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Proposal of a Train Localisation Method Based on the Addition of Cubic Code

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Abstract

Train localisation is a crucial aspect of railway signalling systems, essential for ensuring safety and efficiency. Traditional methods mainly depend on track circuits, tachometers, and balises. These systems often encounter cost, maintenance, and accuracy challenges despite their usefulness. This study introduces an innovative approach to accurate train localisation using cost-effective onboard sensors, notably a one-dimensional Light Detection and Ranging sensor mounted atop train carriages. This arrangement allows for precise measurement of the distance from the train to the lowest part of surrounding structures. Introducing a small, recognisable marker, called cubic code, on these structures aids in their identification. Our methodology achieved a 100 % success rate in cubic code detection across 320 evaluations. This research highlights the feasibility of employing cubic codes and onboard sensors for effective train localisation.

Keywords: train localisation, one-dimensional light detection and ranging sensor, onboard sensor fusion, addition of a tiny specific structure, moving average, robust estimation.

1 Introduction

Train localisation is critical to modern railway systems [1, 2], especially for controlling trains closely and safely with technologies like moving blocks [3] and automatic operation. It helps manage how trains move and stop, making it very important for keeping trains running smoothly and safely. However, the reliance on diverse sensors, such as track circuits, balises, and tachometer generators [2], introduces significant challenges. For example, it is a problem that high costs and maintenance demands are associated with widespread sensor deployment across tracks. Moreover, the accuracy issues stem from wheel slip and slide — exacerbated by the inherent low friction between steel rails and wheels. These problems lead to a significant challenge: finding better and cheaper ways to detect train locations anytime. This need shows that developing new solutions for train localisation is essential.

To address the challenges, researchers have been combining various onboard sensors like Global Navigation Satellite System (GNSS), inertial sensors, LiDAR (Light Detection and Ranging) sensors, and tachometer generators through a method known as sensor fusion [4–6]. This combination is not only more cost-effective but also able to avoid problems associated with ground-fixed equipment. Each type of sensor, however, has its limitations. GNSS's performance can be hindered by the local environment [7], while inertial sensors may become less accurate over time. We must select and combine these sensors effectively, utilising their unique strengths. LiDAR sensors, for instance, stand out for their ability to measure distances by analysing reflected light, proving especially useful in dimly lit conditions, such as tunnels, where cameras fail. Past studies have explored mounting these sensors on trains to identify track features, including switches and tunnels [7, 8]. A novel approach uses LiDAR to read markers between tracks, offering a fresh perspective on train localisation [9]. This method is also less susceptible to the accumulated errors of other sensors, making it capable of replacing the role of conventional balises. In this sense, we can construct virtual balises using a sensor fusion approach.

In addressing the shortcomings of current train localisation methods, it's clear that both LiDAR sensors and the GNSS and inertial sensor fusion face distinct challenges. LiDAR's reliance on physical features for detection significantly limits its utility on featureless tracks, reducing its localisation accuracy. Additionally, its standard measurement frequency is too low for practical use on high-speed railways, as the train's speed outpaces the sensor's ability to detect smaller structures accurately. Due to signal obstruction, the GNSS and inertial sensor combination struggles in extended GNSS-dark areas. Inertial sensors are prone to accumulating errors that further degrade localisation precision. These issues collectively underscore a pressing need for advancements in train localisation technology, specifically designed to overcome the limitations faced by high-speed rail systems and in areas with poor GNSS coverage.

This paper introduces a novel train localisation method using a 1D LiDAR sensor for high-speed measurements to surpass traditional methods in accuracy and cost.

Our approach employs "cubic code" [10] identifiers attached to structures above the tracks, offering improved localisation precision. By replacing traditional balises with cubic codes, we leverage their design for enhanced accuracy at lower costs. We detail the implementation of this strategy, highlighting the advantages of 1D LiDAR sensors combined with cubic code and its efficacy throughout experiments using a scaling mock-up. The main contributions of this paper include refining the cubic code extraction method, applying robust estimation for reading cubic code, and validating the proposed method's effectiveness with expanded experimental setups and an increased number of trials.

This paper is structured as follows: Section 2 introduces the limitations of previous studies, and the problem considered in this study is formulated. Section 3 explains the proposed method for train localisation based on cubic code addition, which improves the existing methods. Section 4 presents experiments using a scaling model to demonstrate the usefulness of the proposed method. Section 5 concludes with future prospects.

