outside of the compartment. Because the transportation compartment is a metal space environment, positioning technologies such as GPS [9, 10] or BeiDou [2] will not receive signals and become invalid.

There are two main types of positioning methods based on wireless signal strength data (RSSI): ranging and non-ranging. The positioning method based on ranging first converts the wireless signal strength into the distance between two nodes and then uses related geometric methods, such as the relationship between three sides or triangles for positioning [11]. The positioning method based on non-ranging only determines the number of hops between nodes in the network, then estimates the approximate distance of each hop, then multiplies it to get the approximate distance, and then uses geometric relationships to locate [12]. The accuracy of the latter positioning method is lower. In this paper, based on the wireless signal strength (RSSI) data, a space triangle method is proposed to locate the radioactive material in the transport compartment to identify whether it moves outside of the compartment.

3. Model and Method of Illegal Movement Detection Based on Space Triangle

Arrange anchor nodes in the transport compartment. The anchor nodes broadcast wireless positioning signals in turn. After receiving the wireless positioning signals, the self-

TABLE 1: Targets of illegal movement detection function under different transportation security levels.

	Basic transport security level	Enhanced transport security level	Additional security measures
Detection	Provide detection of any unauthorized removal of the package	Provide detection of any attempted unauthorized removal of the package	Provide immediate detection of any attempted unauthorized removal of the package

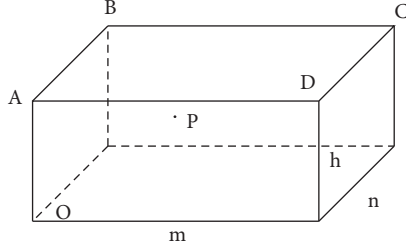


FIGURE 3: A simple scheme of the different elements of the detection model.

security devices extract the corresponding wireless signal strength and convert it to a spatial distance. Use these distances to construct a spatial triangle and determine whether the self-security device has moved outside of the compartment. This judgment result is sent to the bicycle security platform via the wireless network to provide data support for its alarm decision-making.

3.1. Illegal Movement Detection Model Based on Space Triangle. The four anchor nodes are installed in the four corners of the compartment close to the roof (in order not to affect the wireless communication effect, the antenna is at least 10 cm away from the roof and the inner wall of the compartment), in a rectangular arrangement, as shown in Figure 4. Point A is at the front left, and point B is at the front right. Point C is at the right rear, and point D is at the left rear. The area of ABCD represents the internal area of the compartment. The radioactive material (container) is placed in a single layer, and the self-security device is installed on the top of the container; particularly, the antenna cannot be blocked. The self-security device P forms a triangle ABP, BCP, CDP, and DAP with points A, B, C, and D. Due to the different heights of the radioactive materials (containers), point P and points A, B, C, and D will not be on the same plane. In Figure 3, m represents the length of the compartment, n represents the width of the compartment, h represents the height of the compartment, and point O represents the lower left corner of the compartment.

When the self-security device P is located in the compartment, as shown in Figure 4, cross point P to make a vertical plane with the planes ABCD and ABO, cross the line AB at point E, and cross the line CD at point F. PE is perpendicular to AB in the triangle PAB. PF is perpendicular to CD in the triangle PCD. In triangular PEF, the angles $\angle PFE$ and $\angle PEF$ are both less than 90° . The cosine law of $\angle PFE$ is as shown in the following formula:

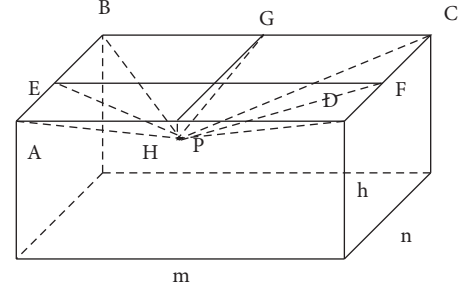


FIGURE 4: Point P is located.

$$2 * m * d_{PF} * \cos \angle P_{FE} = (d_{PF})^2 + (d_{EF})^2 - (d_{PE})^2. \quad (1)$$

If it does not leave from the rear of the car, then point P has no projection online AB, and there is no formula (1). The left part of formula (1) will be greater than 0. When the self-security device P is moved to outside from the rear door of the compartment, as shown in Figure 5, the angle $\angle PFE$ in triangular PEF is greater than 90° . The left part of formula (1) will be less than 0. Therefore, in theory, formula (2) can be used as a criterion for the point P to move out of the rear door of the compartment.

$$(d_{PF})^2 + (d_{EF})^2 - (d_{PE})^2 < 0. \quad (2)$$

Cross point P to make a vertical plane with the planes ABCD and ADO, and cross the line BC at point G, and cross the line AD at point H. PG is perpendicular to BC in the triangle PBC. PH is perpendicular to AD in the triangle PAD. In triangular PGH, the angles $\angle PGH$ and $\angle PHG$ are both less than 90° .

