Research on High Quality Information Data Detection Technology in Complex Environments Based on Fractional Calculus

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Abstract: Information data are inevitably affected by factors in engineering practice such as equipment performance, working environment. resulting in unpredictable measurement errors. This article studies the theory of fractional calculus and concludes that fractional differential operators have the dual advantages of reducing the differences between information data and improving signal strength. They can improve the accuracy of information data by reducing the differences between information data and enhancing the anti-interference ability of signals during transmission by increasing information strength. Established an information data fusion model based on fractional order differentiation (FOD) algorithm, which can improve the accuracy of information data; A signal strength calculation model based on FOD algorithm has been established, which can enhance the signal strength of detection information. By combining the information data fusion model with the signal strength calculation model, the detection function of high-quality information data is achieved.

Keywords: Complex environment. Information detection. Fractional differentiation. High quality data.

1 Introduction

Currently, the manufacturing industry is developing towards "intelligent manufacturing; however, the prerequisite for achieving intelligent manufacturing is to obtain accurate production information of manufacturing resources in real time. With the development of network technology, information-detection systems have achieved new real-time problems in information-data collection. However, owing to multiple factors, obtaining accurate information data has become an urgent problem and challenge for information detection systems. The process of collecting information consists of three stages: acquisition, transmission, and processing. During the process of obtaining information data, the accuracy of data detection is influenced by factors such as the accuracy of the testing instruments and the working environment. During transmission, information data may experience signal distortion due to signal interference and energy attenuation. Therefore, there are unavoidable detection errors in the information data obtained by the information detection system, which restricts the reliability of the information data processing center and scientific decision-making and directly restricts the development of the manufacturing industry towards "intelligent manufacturing. ” Therefore, research on high-quality information data in complex environments is of great significance for promoting the development of detection technologies.

The current research results indicate that information data accuracy improvement technology can be divided into two categories: hardware and software, the essence of which is to improve the detection accuracy of information data using high-performance detection instruments. The main research results for the hardware methods are as follows: Hu et al. [1] proposed a high-precision safety valve test architecture with three testing channels and effectively solved the problems of current safety valve testing. Huijun et al. [2] developed a comprehensive sliding-separation test platform for RV reducers to realize high-precision and high-display test performance for various RV reducer parameters. Reference [3-4] proposed a load differential radiation pulse on a transient electromagnetic high-performance radiation source for pulse-scanning detection to solve the problems of urban electromagnetic interference and insufficient harmonic components emitted by the radiation sources. Reference [5-7] designed a hardware system based on radar and realized a real-time detection function for underground space-related information by enlarging the detection information. Jiaqi et al. [8] proposed a one-stage remote sensing image object detection model: a multi-feature information complementary detector (MFICDet), which can improve the ability of the model to recognize long-distance dependent information and establish spatial–location relationships between features. However, in engineering applications, we found that the hardware method had the following shortcomings.

1) The essence of improving detection accuracy is to improve the detection accuracy of information data by improving the performance of the information data detection equipment, but the performance of the equipment is closely related to the cost required. Therefore, there is a lack of cost effectiveness.
2) The hardware method improves the detection accuracy of information data by improving the perception

accuracy and signal strength of a single detection device; however, it still cannot eliminate the differences between information data caused by multi-sensor detection during the information detection process.

In recent years, most researchers have attempted to use software methods to achieve high-precision information-data detection to solve the shortage of hardware methods for information-data detection in complex environments. The essence of the software method is the information data-fusion algorithm. Up to now, there have been many research results Common mathematical algorithms are fuzzy set theory [9], fuzzy neural networks [10], probability model [11] and particle swarm optimization algorithm [12], et al. and obtained a regrettable research review. For example, Huo et al. [13] proposed an integral infinite log-ratio algorithm (IILRA) and an integral infinity log-ratio algorithm based on signal-to-noise ratio (BSNR-IILRA) to improve the detection accuracy of the laser communication detection position in the atmosphere. Zhiyuan et al. [14] proposed a normalized-variance-detection method based on compression sensing measurements of received signals, and solved the problem of fast and accurate spectrum sensing technology under the condition of a low signal-to-noise ratio. Liu et al. [15] proposed a target detection algorithm based on the improved RetinaNet, which is suitable for transmission-line defect detection and improves the intelligent detection accuracy of UAV in power systems. Cheng et al. [16] proposed a lightweight ECA-YOLOX-Tiny model by embedding an efficient channel attention (ECA) module, which has a higher response rate for decision areas and special backgrounds, such as overlapping small target insulators, insulators obscured by tower poles, or insulators with high-similarity backgrounds. Liu Wenqiang et al. [17] introduced a point cloud segmentation and recognition method based on three-dimensional convolutional neural networks (3-D CNNs) to determine the different components of the catenary cantilever devices. Yin et al. [18] proposed a complementary symmetric geometry-free (CSGF) method that makes the detection of cycle slips more comprehensive and accurate. Lingfeng et al. [19] established a junction temperature model based on a multiple linear stepwise regression algorithm, and used it to extract high-precision intersection online temperatures. However, through the analysis of various current software methods, the following deficiencies were found in the detection of information in complex environments:

1) They are suitable for the fusion of multisensor information data and, to some extent, improve the detection accuracy of information data. However, they cannot solve the energy loss and signal interference problems that exist in the transmission process of information data, and have shortcomings that cannot be applied in engineering practice.
2) They are suitable for processing information data in ideal environments, but fail to consider multiple factors such as equipment performance and working environment that affect the measured values of information data in detection. Moreover, in the detection of the information data, these influencing factors exhibited irregular changes..

Therefore, an ideal high-precision detection method for information under the joint action of multiple influencing factors has not yet been developed. To solve these problems, our team has been using the method of fractional calculus theory in data processing for many years [20-26] and found that fractional differential operators are suitable for studying nonlinear, non-causal, and non-stationary signals and have dual functions of improving detection information and enhancing signal strength. Therefore, by fusing the differences between information and data, the information and data detection errors caused by various influencing factors can be eliminated. Improving the signal strength of the information can compensate for the energy loss of the signal during the transmission process and improve the anti-interference capability. In this article, we plan to apply fractional calculus theory to the high-precision detection of information data in complex environments based on previous research.

2 Fractional calculus theory

2.1 *Fractional-order Calculus Definition*

Fractional calculus is a branch of calculus derived from the theory of integer order calculus, which first appeared in L'H δ- in the letter written by pit to Leibniz [27]. The theory of fractional calculus was established 300 years ago, but it has long been in the stage of purely mathematical theoretical analysis and derivation by mathematicians. In recent years, renowned mathematicians such as Liouville have begun to focus on the improvement and development of fractional calculus theory and have established a basic system architecture for fractional calculus theory. The fractional derivative is actually any order fractional calculus, which is an important branch of mathematics that has just been developed from the n-th derivative and n-th integral in recent years. Although it has a history of over 300 years, owing to the different research objects in various application fields, fractional calculus has always lacked a unified definition in various fields. Currently, there are three well-known definitions of fractional derivatives in basic theory and engineering application research: Grunwald Letnikov, Riemann Liouville, and Caputo Riesz [28-29].

2.1.1 Grunwald-Letnikov

For any real number v, the integer part of v is denoted by $[v]$. Assuming that the function has $n + 1$ continuous derivatives on the interval $[v, t]$, and when $v > 0$, $n \geq [v]$, the fractional-order v derivative is defined as

$$ {}_aD_t^v f(t) = \lim_{h\to 0} f_h^{(v)}(t) = \lim_{h\to 0} h^{-v} \sum_{j=0}^{\left[\frac{t-v}{h}\right]} (-1)^j \binom{v}{j} f(t-jh) \tag{1} $$

Where $0 \le n-1 < v < n$; $\begin{pmatrix} v \\ j \end{pmatrix}$ is the Binomial coefficient, and

$$\begin{pmatrix} v \\ j \end{pmatrix} = \frac{v(v-1)(v-2)....(v-j+1)}{j!} \qquad (2)$$

This definition is widely used in the field of numerical calculation and has evolved from the classical definition of the integral derivative of a continuous function. If the derivative order in Equation (1) is extended to a fraction, the definition of the Grunwald Letnikov fractional calculus can be obtained.