2 Limitations of the application lines of previous studies and the relationship between the proposed method

This section addresses the challenge of defining a train localisation method suitable for various railway environments. Our proposed solution is designed to be resilient, particularly when existing methods have limitations.

Conventional GNSS-based strategies face difficulties in areas where signals are obstructed, such as dense urban zones with skyscrapers, mountainous regions, and subway lines [7]. Alternative measures like inertial sensors and tachometer generators are typically deployed in these scenarios. Yet, these alternatives have drawbacks, such as gradually accumulating errors with prolonged use. Then, we have to maintain costly ground-based equipment such as balises or track circuits for accuracy. This reliance increases the overall cost due to the augmented sensor requirements without fully resolving the challenges posed by GNSS signal blockages.

LiDAR sensors may offer a solution for navigating GNSS-dark areas without accumulating errors. However, we have to be aware of the train speed and the LiDAR sensor's measurement frequency. A previous study employing 2D LiDAR sensors for tunnel navigation did not necessarily highlight a speed limitation of the sensor itself but tested it at speeds up to 70 km/h [8]. Another literature examining 3D LiDAR sensors indicated a decline in marker reading accuracy at relatively low speeds, such as 35 km/h [9]. The challenge lies in interpreting data at higher speeds, particularly for high-speed railways exceeding 300 km/h. These studies suggest further research to enhance LiDAR's utility at higher velocities.

Recognising these constraints, our study proposes a method suitable for high-speed railways, including sections impervious to GNSS. By applying 1D LiDAR sensors

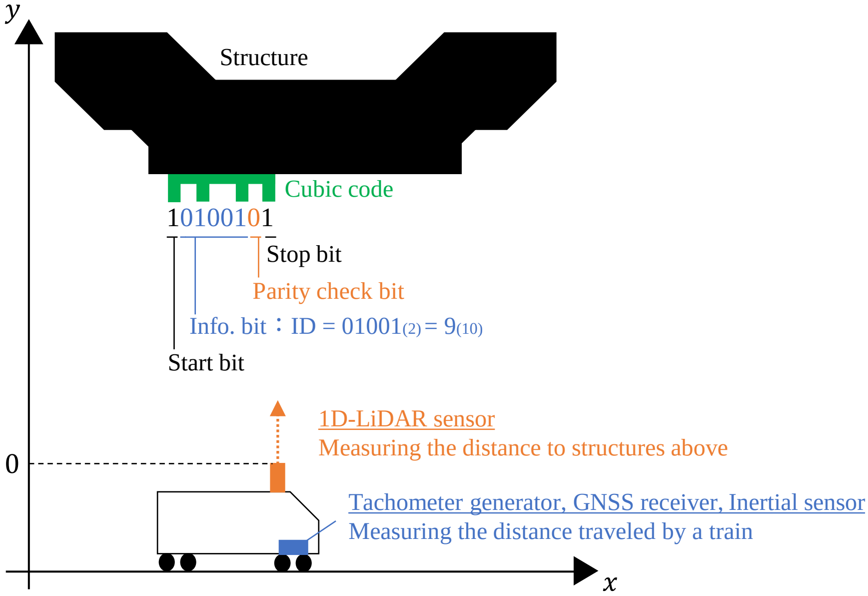

Figure 1: Concept of proposed method; cubic code addition to existing structures and reading them with onboard sensors.

combined with cubic code, our method extends the range of feasible railway lines beyond those achievable in prior studies, effectively negating the necessity for a physical ground presence. This method is poised to offer a more adaptable, cost-efficient solution for train localisation, paving the way for broader application across various challenging rail environments.

3 Proposal of a train localisation method based on the addition of cubic code to structures

3.1 Overview of the proposed method

In this section, we introduce a refined method for train localisation that expands upon our earlier work using cubic codes for identifying structures [10] [11]. We enhance existing structures by attaching cubic codes to their base, allowing onboard sensors to gather precise location data. Figure 1 shows the concept of the proposed method. The cubic code is interpreted in binary numbers; a lower position translates to a 1, and a higher position to a 0. This enables the simplification of obtaining accurate structural information.