Similar to the above reasons, the criterion for point P moving out from the front of the compartment is as formula (3), the criterion for point P moving from the left side of the compartment as formula (4), and the criterion for point P moving out from the right side of the compartment as formula (5).

$$(d_{PF})^2 + (d_{EF})^2 - (d_{PE})^2 < 0, \quad (3)$$

$$(d_{PH})^2 + (d_{GH})^2 - (d_{PG})^2 < 0, \quad (4)$$

$$(d_{PG})^2 + (d_{HG})^2 - (d_{PH})^2 < 0. \quad (5)$$

In the triangle APB, the area is expressed as follows:

$$S_{APB} = \frac{1}{2} d_{AB} d_{PE} = \frac{1}{2} n d_{PE}. \quad (6)$$

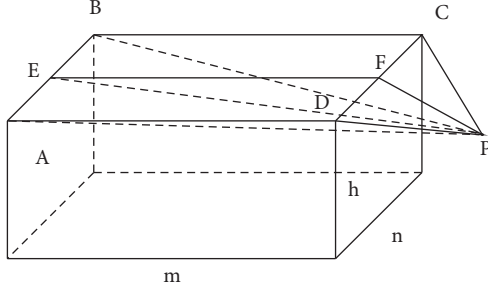


FIGURE 5: Point P is located outside, in the backdoor of the compartment.

According to Heron's formula, the area of a triangle APB can also be expressed as follows:

$$S_{ABP} = \sqrt{L(L - d_{AB})(L - d_{AP})(L - d_{BP})}. \quad (7)$$

L is half of the circumference, which can be expressed by the following equation:

$$L = \frac{(d_{AB} + d_{AP} + d_{BP})}{2}. \quad (8)$$

According to formulas (6) and (7), the following formula is obtained:

$$d_{PE} = \frac{2\sqrt{L(L - d_{AB})(L - d_{AP})(L - d_{BP})}}{n}, \quad (9)$$

where d_{PF} , d_{PG} , and d_{PH} can be obtained similarly. d_{AP} , d_{BP} , d_{CP} , and d_{DP} can be calculated by wireless signal strength.

3.2. Illegal Movement Detection Method Based on Space Triangle

- (1) The 4 anchor nodes broadcast frame with their own addresses every 1S to provide RSSI. The time interval between the four anchor nodes to send frames is very short, and the time difference can be basically ignored.
- (2) According to formula (10), if the noise is filtered out, the distance d can be obtained through the RSSI value [12].

$$RSSI_{(k,i)} = A_k - 10\eta_k \log(d_{ik}) + v_{(k,i)}. \quad (10)$$

$RSSI_{(k,i)}$ indicates the wireless signal strength of the data sent by anchor node i received by node k ; A_k represents the wireless signal strength value one meter away from the anchor node i ; η_k indicates the environmental attenuation factor; d_{ik} indicates the distance from node k to anchor node i ; $v_{(k,i)}$ represents a noise signal with a mean value of 0.

- (3) After filtering the mean value of RSSI data between anchor nodes, A_k and η_k are calculated. The self-security intelligent device is, respectively, placed at a distance of 1 meter from the anchor node k (near the center of the compartment) to actually measure the

average value of RSSI. This value is taken as A_k . Along the neutral line of the rear door of the carriage, measure the average RSSI at 10 meters away from the k anchor node, and then derive η_k .

- (4) Taking into account the multipath effect, path attenuation, and occlusion effects of the wireless signal in the vehicle compartment, there may be an error in the RSSI value, which generally conforms to the Gaussian distribution. Therefore, it is necessary to perform mean filtering on the RSSI data on the self-security device and then calculate it according to the following formula:

$$d_{ik} = 10^{((A_k - RSSI_{(k,i)})/10\eta_k)}. \quad (11)$$

According to formula (11), the distances d_{AP} , d_{BP} , d_{CP} , and d_{DP} can be calculated.