2.1.2 Riemann-Liouville Fractional Calculus

According to Cauchy Antiderivative formula, we can get:

$$_aD_t^v f(t) = \frac{d^n}{dt^n}\left[{}_aD^{v-n} f(t)\right] = \frac{1}{\Gamma(n-v)}\frac{d^n}{dt^n}\int_a^t (t-\tau)^{n-v-1} f(\tau)\,d\tau \qquad (3)$$

Where $0 \le n-1 < v < n$

This definition is an improved expression of Grunwald Letnikov's definition, which simplifies the calculation process of fractional calculus based on its basic properties of fractional calculus. The definition of Riemann-Liouville fractional calculus can be obtained from Equations (3).

2.1.3 Caputo Fractional Calculus

In fact, the Caputo fractional calculus definition is the same as the R-L definition. The Equation is:

$$^C_aD_t^v f(t) = {}_aD_t^{-(n-v)}\left[D^n f(x)\right] \qquad (4)$$

Where $0 \le n-1 < \beta < n$

Because the above two definitions tend to generate some residual terms during some transformations, this definition is an improvement of the Grunwald- Letnikov definition from another perspective, making its calculations more concise in some engineering applications.

From the above discussion, it can be seen that there are certain connections and differences between the three definitions of fractional calculus or that they can be transformed into each other under certain conditions. Because the Grunwald–Letnikov definition can be easily converted into a series expression using a step-by-step integration formula, its application scope is more extensive. Therefore, this study applies fractional calculus theory based on the Grunwald-Letnikov fractional calculus definition to conduct research on underground spatial information data detection technology.

2.2 Spectral characteristics of fractional calculus operators

2.2.1 Spectral characteristics of fractional Differential operator

The acquisition of detection data comes from the analysis and processing of the detection information. Therefore, the measurement errors generated during the acquisition and transmission of detection information directly affect the accuracy of detection data. In terms of mathematical properties, because the signal itself has the characteristic of a fractional derivative in structure, it is not suitable for using integer-order differential operators for fusion processing. In recent years, fractional calculus has been discovered by many mathematicians and scientists to have good fusion effects in signal processing, leading to the rapid development of fractional calculus theory. Many scholars have applied fractional calculus theory to signal enhancement and have achieved good results.

Many experiments have proven that fractional differentiation can improve the high-frequency component of the signal while nonlinearly retaining the very low-frequency part of the signal. Therefore, applying this theory to detection signal enhancement can increase the signal strength to make the edge of the signal clearer while retaining the smooth information area. The key to applying FOD digital signals lies in the increased degree of freedom value, which can be adjusted to obtain the signal enhancement effect required by different systems by adjusting the magnitude of the order v ($0 < v < 1$).

In engineering practice, the detection signals collected and transmitted through sensors and networks are square-integrable energy signals. Assuming the presence of a detection signal $F(t)$ and $F(t) \in L^2$(t), the Fourier transform of $F(t)$ can be transformed into:

$$S(\hat{\omega}) = \int_R S(t)e^{-i\omega t}dt \qquad (5)$$

If the fractional derivative of order v is recorded as $S^v(t)$, then according to the Fourier transform property, the differential operator of order v is equal to the multiplicative operator $d(\omega) = (i\omega)^v$ of the differential multiplier function of order v, and the following Equation can be obtained:

$$D^v S(t) \overset{FT}{\Leftrightarrow} \left(\hat{D}S\right)^v(\omega) = (i\omega)^v S(\hat{\omega}) = |\omega|^v e^{i\theta^v(\omega)} S(\hat{\omega}) \qquad (6)$$

Make $d^v(\hat{\omega}) = |\omega|^v e^{i\theta^v(\omega)}, \theta^v(\hat{\omega}) = \frac{v\pi}{2}\mathrm{sgn}(\omega)$, Then the Equation (6) can be simplified as:

$$D^v S(t) \overset{FT}{\Leftrightarrow} \left(\hat{D}S\right)^v(\omega) = (i\omega)^v S(\hat{\omega}) = d^v(\hat{\omega}) S(\hat{\omega}) \qquad (7)$$

Therefore, from the perspective of signal modulation, the physical meaning of detecting the fractional differentiation of signals is equivalent to generalized amplitude and phase modulation. From the perspective of signal processing, the v-order fractional calculus operation of the detected signal is equivalent to establishing a linear time-invariant filtering system for the signal. The filtering function of the time-invariant filtering system is $d^v(\hat{\omega}) = (i\omega)^v = |\omega|^v e^{i\theta_v(\omega)}$.

Figure 1 shows the amplitude–frequency characteristics of the fractional differential operator when the fractional order v takes different values. From figure1, it can be seen that:

① The FOD operator plays an auxiliary role in the signal strength. When the signal is fused, if the fractional-order operator value and signal frequency are increased simultaneously, the signal strength can be rapidly increased.

② When v = 0, fractional Differential operator does not enhance the network signal.

③ When $0 < v < 1$, the fractional differential operator has the function of raising and improving the intensity/amplitude of the low-frequency part of the signal, and the increasing amplitude is slightly larger than that of the first- and second-order differential operators.

④ Fractional differentiation improves the strength and amplitude of the high-frequency part of the signal, but its effect is significantly smaller than that of first- and second-order differentiations.

According to the relationship between signal strength and the fractional differential operator shown in Figure 1, scientists found that fractional calculus under different differential operators has different enhancement effects on signals; for example, lower frequency components can be kept nonlinear. From a physical perspective, the fractional differential processing of signals can be understood as a generalized amplitude phase modulation. Because the fractional differential operator has the function of significantly strengthening its signal strength when processing high-frequency signals, it can significantly improve the strength of high-frequency and low-frequency signals. Therefore, in the FOD operator signal denoising process, the key information of the signal edge area can be maintained, and the basic information of the signal middle area can be well preserved, which can significantly improve the signal strength.

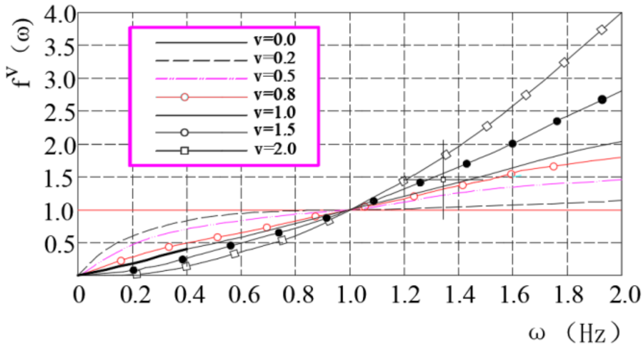

Fig. 1. The Amplitude-frequency Curve of the fractional differential operator

2.2.2 Spectral Characteristics of Fractional Order Integral Operators

In fractional calculus, fractional differentiation and fractional integration are inverse operations. In the above sections, it has been proved that the low-order FOD operator enhances the detection signal. This paper attempts to break the traditional idea of a signal denoising algorithm based on the integer order integral theory and uses the fractional-order integral theory to fuse the online collected detection information. By setting a smaller fractional integration order to construct the corresponding detection signal fusion model and using iterative methods to control the effectiveness of signal fusion, we explored the fusion processing effect of fractional integration theory on differential online detection data.

In engineering practice, the detection signals collected and transmitted through sensors and networks are square-integrable energy signals. Assuming the presence of a detection signal $F(t)$ and $F(t) \in L^2(t)$, the Fourier transform of $F(t)$ can be transformed into $S(\hat{\omega}) = \int_R S(t) e^{-i\omega t} dt$.

If the fractional derivative of order v is recorded as $F^v(t)$, then, according to the Fourier transform property, the differential operator of order v is equal to the multiplicative operator $\hat{d}(\omega) = (i\omega)^v$ of the differential multiplier function of order v, and the following Equation can be obtained:

$$D^v S(t) \overset{FT}{\Leftrightarrow} (\hat{D}S)^v(\omega) = (i\omega)^v S(\hat{\omega}) = |\omega|^v e^{i\theta^v(\omega)} S(\hat{\omega}) \tag{8}$$

Make $d^v(\hat{\omega}) = |\omega|^v e^{i\theta^v(\omega)}, \theta^v(\hat{\omega}) = \dfrac{v\pi}{2}\operatorname{sgn}(\omega)$,

Then the Equation (8) can be simplified as:

$$D^v S(t) \overset{FT}{\Leftrightarrow} (\hat{D}S)^v(\omega) = (i\omega)^v S(\hat{\omega}) = d^v(\hat{\omega}) S(\hat{\omega}) \tag{9}$$

As mentioned in Section 2.2.1, assuming that the information detection system collects a squared energy signal $F(t)$ and $F(t) \in L^2(t)$, the Fourier of $F(t)$ can be transformed into $F(\hat{\omega}) = \int_R F(t) e^{-i\omega t} dt$.