Our approach involves two key steps: first, we extract the cubic code from the detailed measurement data of a structure, and second, we interpret the extracted cubic code. A flowchart in Figure 2 visually explains these steps. We mainly focus on the actions taken after the measurement data of a structure is gathered. This aspect of our method represents a departure from previous studies [11]. Before introducing these

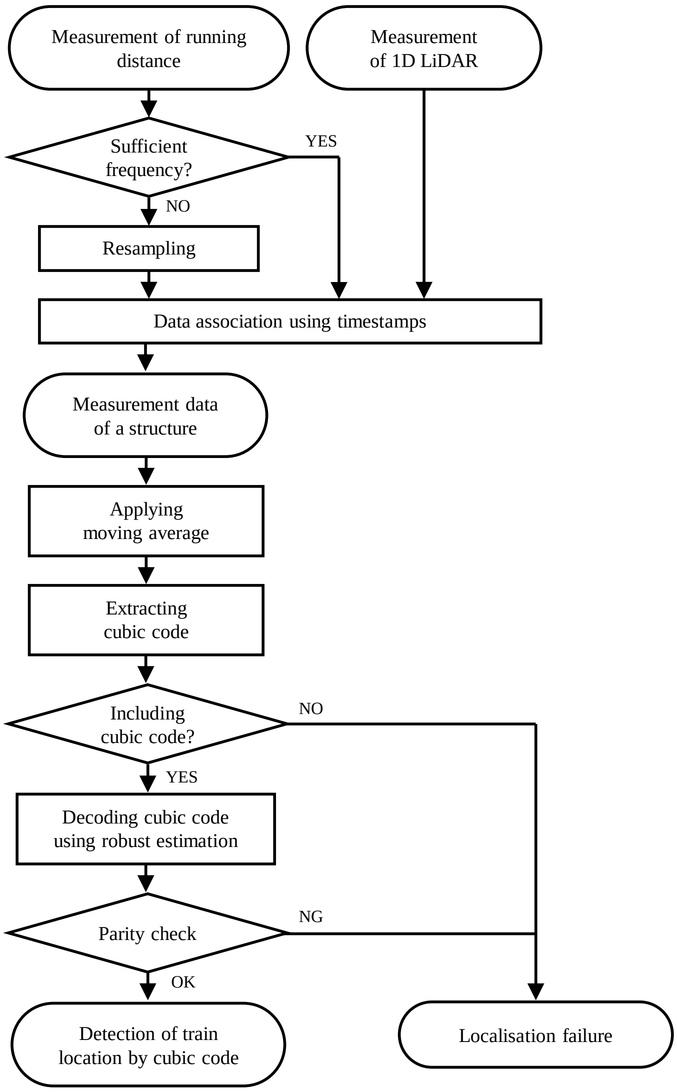

Figure 2: A flowchart of the proposed method.

two steps, we discuss the shape of the cubic code below.

3.2 The structure of a cubic code

In this subsection, we describe the characteristics of the cubic code's shape, which plays a crucial role in our localisation method. The structure of a cubic code, as illustrated in Figure 3, is defined by several key features:

- Bit Arrangement: Bits are placed at intervals of l_1 along the x-axis. The total length of cubic code in the x-axis is l_8.

- Y-Axis Representation: The vertical position of each bit indicates its value; a

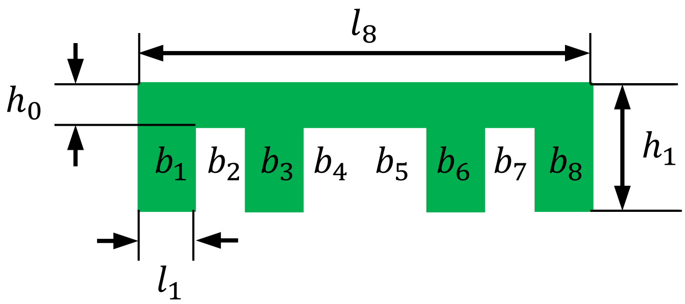

Figure 3: The structure of a cubic code. (This figure is a revision of the figure in the reference [10].)

lower position corresponds to 1, while a higher position signifies 0. For example, in Figure 3, b_1, b_3, b_6, b_8 indicate 1, while the other bits indicate 0.

- Start and Stop Bits: The sequence begins and ends with specific bits known as the start bit (b_1) and the stop bit (b_8), respectively. These are always set to 1, framing the data sequence and ensuring clear demarcation.

- Information Bits: Positioned from the second (b_2) to the sixth bit (b_6), these form the core of the code, representing the structure's unique ID in binary numbers. The length of these bits is flexible. This flexibility allows for a broad range of identifiers.

- Parity Check Bit: The seventh bit (b_7) serves as a parity check bit. This bit is a safeguard against errors within the information bits. It is set to 1 if the number of ones in the information bits is odd and 0 if it is even. This simple mechanism enhances the reliability of the data encoded by the cubic code.