- (5) According to formula (9), the distance d_{PE} can be obtained. In the same way, d_{PF} , d_{PG} , and d_{PH} can be obtained.
- (6) Calculate the differential of formula (11); we can obtain the following formula:

$$\Delta d_{ik} = 10^{((A_k - RSSI_{(k,i)})/10\eta_k)} * \left(-\frac{1}{10\eta_k}\right) \Delta RSSI_{(k,i)}. \quad (12)$$

Simplifying formula (12), we get the following formula:

$$\Delta d_{ik} = d_{ik} * \left(-\frac{1}{10\eta_k}\right) \Delta RSSI_{(k,i)}. \quad (13)$$

According to formula (13), when the RSSI deviation value is constant, the greater the distance d , the greater the distance deviation Δd . Therefore, the d_{PE} deviation is greater than d_{PF} , so the right part of formula (1) measurement error d_{err} should be a negative number. Formulas (2)–(5) are changed to formulas (14)–(17).

$$(d_{PF})^2 + (d_{EF})^2 - (d_{PE})^2 < d_{errset}, \quad (14)$$

$$(d_{PE})^2 + (d_{EF})^2 - (d_{PF})^2 < d_{errset}, \quad (15)$$

$$(d_{PH})^2 + (d_{GH})^2 - (d_{PG})^2 < d_{errset}, \quad (16)$$

$$(d_{PG})^2 + (d_{HG})^2 - (d_{PH})^2 < d_{errset}, \quad (17)$$

where d_{errset} is the error threshold, which is a negative number. Ensure that there is no false alarm in the carriage, and the alarm is required when leaving a certain distance.

3.3. Wireless Signal Strength Data Filtering. When there is less radioactive material in the transport vehicle, the wireless signal is less blocked by obstacles, but the multipath effect

will be caused by reflection. When there are more radioactive materials in the transport vehicle, the wireless signal is more affected by the obstruction. Multipath effects and obstructions will cause fluctuations in wireless signal strength. This can be seen as noise superimposed on the RSSI value. This noise characteristic generally corresponds to Gaussian noise. Direct use of the raw RSSI data obtained by the measurement will result in larger errors. Therefore, the signal measurement value must be smoothed and preprocessed to eliminate noise.

Here, the mean filtering method is used for filtering. For the 12 RSSI data received from an anchor node, the maximum and minimum values are removed, and the average of the remaining 10 values is calculated. It is shown in the following formula:

$$\overline{RSSI} = \frac{1}{10} \sum_{i=1}^{10} RSSI_i. \quad (18)$$

where \overline{RSSI} represents the average value of RSSI and $RSSI_i$ represents the i -th RSSI measurement.

4. Simulation

Hongyu brand HYJ5060XFS-JX radioactive material van is shown in Figure 6. The external dimensions are $6350 \times 2120 \times 2800$ (mm), and the size of the cargo compartment is $4260 \times 2005 \times 1730$ (mm). The height of the compartment from the ground is 450 mm.

The simulation area is larger than the size of the compartment and is set as $20\text{ m} \times 1.9\text{ m}$ (assuming that the antenna is 0.1 m away from the inner wall of the compartment). It is assumed that the antenna of the self-security device is 1.5 m away from the top of the compartment. Take the plane where the antenna height is located as the coordinate plane and the lower left corner as the origin to establish a coordinate system. The horizontal and vertical intervals of the grid lines are both 0.5 meters. The entire simulation area is shown in Figure 7. The positions of the four anchor nodes inside the compartment are A (0.15 m, 0.1 m, 1.5 m), B (0.15 m, 1.85 m, 1.5 m), C (3.45 m, 0.1 m, 1.5 m), and D (3.45 m, 1.85 m, 1.5 m).

The thief moved the radioactive material container to the back door of the compartment at a speed of 2.25 m/s. When it was next to the door, the speed slowed down. After getting off the car, he still walked at a speed of 2.25 m/s. The movement trajectory of the abovementioned radioactive material is indicated by a hollow circle in Figure 8. The solid point represents the d_{err} value, which is expressed as follows:

$$d_{err} = (d_{PF})^2 + (d_{EF})^2 - (d_{PE})^2. \quad (19)$$

It can be seen from Figure 8 that when the radioactive material is inside the compartment, the d_{err} value is positive. When it moves outside the back door of the compartment, the d_{err} value is negative. The d_{err} value is monotonically decreasing. So as long as the appropriate d_{errset} value is set, equation (14) is true. When the d_{errset} value is set to -5.7956 , and when the radioactive material moves to 14.3 meters from the front of the compartment, that is, 10.1 meters from



FIGURE 6: HYJ5060XFS-JX radioactive material van.

the compartment, the security system can correctly identify the illegal movement. The radioactive material was found missing when it was far away from the compartment. The reason is that the mean filtering algorithm is adopted and RSSI values are sampled only once every second.