If the fractional-order derivative of $F(t)$ is denoted as $F^v(t)$ ($v \in R+$), then the following Equation can be obtained based on the Fourier transform properties:

$$D^v F(t) \overset{FT}{\Leftrightarrow} (\hat{D}F)^v(\omega) = (i\omega)^v F(\hat{\omega}) = d^v(\hat{\omega}) F(\hat{\omega}) \tag{10}$$

Where $d^v(\hat{\omega}) = |\omega|^v e^{i\theta^v(\omega)}, \theta^v(\hat{\omega}) = \dfrac{v\pi}{2}\operatorname{sgn}(\omega)$

Thus, when $v \in R+$, Equation (10) can be transformed into the fractional-order integral Equation, and $v' = -v$, the Fourier transform format of the following fractional-order integral operator can be obtained. Thus, when $v \in R+$, Equation (10) can be transformed into the fractional-order integral Equation, and $v' = -v$, the Fourier transform format of the following fractional-order integral operator can be obtained.

$$J^{v'} F(t) \overset{FT}{\Leftrightarrow} (\hat{J}F)^{v'}(\omega) = (i\omega)^{v'} F(\hat{\omega}) = i^{v'}(\hat{\omega}) \cdot F(\hat{\omega}) \tag{11}$$

Where $i^{v'}(\hat{\omega}) = |\omega|^{-v'} e^{i\theta^{v'}(\omega)}, \theta^{v'}(\hat{\omega}) = \dfrac{-v'\pi}{2}\operatorname{sgn}(\omega)$.

Therefore, the v-order fractional integration operation of the detection signal is equivalent to establishing a linear time-invariant filtering function

$$i^{\hat{v}}\left(\hat{\omega}\right)=\left|\omega\right|^{-\hat{v}} e^{i\theta_v(\omega)} . \tag{12}$$

According to Equations (12), the amplitude frequency characteristics of fractional-order integration operators at different orders can be obtained, as shown in Figure 2.

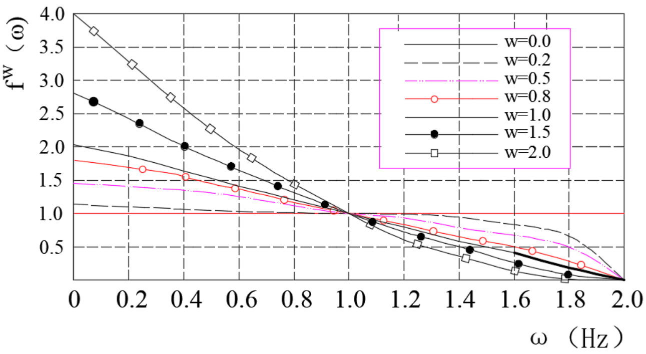

Fig. 2. The Amplitude-frequency Curve of the fractional integral operator

As shown in Figure 1, the fractional-order integration operator has the following characteristics.

1) The fractional-order integration operator attenuates the signal strength, and the attenuation of the information strength becomes more pronounced with higher integration orders. As the signal frequency increased, the signal strength decayed nonlinearly.
2) In the integer order, the second-order integration operator has a greater improvement in the low-frequency components of the signal than the first-order integration operator, and the second-order integration operator also weakens the high-frequency components of the signal more significantly than the first-order integration operator.
3) Specifically, when the fractional order $v = 0$, the amplitude-frequency characteristic curve of the signal shows no change in signal strength after being processed by the fractional-order integration operator.
4) When the fractional order is $0 < v < 1$, it can be analyzed in two situations: when the frequency of the signal is $0 < \omega < t_1$ h, fractional-order integration operators enhance information intensity, but the enhancement amplitude is much smaller than that of integral operators with integer orders $v = 1$ and $v = 2$, and at the frequency of the signal $\omega > 1$, the fractional-order integration operator weakens the information intensity, but the weakening amplitude is also significantly smaller than the integer order $v = 1$ and $v = 2$.

From the above four characteristics, it can be concluded that the fractional-order integral operator effectively weakens the information intensity of the high-frequency part of the signal while achieving nonlinear preservation of the highest frequency part of the signal. While effectively enhancing the low-frequency part of the signal, it also achieves a certain degree of preservation of the lowest frequency part of the signal.

By comparing the spectral characteristics of the FOD operator and fractional-order integral operator, it can be found that both operators have high data fusion accuracy in the long-distance transmission of complex signals; however, unlike the fractional-order integral operator, the FOD operator has the characteristics of improving signal strength, which can overcome the problem of signal distortion caused by energy loss during long-distance information transmission. Therefore, this study used the FOD operator to study the detection of underground space information.

.2.3 The Solution of Fractional Differential Based on G-L Definition

2.3.1 Transformation of fractional order differentiation

In the solution of the FOD Equation, a certain integral transform is used; therefore, differential transformation is the main means of solving the differential Equation. The differential Equation can be transformed into expressions in other domains by mapping so that more complex problems can be simplified, and the analysis and solution of complex problems can be simplified. Therefore, the calculation process for fractional calculus cannot be separated from the transformation of fractional calculus Equations. At present, the most commonly used transformation methods in the fractional calculus Equation are Laplace and Fourier transformations.

2.3.1 Laplace Transform of Fractional Calculus

The Laplace transform has become an indispensable operational tool in the study of calculus theory, and is widely applied in various fields of engineering technology research. It converts the system from the time domain to the frequency domain. Previously, it was mainly used in the conversion of calculi; however, it has now been applied to fractional calculi.

The Laplace transformation of function $F(t)$ is defined by complex variables to define function $F(s)$:

$$F(s)=L\left\{F(t)\right\}=\int_0^{\infty} e^{-st}F(t)\,dt \tag{13}$$

Similarly, the original function $F(t)$ can be obtained through the Laplace inverse transformation of the $F(s)$ function:

$$F(t)=L^{-1}\left\{F(s)\right\}=\frac{1}{2\pi j}\lim_{b\to 0}\int_{a-jb}^{a+jb} e^{-st}F(s)\,ds \tag{14}$$

Therefore, the Laplace transform Equation for the v ($v \in R+$)-order differential of the signal at $t = 0$ can be obtained as follows:

$$\begin{aligned} L^{-1}\left\{D^{v}F(t)\right\} &= \int_0^{\infty} e^{-st}\,{}_0D_t^{v}F(t)\,dt \\ &= s^{v}F(s)-\sum_{j=0}^{m-1}s^{j}\,{}_0D_t^{v-j-1}F(t)\Big|_{t=0} \end{aligned} \tag{15}$$

From this, the Laplace transform Equation based on the G-L definition of fractional calculus can be obtained.

$$L\left\{ {}_{0}D_{t}^{v}F\left(t\right)\right\} =\int_{0}^{\infty}e^{-st}\,{}_{0}D_{t}^{v}F\left(t\right)dt=s^{v}F\left(s\right) \tag{16}$$

2.3.2 Fourier Transform of Fractional Calculus

If signal S (t) is a square integrable signal, then the S (t) Fourier transform of signal S (t) is defined as:

$$F\left\{F\left(t\right);\omega\right\}=\int_{-\infty}^{\infty}e^{j\omega t}F\left(t\right)dt \tag{17}$$

Therefore, after the Fourier transform, the signal S (t) can be transformed into

$$F\left(t\right)=\frac{1}{2\pi}\int_{-\infty}^{\infty}e^{-j\omega t}F\left(\omega\right)dt \tag{18}$$

Assuming that the n-th derivative expression of the signal S (t) is S^{v} (t), then according to the Fourier transform definition of the integrable function, the Fourier transform expression of the signal S^{n} (t) can be obtained as

$$F\left\{F^{n}\left(t\right);\omega\right\}=\left(-j\omega\right)^{n}F\left(\omega\right) \tag{19}$$

By expanding the order of signal F (t) from integer order n to fractional order, the fractional derivative F^{v} of signal F (t) can be obtained β (t), the Fourier transform is applied to signal β (t), and the following fractional calculus Fourier transform Equation can be obtained:

$$F\left\{{}_{-\infty}D_{t}^{\beta}F\left(t\right);\omega\right\}=\left(-j\omega\right)^{\beta}F\left(\omega\right) \tag{20}$$

① When $0\leqslant n\text{-}1<\beta<n$ ($n\in+N$), Equation (15) is the Fourier transform equation for fractional order differentiation:

② When $n<\beta<n\text{-}1\leqslant 0$ ($n\in-N$), Equation (15) is a Fourier transform equation for fractional order integration.