In this paper, the values for l_1, l_8, h_0, and h_1 are defined empirically as $0.2\,\mathrm{m}$, $1.6\,\mathrm{m}$, $0.1\,\mathrm{m}$, and $0.5\,\mathrm{m}$ respectively. The cubic code offers robust and efficient means of conveying structure-specific information through these features.

3.3 Extraction of cubic code from the entire measurement data decreasing the effect of outliers and noises

This subsection details the process for extracting cubic codes from measurement data. Past research has identified that measurement noise can sometimes prevent the successful extraction of cubic codes [10]. To address this issue, we utilise a moving average technique. Moving average processing can smooth the data by averaging five adjacent points around each measurement point along the x-axis in terms of their y-axis values. This smoothing process makes the cubic code extraction process more robust to outliers and measurement noises.

Below is a detailed description of the method for extracting cubic code. The separation distance in the y-axis direction of the lowest part of the existing structure is represented by y_{min}. The separation distance y_{sep0} of the bit representing 0 is expressed by the following equation;

$$y_{sep0} = y_{min} - h_0. \tag{1}$$

In the same way, the separation distance of the bit representing 1, y_{sep1}, is expressed by the following equation;

$$y_{sep1} = y_{min} - h_1. \tag{2}$$

Since the start and stop bits are always 1, the start and end points of the cubic code can be identified by detecting these bits. The separation distance between y_{sep0} and y_{sep1} calculated from Equations (1) and (2) is expressed by the following equation;

$$y_{mid} = \frac{y_{sep0} + y_{sep1}}{2} = y_{min} - \frac{h_0 + h_1}{2}. \tag{3}$$

Points lower than y_{mid} in the y-axis direction always contain a start and stop bit. The complete cubic code can be obtained by extracting all measurement points from the first to the last point in the extracted points.

In addition, our method also checks the extraction status of cubic code. The total length in the x-axis direction of the cubic code extracted by the above operation is l_8^*. This is the measured value of l_8 in Figure 3. If l_8^* and l_8 significantly deviate from each other, it is likely that the extraction of cubic codes from the measurement data has failed. This could be due to measurement outliers or the absence of cubic code. Thus, we determine that the cubic code has been extracted successfully only if equation (4) is satisfied; otherwise, we consider the extraction to have failed. We decode the cubic code only upon successful extraction.

$$\frac{9}{10} l_8 \leq l_8^* \leq \frac{11}{10} l_8. \tag{4}$$

3.4 Decoding extracted cubic code using M-estimation

In this subsection, we explain the technique for decoding cubic code that has been correctly extracted. This process involves determining the numbers represented by each bit and detecting errors in the information bits using the parity check bit.

First, we should use measurement data without applying the moving average process when decoding cubic code. In certain situations, the previously mentioned moving average process can reduce the accuracy of the measurement. For example, Figure 4 displays an enlarged section of the cubic code. In the figure, orange dots represent data before applying the moving average, while blue dots represent data after. The accuracy of measurements at points where the y-axis height of the measurement points changes can be said to decrease in the blue dots. These points indicate that the moving average process should be used only when extracting cubic code from entire measurement data.

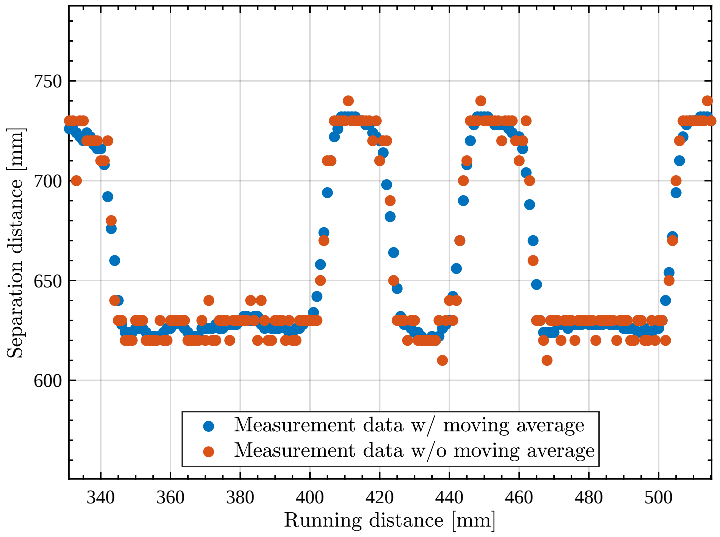

Figure 4: Cubic code in measurement data after applying moving average.