If the thief leaves the compartment at a speed of 0.5 m/s, the simulation results are shown in Figure 9. When the d_{errset} value is set to -2.434 , and when the radioactive material moves to 5.3 meters from the front of the compartment, that is, 1.1 meters from the compartment, the security system can correctly identify the illegal movement.

After many simulations, when the radioactive material moves from the inside of the compartment to the outside through the back door of the compartment, the d_{err} is monotonously decreasing. So as long as the appropriate d_{errset} value is set, formula (14) is valid. When radioactive materials are moved from the front and other sides of the compartment, formulas (15), (16), and (17) can also be valid. The farther away from the compartment, the greater the d_{err} value, so the more sensitive the criterion. It should be noted that when the radioactive material is too far away from the compartment, the wireless signal is too weak. This may cause the self-security device to fail to detect. At the same time, the vehicle security platform will also detect the failure of the communication with the self-security device, and a direct alarm will be issued.

5. Test Analysis and Discussion

The experimental system consists of 4 Zigbee terminal nodes as anchor nodes, and one coordinator node as blind node, which is directly connected with the computer. The unauthorized removal detection program and interface based on the space projection angle are realized on the computer. The carriage has only one door, which is located in the rear of the carriage. The internal space dimensions of the carriage are as follows: 3.16 meters in length, 1.74 meters in width, and 1.66 meters in height. After measurement, the height of the bottom of the carriage from the ground is 0.86 meters. During the experiment, the anchor nodes were pasted by transparent glue on the inner wall of the carriage at a height of 1.59 meters, and the layout is shown in Figures 10 and 11. Figure 10 shows the arrangement of anchor nodes at the rear

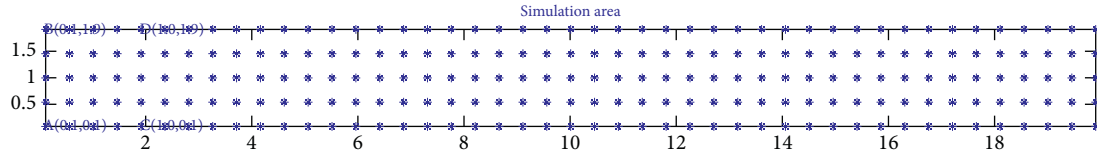


FIGURE 7: The entire simulation area.

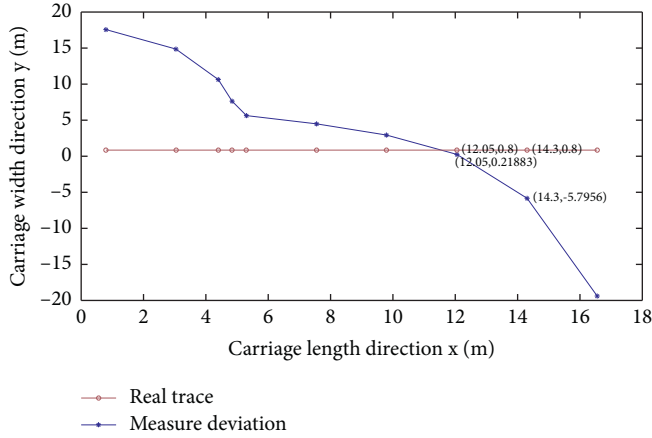


FIGURE 8: Simulation results.

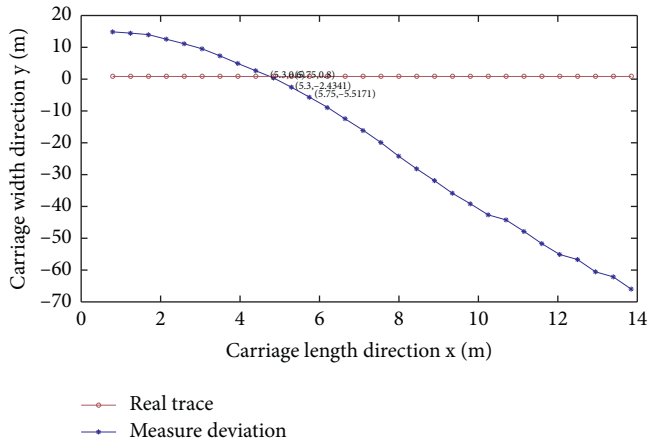


FIGURE 9: Simulation results at 2.25 m/s walking speed at 0.5 m/s walking speed.

of the carriage, which is 0.15 meters away from the frame. Figure 11 shows the arrangement of the anchor nodes in the front of the carriage, which is also 0.15 meters away from the front of the carriage. The anchor node and the blind node use the same hardware, including Zigbee modules, antennas, buzzers, backplanes, and batteries. In order to facilitate the test, the self-security device is placed in the vehicle compartment 1 meter away from each anchor node, and the measured RSSI is filtered by the mean value as the A value, as shown in Figures 12 and 13. After measurement, the A values of the four anchor nodes are 207 dbm, 207 dbm, 206 dbm, and 206 dbm, and the η values are 2.41, 2.41, 2.43, and 2.43, respectively.