2.3.3 Calculation of fractional order factorization

The solution of fractional calculus is the premise for realizing its application of fractional calculus. At present, the commonly used calculation methods of fractional calculus include the Fourier series method for calculating the periodic function, Grumwald-Letnikov fractional calculus definition direct calculation method, Fourier transform method for calculating fractional calculus, frequency domain filtering algorithm, and digital filtering algorithm.

Because this article adopts an information data fusion algorithm based on the Grumwald-Letnikov fractional calculus definition, only the Grumwald-Letnikov fractional calculus definition direct calculation method for fractional calculus is discussed.

From the above discussion, it can be seen that the definition of Grumwald-Letnikov fractional calculus is derived from the definition of integer-order calculus, which is a discrete definition suitable for numerical calculations.

$$\begin{aligned}{}_{a}D_{t}^{v}F\left(t\right)&=\lim_{h\to 0}\frac{1}{h^{v}}\sum_{k=0}^{\left[\frac{t-a}{h}\right]}\left(-1\right)^{k}\binom{v}{j}F\left(t-kh\right)\\&=\lim_{h\to 0}\frac{1}{h^{v}}\sum_{k=0}^{\left[\frac{t-a}{h}\right]}w_{k}^{v}F\left(t-kh\right)\end{aligned} \tag{21}$$

Where $w_{k}^{v}=\left(-1\right)^{k}\binom{v}{k}$ is the polynomial weight coefficient, which can be obtained using the following formula:

$$\left(1-e^{j\omega}\right)^{v}=\sum_{k=0}^{\infty}w_{k}^{v}e^{-jk\omega} \tag{22}$$

The following formula can be obtained from the inverse Fourier transform of the above Equation.

$$w_{k}^{v}=\frac{1}{2\pi}\int_{0}^{2\pi}\left(1-e^{j\omega}\right)^{v}e^{jk\omega}d\omega \tag{23}$$

2.4 Application of Fractional Calculus

In the expression of the fractional-order calculus under the G-L definition, ω is the influence factor of the Signal F (ω), Signal F (ω) Differential result is F^{v} (ω), where $\omega\in[\omega_{1},\ \omega_{2}]$ The frequency ω can be adjusted. If the measured value of is regarded as the corresponding variable x, then $\omega_{i}=x_{i}$, and $\left[\omega_{1},\omega_{2}\right]\Leftrightarrow\left[a,b\right]$, the function f (x) is a function of the influence factor x. Referring to Figure 1, we can obtain a schematic of the FOD function f^{v} (x) with the variable function f (x), as shown in Figure 3.

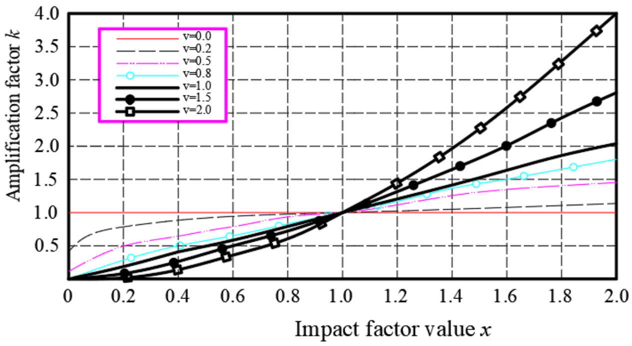

Fig. 3. Schematic diagram of fractional differential processing effect for information data

From figure 3, we can see that the relationship between the amplification coefficient k and the influencing factor x of the function information data after fractional differentiation processing is as follows:

1) FOD operators play an auxiliary role in signal-data processing. After the signal data are processed by FOD operators, the value of the information data increases with an increase in the fractional order v and influence factor x.
2) When v = 0, the fractional differentiation operator does not amplify the measured values of information data.

3) When $0 < v < 1$, the value of the fused information data is amplified, but the differential order v remains the same. As the value of the influencing factor x increases, the value of the fused information data is amplified, but the growth amplitude of the amplification coefficient k gradually decreases.
4) When $0 < v < 1$ and the influence factor x has the same value, the amplification coefficient k of the FOD operator on the information data value increases with an increase in the fractional order v. However, as the influence factor x increases, the difference between the amplification coefficients k of different orders v in the information data gradually decreases.

Referring to Equation (21), it can be seen that the fusion model of data values for functions $f(x)$, $x \in [a, b]$ is obtained by using a fractional order v ($0 < v < 1$) differential operator.

$$ {}_a^G D_t^v F(t) \Leftrightarrow {}_a^G D_x^v f(x) = \lim_{h\to 0} h^{-v} \sum_{i=0}^{\left[\frac{b-a}{h}\right]} (-1)^i \binom{v}{i} f(x-ih). \tag{24}$$

where $h \to 0$, and $n \to +\infty$, $h = (b - a)/n$.

When $0 < n-1 < n$, $\binom{v}{i}$ is a binomial coefficient defined as:

$$\binom{v}{i} = \frac{v(v-1)(v-2)....(v-i+1)}{i!}. \tag{25}$$

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In recent years, many experts and scholars have studied the theory of fractional-order calculus and found that it is suitable for the study of signals with undesirable characteristics, such as nonlinearity, noncausality, and nonstationarity, and for various data applications [30]. Various research results have been used to solve technical problems in the study of temperature field distributions, image processing, mechanical analysis, and detection technology [31-35]. For example, Bao et al. [36] applied fractional partial derivatives to the thickness design of high-temperature protective clothing under limited conditions. Zhou et al. [37] applied fractional derivatives to demonstrate their advantages in image denoising and reducing the step effect, as well as in signal denoising and super-resolution reconstruction. Tianlong [38] applied fractional partial derivatives to fluid mechanics. The working environment of an underground space is complex and changeable, and all types of information have the characteristics of irregular changes. Therefore, the FOD operators can be used to process various underground signals. This can solve the problem of application field limitations in current underground space information detection methods. High-precision detection

3 The high-precision detection method for information data in complex environments based on fractal differentiation algorithm

3.1 Fundamental principle

From the distribution line of information data processed by the fractional differentiation of function $f(x)$ shown in Figure 3, it can be seen that the distribution line is a smooth curve. However, according to the FOD processing Equation (24) based on the G–L definition, after the FOD processing of function $f(x)$, the connection between the information data is a continuous broken line. As the step size h decreases, the error between the shape of the broken line and the theoretical curve decreases. When $h \to 0$, the error between the continuous broken line and theoretical curve is $s \to 0$.

To analyze the relationship between the detection accuracy of information data and FOD operators, a graph with fractional order v and influence factor $x \in [a, b]$ is now taken from Figure 3 for analysis. The captured graph is shown in Figure 4. In Figure 4, the smooth curve is the theoretical curve of the function $f(x)$ processed by the v-order differential operator, the line is the fitting line of the function $f(x)$ processed by the v-order differential operator under the G–L definition, and the gap between the line and curve is the fitting error of the information data. Combining Figure 3 and Figure 4, the accuracy S of the information data after fractional calculus processing shows the following characteristics.

① When parameters a, b, and h are fixed values, the accuracy of the information data fusion decreases with an increase in fractional order v.
② When the parameters v, a, and b are fixed values, the accuracy of information data fusion S decreases with an increase in the step size h.