Next, We describe how to determine the numbers represented by each bit. The following equation expresses the length l_1^* in the x-axis direction for one bit;

$$l_1^* = \frac{1}{8} l_8^*. \tag{5}$$

The extracted cubic code is divided into sections for each l_1^* in the x-axis direction. In each section, we estimate the average height of measurement points, denoting μ. If μ is lower than y_{mid}, the bit of that section should represent 1; otherwise, the bit seems to represent 0.

In this paper, we propose a more accurate method of estimating μ using M-estimation [12]. M-estimation is robust to outliers and provides maximum likelihood estimation. M-estimation improves the robustness of outliers by reducing the contribution of values far from the mean of the points. We use Bisquare type of weighting.

For the Bisquare type, we consider the following equation [12]. c is a constant.

$$\psi(y-\mu) = \begin{cases} (y-\mu)\{1-(\frac{y-\mu}{c})^2\}^2 & (|y-\mu| < c) \\ 0 & (|y-\mu| \geq c) \end{cases}. \tag{6}$$

Let S_i $(i = 1, ..., 8)$ denote each section, and N_i denote the total number of measuring points contained in S_i. Let $\boldsymbol{p}_{ij} = (x_{ij}, y_{ij})$ $(j = 1, ..., N_i)$ denote each measuring point. We solve the following equation to estimate μ;

$$\sum_{j=1}^{N_i} \psi(y_{ij} - \mu) = 0. \tag{7}$$

If the estimated $\mu \leq y_{mid}$, we judge that the bit b_i in that interval represents 1, and if $\mu > y_{mid}$, we judge that it represents 0. The cubic code can be decoded by applying these procedures to each interval.

After determining the numbers each bit represents using the method mentioned above, error detection is performed using the parity check bit (b_7). Data is considered error-free and accurate if it meets one of these conditions:

- If the total number of ones from b_2 to b_6 is odd and b_7 is 1.
- If the total number of ones from b_2 to b_6 is even and b_7 is 0.

If no errors are detected, train localisation is successfully achieved. However, if an error is found, that particular cubic code is not used for train localisation. This mechanism provides a reliable way to verify the accuracy of the information bits, playing a crucial role in maintaining the integrity of the train localisation process.

4 Experiments with scaling models

4.1 Experimental setup

To validate the effectiveness of our proposed method, we conducted experiments using linear motors and a scaling model. This is a practical choice to avoid the high costs and logistical challenges of implementing cubic codes on actual railway structures. Our model operates at a $\frac{1}{10}$ scale, offering a manageable testing approach while maintaining relevance to railway applications.

However, we must consider a reduction in measurement accuracy proportional to the inverse of the scale of the cubic code. This is because the resolution of the 1D LiDAR sensor used in our experiments isn't adjusted to match this scaling. To mitigate this issue and improve the precision of our data, we've adjusted the height (y-axis) of the cubic code to a $\frac{1}{5}$ scale in our experimental setup. This adaptation aims to counterbalance the resolution limitation of the 1D LiDAR sensor, ensuring our experimental results more accurately reflect the potential of the proposed localisation method in real-world applications.

Figure 5 shows an overview of the experimental setup. In our experimental setup, a 1D LiDAR sensor is attached to the moving magnet of the linear motor. This sensor points upwards to measure distances, and a model structure with a cubic code on its underside is placed over the track of the linear motor. By adjusting the motor's speed and the 1D LiDAR sensor's measurement frequency, we collect data every time the motor moves by $1\,\mathrm{mm}$. This setup mirrors real-world conditions where a measurement would be taken for every 10mm a train travels. Such precision is within the capabilities of current market-available 1D LiDAR sensors, ensuring our experimental design closely replicates practical train movement scenarios.