FIGURE 10: Rear anchor node in the carriage.



FIGURE 11: Front anchor node in the carriage.



FIGURE 12: Parameter determination process.



FIGURE 13: A value measurement process.



FIGURE 14: Illegal detection test.

The main purpose of our experiment is to verify whether the security system can alarm after the self-security device (blind node) leaves the carriage, and how far away it will alarm. Adjust the threshold to ensure that there is no false alarm in the carriage. After actual measurement, Hderrset, Lderrset, Rderrset, and Bderrset can be selected as -2000 . A person exits from the carriage with a Zigbee coordinator node and stays away (the moving speed is very slow, and the RSSI signal is stable for a period of time after every 0.1 meters of movement). This behavior simulates the loss or theft of the radioactive material container with the electronic equipment from the compartment, as shown in Figure 14. Check the alarm information on the computer, as shown in Figure 15. It is worth pointing out that when the distance

from the left edge of the carriage is less than 0.2 meters, there will be two alarm signals at a certain distance away from the carriage, namely, “illegal movement of the rear” and “illegal movement of the left.” There is a similar phenomenon on the right.

Table 2 shows the test data of the security device away from the carriage in three directions: rear, left, and right. Keep away from the center line of the width and length of the carriage, and keep 1.0 meter above the ground when far away, that is, 0.08 meters above the plane of the bottom of the carriage. For example, when moving rear, the width from the left side of the carriage is 0.86 meters. When moving away from the left and right, the length from the rear of the carriage is 1.58 meters.

串口设置

端口: COM3
波特: 38400
数据: 8
校验: NONE
停止: 1

参考节点参数

	X坐标	Y坐标	Z坐标	Ak	nk
节点A	0	0	1.59	207	2.41
节点B	0	1.6	1.59	207	2.41
节点C	2.86	1.6	1.59	206	2.43
节点D	2.86	0	1.59	206	2.43

放射性物品到参考节点的RSSI值

节点到A的RSSI值: 188.000000
节点到B的RSSI值: 191.000000
节点到C的RSSI值: 179.000000
节点到D的RSSI值: 190.000000

阈值设置

Hderrset: -2000
Lderrset: -2000
Rderrset: -2000
Bderrset: -2000

移动结果显示

	非法移动
Hderr	-8756.914063
Lderr	4262.604492
Rderr	-4246.245117
Bderr	8773.273438

开始 重新计算 结束

FIGURE 15: Illegal detection test result.

TABLE 2: Illegal detection results based on spatial projection angle.

	Alarm distance (unit: meter)									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Rear of the truck	2.6	2.5	2.5	3.4	2.7	2.5	2.8	3.0	2.6	3.1
Left of the truck	1.1	1.3	1.4	1.1	1.2	1.3	1.4	1.2	1.3	1.3
Right of the truck	1.2	1.4	1.2	1.3	1.3	1.2	1.2	1.4	1.2	1.2

Tests have shown that the farthest distance for the alarm when moving to the rear of the truck is 3.4 meters. The farthest alarm distance of the failure detection method in literature [13] is 26 meters. In comparison, the performance of the method proposed in this paper is better. When changing the d_{errset} threshold, while maintaining communication, the smaller the d_{errset} setting (that is, the more negative), the farther the alarm distance will be, but the higher the reliability. It will also alarm when it is far away from the left and right, and when it is very close to the carriage. This is because the iron sheet material of the carriage shields the signal. When away from the front, the security system will directly alarm. Because the enclosed compartment shields the wireless signal, the front of the vehicle cannot receive the wireless signal.

6. Conclusions

In view of the different characteristics of normal movement and illegal movement during the transportation of radioactive materials, the movement to the outside of the compartment is proposed as the detection standard for "illegal movement." Four anchor nodes are installed in the

compartment, and the self-security device receives wireless signals. The wireless signal strength data is filtered and converted into distance data. Based on the distance data, a spatial triangle is constructed, and an "illegal movement" sensing method is proposed. The simulation and field test show that the method proposed in this paper is feasible.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding this publication of this study.

Acknowledgments

This study was funded by China's 13th Five-Year Nuclear Energy Development Project "Individual Self-Security Intelligence of Radioactive Material."

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