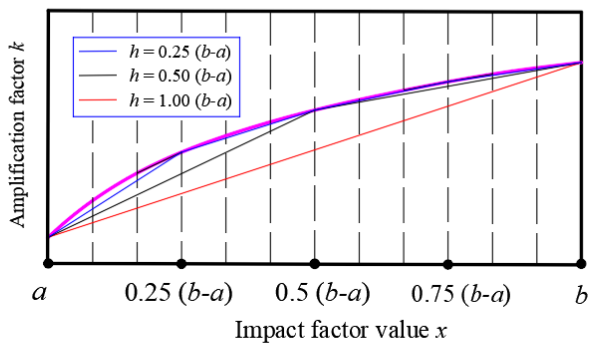

Fig. 3. Data fitting accuracy for FOD operators of the same order

3.2 Mathematical model

The optimal fractional order v for FOD processing of the data was selected according to the signal characteristics and spectral properties of the FOD operator. Referring to Equation (24), the system obtains the functional Equation $f(x)$ that relates the data value $f(x_i)$ and the impact parameter x_i, where $x \in (a, b)$. According to Equation (24), the derivative processing Equation of $f(x)$ at fractional order v can be obtained as follows:

$$ {}_aD_x^v f(x) = \lim_{h\to 0} f_h^v(x) = h^{-v}\sum_{i=0}^{n}(-1)^i \binom{v}{i} f(x_i - ih), \tag{26} $$

where $\binom{v}{i} = \frac{v(v-1)(v-2)....(v-i+1)}{i!}$, and $n = [b-a]/h$

According to the above analysis of the spectral characteristics of the FOD operator, the FOD operator enhances signal intensity. Suppose that when x takes the value interval $[a, b]$, the amplification factor of the data value of the function $f(x)$ after differentiation of order v is k. For comparison, the data value after v-order differentiation is divided by the amplification coefficient k. The result is combined with the formula for the standard deviation S of the data as follows:

$$ S = \left(\frac{\left(f_a^v - \bar{f}^v\right)^2 + \left(f_{a+h}^v - \bar{f}^v\right)^2 + \left(f_{a+2h}^v - \bar{f}^v\right)^2 .... + f\left(f_b^v - \bar{f}^v\right)^2}{nk} \right)^{0.5} = \left(\frac{\sum_{i=0}^{n_1}(f_{a+ih}^v - \bar{f}^v)^2}{nk} \right)^{0.5}, \tag{27} $$

where

$$ f_{a+ih}^v = \lim_{h\to 0} f_h^v(a+ih) = h^{-v}\sum_{i=0}^{n}(-1)^i \begin{bmatrix} v \\ i \end{bmatrix} f(x_i), \tag{28} $$

$$ \bar{f}^v = \frac{f_a^v + f_{a+h}^v + f_{a+2h}^v + \cdots + f_b^v}{n} = \sum_{i=0}^{n} f_{a+ih}^v / n, \tag{29} $$

$$ k = \frac{f_a^v + f_{a+h}^v + f_{a+2h}^v + \cdots + f_b^v}{f_a + f_{a+h} + f_{a+2h} + \cdots + f_b} = \sum_{i=0}^{n} f_{a+ih}^v \Big/ \sum_{i=0}^{n} f_{a+ih} . \tag{30} $$

By substituting (28), (29), and (30) into (27), we obtain

$$ S = \left(\frac{\sum_{i=0}^{n}(f_{a+ih}^v - \bar{f}^v)^2}{n\sum_{i=0}^{n} f_{a+ih}^v \Big/ \sum_{i=0}^{n} f_{a+ih}} \right)^v . \tag{31} $$

3.3 Implementation steps

Based on the above fundamental principle and mathematical model, the implementation steps of the high-precision data detection method for underground spaces are as follows:

1) Based on the characteristics of the detected signal and the spectral characteristics of the FOD operator, the optimal fractional derivative order v is selected for data $f(x)$.
2) Referring to Equations (1) and (31), the derivative-processed model $f^v(x)$ of the corresponding data function $f(x)$ is established at fractional order v.
3) The functional Equation $S(h)$ relating the standard deviation S of the data and the step size h was established based on the calculated value of $f^v(x)$.
4) The initial step value h is set, and use MATLAB mathematical simulation software to calculate the standard deviation $S(h)$ of the standard deviation $S(h)$ of the detection data when the step value is h is calculated based on the functional Equation $S(h)$.
5) The error between the standard deviation $S(h)$ and the specified standard deviation S_g threshold of the information detection system was compared, and the step value h was continuously adjusted based on the error value between them.
6) If the standard deviation $S(h_k)$ is slightly less than the specified standard deviation S_g threshold, h_k is selected as the best step value to satisfy the accuracy requirement of the underground space information detection system.

4 The Method for Amplifying Detection Information in Complex Environments Based on Fractal Differentiation Algorithm

4.1 Fundamental principle

We assume that the system detects energy signal $F(t)$, where $t \in (t_1, t_2)$. We can obtain the corresponding Equation detection information data to fit the Equations of $f(x)$ and $x \in (a, b)$. By combining the function $f(x)$ FOD operator fusion curve shown in Figure 3, a schematic diagram of the amplification coefficient of the information data after fractional differentiation can be drawn with corresponding parameters v, a, b, and h. Combining Figure 3 and Figure 4, it can be seen that when the influence factor value interval $x \in [a, b]$, the accuracy of the function fitting function Equation of $f(x)$ processed by fractional calculus shows the following characteristics:

(35)

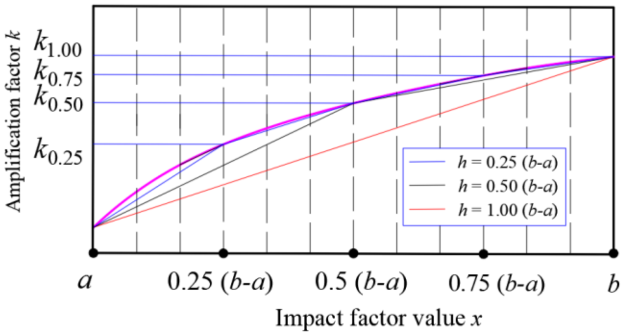

Fig. 4. The schematic diagram of the amplification coefficient of the information data after fractional differentiation

1) When the interval between the fractional order v and the influencing factor $[a, b]$ is a fixed value, the final amplification coefficient k of the information data depends on the parameter value of step h.
2) The amplification coefficient k of the information data depends on the parameter value h and is independent of the detection accuracy S.

4.2 Mathematical model

Based on the above discussion, it can be seen that the amplification coefficient k of the information data after fractional differentiation processing is only related to the range of fractional order v and the influencing factor x, and is not related to the step value h. Therefore, the amplification coefficient calculation Equation for information data processed by a fractional order v differential operator is

$$k = f^{v}(b) / f^{v}(a). \tag{32}$$

Where

$$\begin{cases} f^{v}(b) = \lim\limits_{h\to 0} f_h^{(v)}(b) = h^{-v}\sum\limits_{i=0}^{n}(-1)^i\binom{v}{i} f(b-ih) \\ f^{v}(a) = \lim\limits_{h\to 0} f_h^{(v)}(a) = h^{-v}\sum\limits_{i=0}^{n}(-1)^i\binom{v}{i} f(a-ih) \end{cases} \tag{33}$$

where $\binom{v}{i} = \dfrac{v(v-1)(v-2)....(v-i+1)}{i!}.,$

Because the amplification coefficient of the information data depends on parameters a and b, and is independent of the step size value h. Therefore, from the perspective of simple calculation, we now take $h = b\text{-}a$, where $n = 1$, and obtain the following formula:

$$\begin{cases} f^{v}(b) = (b-a)^{-v}\sum\limits_{i=0}^{1}(-1)^i\binom{v}{i} f[b-i(b-a)] \\ f^{v}(a) = (b-a)^{-v}\sum\limits_{i=0}^{1}(-1)^i\binom{v}{i} f[a-i(b-a)] \end{cases} \tag{34}$$

Therefore, after the functions $f(x)$ and $x \in [a, b]$ are processed by the v-order differential operator, the amplification coefficient k of the information data is

$$K = f^{v}(b) / f^{v}(a) = [(v+1)f(b) - vf(a)] / [(v+1)f(a) - vf(b)]$$

(35)

4.3 Implementation steps

The premise of realizing remote detection of complex information data is to obtain the detection value $f(x_i)$ of the signal $F(t)$ at different time points in real time and then analyze the main impact parameter $x \in [a, b]$ based on the data. This lays the foundation for the long-distance transmission of detection data. The specific implementation process of the information data amplification method in complex environments is as follows.