4.2 Experimental results

320 experiments confirmed the success or failure of cubic code extraction and decoding. Table 1 shows the detailed experimental results. The experiments were performed

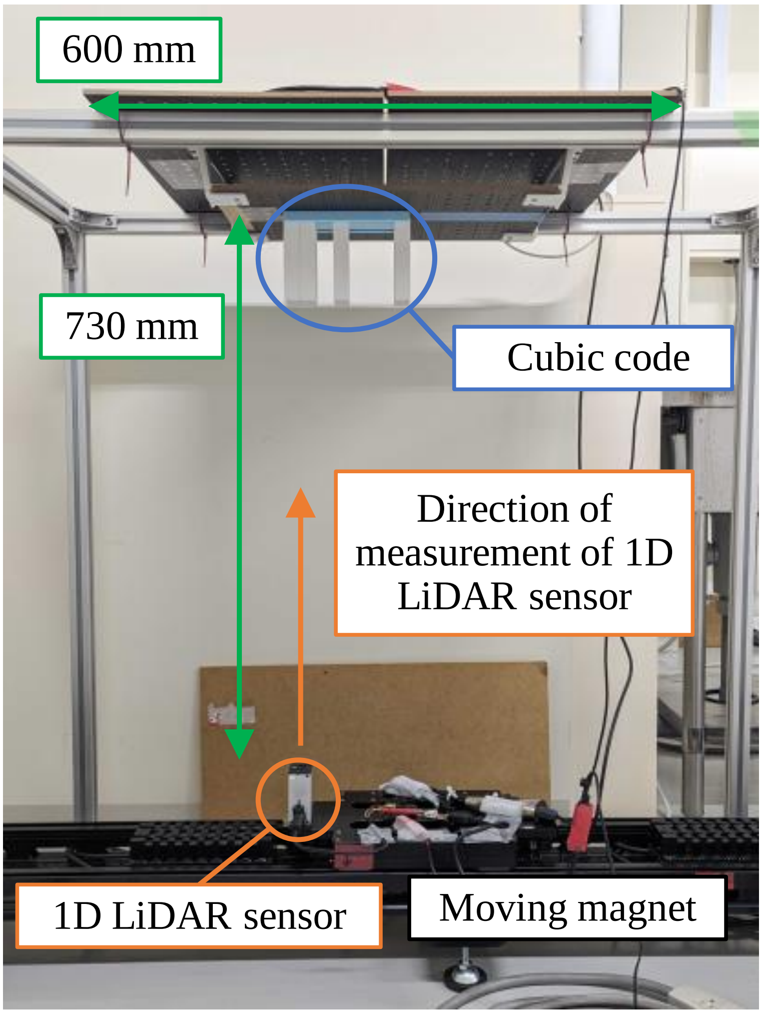

Figure 5: Experimental setup with scaling model.

10 times for every 32 patterns that can be realised with 5 information bits.

We succeeded in extracting and decoding the cubic codes in all 320 cases. First, by improving the extraction method proposed in this paper, we increased the success rate of extraction to 100 %. This success rate was about 84 % in previous studies [10]. These percentages indicate that applying moving average processing to the measurement data has improved the ability to extract cubic code. Moreover, since the cubic codes were successfully decoded in all cases after extraction, the M-estimation method proposed in this paper effectively determines the bits. Although the conventional method also successfully decodes cubic codes on the present dataset, the proposed method estimates mean values that are farther away from the y_{mid} at the rate of 87 %. This suggests that the proposed method is more robust to data with more outliers than the existing methods.

Furthermore, since the cubic code was successfully decoded even at the $\frac{1}{5}$ scale, i.e., $h_1 = 0.1$ m, we believe that h_1 can be made smaller than the current setting of $0.5\,\mathrm{m}$ in practical applications. In particular, since the measurement accuracy of the

Extraction success	
Decoding: OK & Parity check: OK	320
Decoding: OK & Parity check: NG	0
Decoding: NG & Parity check: OK	0
Decoding: NG & Parity check: NG	0
Extraction failure	0
Total	320

Table 1: The results of the extracting and decoding cubic code in the experiments.

1D LiDAR sensor used in this study was about $50\,\mathrm{mm}$, there is a possibility that h_1 can be set to about $0.2\,\mathrm{m}$. This leads to a reduction in the size of the cubic code, which improves the feasibility of the proposed method.

5 Concluding remarks and future prospects

This study proposes a novel train localisation technique employing cubic code. Applying moving average processing to the collected measurement data facilitated the successful extraction of cubic codes across all 320 conducted experiments. Compared to prior research, incorporating a robust estimation method significantly enhances the tolerance for outliers in decoding cubic codes.

The experimental results underscore the efficacy of the proposed localisation method and suggest the potential for minimising the dimensions of the cubic code beyond its current specifications. While the cubic code was initially designed to encapsulate 5 bits of information, the method's adaptability permits the modification of this bit count, thereby extending its applicability to a broader spectrum of railway lines.

Future research will aim to augment the proposed method's effectiveness through empirical studies conducted under conditions that closely replicate actual speeds, scales, and environmental settings.

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