1) Obtain the detection value $f(x_i)$ of signal $F(t)$ for underground space information at different time points, and analyze the influencing parameter x and its value interval $[a.b]$.
2) The acquired detection values $f(x_i)$ and the values of their corresponding impact parameters x_i are used to fit a function $f(x)$.
3) Considering the signal characteristics of $F(t)$ and the spectral characteristics of the FOD operator, a suitable fractional order v was selected.
4) The amplification factor K of the fractional-order differential operator is calculated based on the fractional order v and the data function $f(x)$.
5) The energy loss of the signal transmitted under the existing conditions was calculated by formulating a transmission method based on the characteristics of the signal $F(t)$.
6) The amplification factor K_g required for the effective transmission of signal $F(t)$ is calculated using the detection system based on the transmission distance L of the system.
7) The required amplification factors K_g and K are combined, and the number m of differential processing cycles m required by the system is calculated to realize the remote transmission target of the information dataset by the underground space detection system.

5 High quality information data detection technology in complex environments based on fractional order differentiation algorithm

5.1 Fundamental principle

The quality of the information is reflected in its detection accuracy and signal strength. Therefore, high-quality information data can be obtained only when both information data accuracy and signal strength are satisfied. As mentioned above, the transmission of data over a desired distance can be achieved by setting the number of iterations m of the differential operator for data processing, based on the amplification factor K of the FOD operator and the established amplification factor K_G of the detection system. The detection accuracy of the data can be achieved by comparing the established accuracy S_G of the system and the accuracy S of the FOD operator, and gradually adjusting the step value h of the FOD operator so that S_G can be approximately achieved. Therefore, obtaining the step value

h and amplification factor K required by the FOD operator in data processing under the established conditions is a prerequisite for achieving the research objectives. According to the results of the above research, it is known that the accuracy of data detection at the same fractional order depends on the step value h of the FOD operator, independent of the amplification factor K. The calculation of the amplification factor k of the FOD operator must be based on the fact that step value h is known. Therefore, we can improve the quality of the underground spatial information data by sequentially calculating the step size value h required to meet the established goal and then applying it to the method of calculating the amplification coefficient K of the FOD operator.

5.2 Mathematical model

The information detection system is assumed to transmit an energy signal F (t) to a location at a distance L, and the accuracy of the acquired data must not be lower than S_G. To ensure the reliability of the data detection system, the detection signal must be amplified, and the enhancement factor must not be lower than K_G. The data $f(x_i)$ of signal F (t) at different time points t_i were collected. The main impact parameter of the obtained data is x, and $x \in [a, b]$. A function $f(x)$ relating the detection data values $f(x_i)$ and x_i is fitted. According to the signal characteristics of the signal F (t) and the spectral characteristics of the FOD operator, the proposed method of applying the differential operator at fractional order v for the long-range, high-precision detection of data was used.

According to the above theory on improving the accuracy and intensity of detection information and referring to Equation (26), the standard deviation of the data is calculated after the FOD operator is applied as follows:

$$S = \left(\sum_{i=0}^{n} (f_{a+ih}^{v} - \bar{f}^{v}) \ /K \right)^{0.5} . \tag{36}$$

If the detection accuracy target set by the system is to be achieved, the following conditions must be satisfied:

$$\begin{cases} S \leqslant S_G \\ S_G - S \approx 0 \end{cases} . \tag{37}$$

As mentioned above, if the step value of the FOD operator is h, the system can be calculated using a stepwise approximation method to meet the system accuracy target S_G. Then, h is introduced to obtain the amplification factor of the detection data after processing by the v-order differential operator, as follows:

$$k = \bar{f}^{v}(x) / \bar{f}(x) = h^{-v} \sum_{i=0}^{n} \sum_{i=0}^{n} (-1)^{i} \binom{v}{i} f(x - ih) / \sum_{i=0}^{n} f(a + ih) \cdot \tag{38}$$

By combining the required data enhancement factor K_G of the detection system and referring to Equation (36), the number of fractional-order differentiations m required to detect the data is.

$$\begin{aligned} m &= K_G / k = K_G \bar{f}(x) / \bar{f}^{v}(x) = \\ & K_G h^{v} \sum_{i=0}^{n} f(a + ih) / \sum_{i=0}^{n} \sum_{i=0}^{n} (-1)^{i} \binom{v}{i} f(x - ih) \end{aligned} . \tag{39}$$

The number of fractional order differentiation processes for the detection data is m.

5.3 Implementation steps

Suppose that the underground space information detection system detects an energy signal F (t), where $t \in (t_1, t_2)$. Referring to Equation (24), we obtain the corresponding Equation of $f(x)$, $x \in [a, b]$. The signal characteristics of the data to be detected and their usage requirements were analyzed. The data accuracy S_G and amplification factor K_G required to achieve the data detection target were set. According to the above fundamental principle, the remote and high-precision detection methods for underground space information data are as follows.

1) A data processing scheme was developed for information data in complex environments based on fractional calculus theory, according to the set data accuracy S_G and signal amplification coefficient K_G.
2) The collected data $f(x_i)$ of the underground space information are applied to analyze the important impact parameter x, and the functional relationship between the data and the impact parameter Equation of $f(x)$ is obtained by fitting.
3) The appropriate fractional order v for data processing is selected based on the characteristics of the detection data signal and the amplitude and frequency characteristics of the FOD operator.
4) The step value h required to achieve the required accuracy S_G of the system was calculated based on the mathematical model shown in Equation (31).
5) The amplification factor K of the FOD operator was calculated based on the data, and the number of differential processes m required to achieve the data amplification factor K_G was determined.

Through the integration of high-precision detection methods and long-distance transmission methods for underground space information data, the quality of information data that improves the function of a signal in an underground space is realized. It not only successfully solves the problem that the two functions of the current method cannot be considered, but also realizes the detection technology of information data under the established detection target.

6 Application examples

6.1 Experimental environment

Huainan City is an important coal production base in China, and the prominent feature of its coal mines is that there are more "high-gas" mines. The output of high-gas mining faces accounted for more than 70% of the total output of the region. Therefore, controlling the gas concentration at the working face is a key issue, and it is difficult to ensure safe mine production. To realize the effective control of the gas concentration at the working surface, we first need to accurately measure the gas concentration at the working surface and transmit the detection data in real time. However, the transmission distance and accuracy of the detection data are limited by the properties of the detection instruments, working environment, signal interference, and other factors.

Therefore, achieving accurate measurement and long-distance transmission of gas concentration at the working surface has always been a technical problem in the safety management of high-gas coal mines.

To test the application of fractional-order calculus theory in data detection, the 151302 working surface of a mine in Huainan City was considered, which is located approximately 500 m from the surface and 2 km from the main shaft. The test required real-time accurate detection of the gas concentration at the working site under existing conditions. The experiment required a real-time accurate gas concentration detection function for the operation site under existing conditions. Owing to the long distances and dynamic changes in the operation site at the coal mine working face, the experiment required a wireless network to realize the real-time long-distance transmission of the collected data. To ensure the normal production of the working surface and the safety of the experiment site, after considering various factors, we designed a structural diagram of the gas concentration detection system, which is shown in Figure 4, and developed the corresponding data detection scheme. The data sensed by the gas concentration sensor were first transmitted to the gas concentration detection system near the working face by Wi-Fi wireless network transmission, and then the data processed by fractional-order differentiation were transmitted to the underground data center by an optical fiber transmission method. Finally, the data collected by the underground data center were transmitted to the surface data management center using a Controller Area Network (CAN).

Owing to the complex spatial environment of the underground structure and the twists and turns of the fiber arrangement path, the traditional calculation of the fiber energy attenuation coefficient is not suitable for this case. To obtain accurate experimental results, this study adopts an experimental method to calculate the energy attenuation coefficient during signal transmission under existing working conditions. In the experiment, we chose an information transmission distance of 100 m and found its energy attenuation coefficient to be 0.63 after testing. Therefore, the data management center needs to amplify the signal strength by more than 8.5 times to achieve effective sensing and high-precision collection of data on the operating surface 2 km away. To ensure the detection quality of the collected data, the standard deviation of the data should not exceed 0.05.

The development of larger and more complex underground spaces has become a trend for future underground space development [39]. Underground space has the characteristics of "deep, large, clustered, and hidden." Once an accident occurs, it can easily cause catastrophic impact [40-41]. However, existing safety perception and prediction technology for underground space structures cannot guarantee the safety of underground space structure construction and operation. In particular, urgent problems still need to be solved in terms of state perception, disease identification, and mechanistic analysis [42]. In addition, the working environment of an underground space measuring instrument FOD is complex, spatiotemporal monitoring data are unusually diverse, and the quality is uneven, which often causes problems such as "unclear detection, inaccurate measurement, and inaccurate judgment" of the underground space, thus leading to an incorrect estimation of the safety status of the underground space, which may endanger the safety of the underground space [43]. Therefore, improving the global awareness of underground spaces and the quality of data detection have become urgent problems to be solved in the construction of underground spaces.

The detection objects of underground space information include the detection of underground tangible objects and intangible material parameters. However, the essence of realizing their information data detection quality lies in improving the detection accuracy of information data and the strength of signal transmission. Tangible objects in the underground space include the underground space structure, object contour shape, production equipment position, and moving object trajectory. At present, the detection methods for underground space are mainly based on ground-penetrating radar [44], and the portability and high-resolution characteristics of GPR [45-46] make GPR widely used in subgrade surveys and underground space pipeline detection [47]. However, the penetration depth of ground-penetrating radar is limited, and the effective detection depth generally does not exceed 10m [48-49], it can only detect shallow urban facilities, and has no detection capability for underground targets below 30m. The existing shallow surface wave method [50-52] has difficulty meeting the detection requirements of urban geophysical exploration owing to its weak anti-jamming capability. Reference [53-54] proposed a load differential radiation pulse on a transient electromagnetic high-property radiation source for pulse scanning detection to solve the problems of urban electromagnetic interference and insufficient harmonic components emitted by radiation sources. However, the detection method of pulse scanning alone is incomplete and a corresponding imaging method is required. More importantly, the above methods can only be applied to the detection of information tens of meters below the ground, and they cannot be applied to underground spaces hundreds of metres deep.

The objects of detection for intangible substances in underground spaces include gas, pressure, temperature, humidity, noise, and stress. At present, the detection methods for the parameters of underground intangible substances are still the same as those for intangible substances in aboveground space. Reference [55-57] designed a hardware system based on radar and realized the real-time detection function of underground space-related information by enlarging the detection information. However, measurement errors cannot be eliminated or applied to underground spaces with tortuous paths. Reference [58] proposed a three-frequency resonance transmission scheme to solve the problems of low efficiency in the conventional single-frequency transmission method, and high-voltage stress in the multifrequency pseudorandom transmission method. However, the scheme only solves the problem of signal transmission efficiency and does not improve the quality of information data. Reference [59-60]The self-developed rotary drilling system and three-dimensional flexible boundary loading device were developed to carry out the rotary drilling model and realize the detection technology of stress betteen rocks in an underground space. However, they have limitations in the application space and cannot be used for the remote detection of information data. Xuezhao et al. [61] studied a multi-information drilling-detection device based on key technologies, such as multimedia information collection, synchronous transmission, and underground explosion-proof facilities, and realized the collection function of key information data of underground space. However, this method is based on drilling from the ground to the underground space and placing the equipment in the underground space for later detection, so there are shortcomings of low efficiency and information lag. Sun et al. [62] proposed a bionic artificial intelligence algorithm driven by temperature data to detect a fire source in the three-dimensional space of an underground pipe gallery. However, this method can be used only for fire prevention in underground pipelines.

More importantly, these methods have the following shortcomings in the information collection of underground spaces.

1) They are primarily used to detect the position and shape of tangible objects, and there are shortcomings in the field of high-precision remote detection that cannot be applied to object property parameters. Therefore, there are limitations to the application field.
2) Their essence is to highlight the difference between information data to improve the detection accuracy of the difference data, but they fail to eliminate the detection error caused by various factors in the process of long-distance transmission of information data.
3) In the detection process, because the detection object is in a random transformation state, the above information detection system cannot adjust the technical parameters with the changes in the tested object in a timely manner. Therefore, it affects the accuracy and real-time detection of the information.
4) In the detection of underground space information data, the above methods have the disadvantage of large energy loss in application, which restricts the depth and data accuracy of the detection information; therefore, there are limitations in the application space.

Therefore, to date, we have not found any detection methods that can effectively improve the quality of information data for various types of detection objects in underground spaces.. To solve these problems, our team has engaged in research on methods using fractional-order calculus theory in data processing for many years, and found that the FOD operator has the dual function of improving the signal strength and reducing the variability between information data. Therefore, it can effectively improve the transmission distance and detection accuracy of the information [63-67]. Based on previous research, in this study, we applied fractional calculus theory to detect underground space information data.

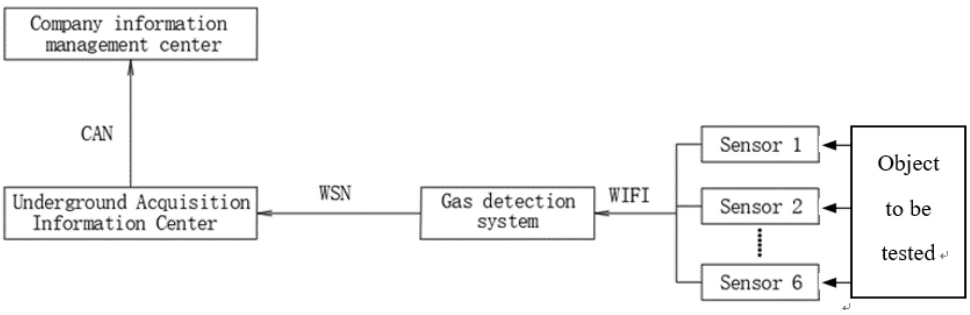

Fig. 5. Structure diagram of gas concentration detection system

To improve the accuracy of the data, six working 3-2.3V LEL combustible gas sensors were used to measure the gas concentration at the working site of the working face. The six sensors worked simultaneously and were measured once every 5 s, and the data collection center collected five gas concentration measurements from the six sensors. Therefore, we can extract 30 data points at the same location in real time as the experimental samples, as shown in Table 1.

Table 1. Experimental Data (%)

Sensor No.	1#	2#	3#	4#	5#	6#
1st measured value	10.28	11.02	11.06	10.48	11.16	10.62

2nd measured value	10.85	10.35	10.66	10.25	10.45	10.55
3rd measured value	10.55	10.28	11.25	10.86	11.35	10.36
4th measured value	11.08	11.31	11.35	11.08	10.58	11.28
5th measured value	10.75	10.56	10.58	10.45	10.25	10.55

6.2 Pre-processing of data

6.2.1 Analysis of data

In the experiment, the average value $\bar{E}$ of five measurements of each sensor and the average value E of all the measurements were considered to be the true values. A summary of gas concentration detection data for the working face is presented in Table 2. The detection data exhibited an irregular distribution around the measured true values. Therefore, influenced by multiple factors, such as the properties of the measuring instrument FOD and the working environment, the initial detection value of the gas concentration at the coal mine working surface had a large detection error, which created difficulties in providing accurate detection values for the safety management of the coal mine and significantly affected the decision-making of the safety management system.

Table 2. Summary of Experimental Data (%)

Sensor No.	1#	2#	3#	4#	5#	6#
Average value $\bar{E}_i$	10.702	10.704	10.980	10.624	10.758	10.672
Standard deviation S	0.27	0.40	0.31	0.30	0.42	0.32
True value E	10.740					
System standard deviation S_x	0.1146					

6.2.2 Impact factors of dat*a*

Owing to the harsh environment and complex working conditions of the underground structural space, the detection data in the transmission process will inevitably be affected by a variety of factors, which results in a large data detection error. All sensors were placed in the same place, and they operated at the same time and at the same frequency to detect the gas concentration at the location. Thus, the effects of the environment and energy losses in the transmission of data were essentially the same, which means that the property of the measuring instruments directly affects the measured value of the information data. Because the standard deviation can effectively reflect the properties of the measuring instrument, it was used as the impact parameter of the measured values of the sensor to analyze the correlation between the properties of the testing equipment and the measured value.

6.2.3 Equation relating concentration data and Impact factors

The least-squares algorithm has a good data fitting accuracy. Therefore, this study applies it to the fitting of the distribution function of underground spatial information data. According to the parameter values f_i and x_i listed in Table 2, the mathematical expression of the function $f(x)$ is assumed to be

$$f(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n \tag{40}$$

According to formula (47), the function formula $E(x)$ depends on the parameters n and a_i (i = 0, 1,... n) in the formula. For the characteristics of the least-squares algorithm, the parameter n of function $f(x)$ should not exceed the number of samples; therefore, $n \in [0, 6]$, and an optimum was found to minimize the error between the function $f(x)$ and the measured true value E when $n \in [0, 6]$. The Polyfit function in the MATLAB software was applied, and the total errors of the fitted values of at different orders are shown in Table3. From the simulation results, we can see that when n = 4, the error between the fitting value and the measured true value is the smallest, and the value is 0.0744. The Equation for the $f(x)$ function is

$$f(x) = -4222.8x^4 + 5403x^3 - 2573.4x^2 + 542.8x - 32.2. \tag{41}$$

Table 3. Summary of Experimental Data (%)

Order *n*.	1	2	3	4	5
Total error	0.0875	0.0824	0.0778	0.0744	0.0928

6.3 High-precision detection of data based on stepwise approximation method

According to the working principle of the stepwise approximation method and the characteristics of the data in this case, the implementation process of the method is as follows:

1) The corresponding mathematical treatment under the FOD was modeled based on the available experimental conditions and data.
2) The appropriate differential order v is selected based on the detection data characteristics and FOD operator properties.
3) The established mathematical model was applied to set the initial step value h, and the initial standard deviation S was calculated under known conditions.
4) The step value h was continuously adjusted by comparing it with the set system threshold S_G until the accuracy met the set system accuracy threshold S_G.

6.3.1 Mathematical model for calculating data precision based on fractional differentiation algorithm

According to Equation (7) and Figure 1, when the differential order $v \in [0, 1]$, the signal strength increases with the increase in the fractional order v at the high frequency stage; however, with the increase in frequency, the difference between the enhancement values of the FOD operator on the signal at different orders shows a downward trend. Therefore, from the perspective of space saving and convenient calculations, this case discusses the application effect of the FOD operator in underground space information data fusion processing when the median value between fractional orders [0, 1] is $v = 0.5$.

According to (27), we can obtain the formula for the standard deviation of the data.

$$S=\left(\frac{\sum_{i=0}^{[b-a]/h}\left(f^{0.5}(x+ih)-\bar{f}^{0.5}(x)\right)^2}{nK}\right)^{0.5}, \tag{42}$$

where

$$f^{0.5}(x+ih)=\lim_{h_4\to 0} f_h^{0.5}(x+ih)=h^{-0.5}\sum_{i=0}^{[b-a]/h}(-1)^i\binom{0.5}{i}f(x-ih) \tag{43}$$

Combined with (28), the data shown in the table were processed by the 0.5-order differential operator, and the result was:

$$f^{0.5}(x_i)=h^{-0.5}\left(\begin{array}{l} f(x_i)-0.5f(x_i-h)-\frac{0.5(1-0.5)}{2!}f(x_i-2h)-\cdots \\ -\frac{\Gamma(1-0.5)}{n!\Gamma(n+1-0.5)}f(x_i-nh)\end{array}\right), \tag{44}$$

where

$b=0.26$; $a=0.07$; $n=[b-a]/h=[0.26-0.07]/h=0.19$.

6.3.2 Calculation of step h method based on gradual approximation

To improve the efficiency of the system, a step-by-step method was used to adjust the step value h to achieve a continuous improvement in the accuracy of the system data and select the best step value in terms of data accuracy and efficiency. MATLAB mathematical simulation software is applied to calculate the fitting accuracy of the information data when h takes different values in Equation (45). After the calculation, it can be concluded that when the step size h = 0.006, the accuracy of the information data fusion was S = 0.052. When the step size is h = 0.005, the accuracy of the fused information data is S = 0.046. Therefore, the step value h = 0.005 was used as the final calculation value.

The above results are simulated using MATLAB software, and we can verify the accuracy of the simulation results through the following calculations.

1. When h = 0.006

Referring to Equation (26), we can obtain the FOD processing Equation for the information data when the detection information has a fractional order of v = 0.5, and a step size of h = 0.006:

$$f_{0.006}^{0.5}(x)=12.9\sum_{i=0}^{32}(-1)^i\binom{0.5}{i}f_{0.006}(x-0.19) \tag{45}$$

According to the data shown in Table1, The data obtained by this process met the system accuracy requirement after being processed by the differential operator with fractional order v = 0.5 and step value h = 0.006.

Table 4. Experimental Data when h = 0.006 (%)

Sensor No.	1#	2#	3#	4#	5#	6#
Average value $\bar{E}_i$	10.702	10.904	10.98	10.624	10.758	10.672
Standard deviation S_i	0.27	0.40	0.31	0.30	0.42	0.32
Measured true value E	10.7400					
Value after fusion $E_{0.006}^i$	19.313	19.525	19.376	19.323	19.542	19.389
Post-fusion mean $E_{0.006}$	19.411					
Amplification factor $K_{0.006}$	1.807					

To facilitate a comparison of the standard deviation between the data before and after data processing, the processing results shown in Table 4 were divided by the amplification factor $K_{0.006}$, and the results are shown in Table 5.

Table 5. Experimental data summared when h = 0.006 (%)

Sensor No.	1#	2#	3#	4#	5#	6#
Average value $\overline{E}_i$	10.702	10.904	10.98	10.624	10.758	10.672
Standard deviation S_i	0.27	0.40	0.31	0.30	0.42	0.32
Fusion final value $\overline{E}^i_{0.01}$	10.688	10.805	10.723	10.693	10.815	10.730
Pre-fusion standard deviation S_q	0.1146					
Post-fusion standard deviation S	0.052					

From the data shown in Table 5, it can be seen that when the fractional order v = 0.5 and step size h = 0.006, the accuracy of the original data after fractional differentiation processing is 0.052. Combined with the accuracy requirement $S_G \leqslant 0.05$ and Equation (41) set by the system, it can be seen that after the fractional order v = 0.5 and step size h = 0.006 differentiation processing of the detection data, the accuracy of the information data has not yet met the required accuracy requirements of the system.

2. When h = 0.005

Based on the above discussion on the decrease in the information detection accuracy value s with a decrease in step size h, we reduce the parameter value $h \to 0.005$. Referring to Equation (26), we can obtain a fractional-order fusion model for detecting information data at fractional order v = 0.5, and step size h = 0.005.

$$f^{0.5}_{0.005}(x) = 14.144\sum_{i=0}^{38}(-1)^i \binom{0.5}{i} f_{0.005}(x - 0.19) \cdot \tag{46}$$

According to the data shown in Table 1, the experimental data shown in Table 6 were obtained for fractional order v = 0.5, and step size h = 0.005.

Table 6. Experimental Data when h = 0.005 (%)

Sensor No.	1#	2#	3#	4#	5#	6#
Average value $\overline{E}_i$	10.702	10.904	10.98	10.624	10.758	10.672
Standard deviation S_i	0.27	0.40	0.31	0.30	0.42	0.32
Measured true value E	10.7400					
Value after fusion $E^i_{0.005}$	22.205	22.432	22.269	22.253	22.464	22.285
Post-fusion mean $E_{0.005}$	22.318					
Amplification factor $K_{0.005}$	2.078					

To facilitate a comparison of the standard deviation between the data before and after data processing, the processing results shown in Table 6 were divided by the amplification factor $K_{0.005}$ = 2.078, and the results are shown in Table 7. From the data shown in the Table 7, it can be seen that when the fractional order v = 0.5, and the step size h = 0.005, the accuracy of the original data after fractional differentiation processing is S = 0.046, which meets the accuracy requirement $S_G \leqslant 0.05$ set by the system.

Table 7. Experimental data summared when h = 0.005 (%)

Sensor No.	1#	2#	3#	4#	5#	6#
Average value $\overline{E}_i$	10.702	10.904	10.98	10.624	10.758	10.672
Standard deviation S_i	0.27	0.40	0.31	0.30	0.42	0.32
Fusion final value $\overline{E}^i_{0.01}$	10.691	10.800	10.722	10.714	10.816	10.729
Pre-fusion standard deviation S_q	0.1146					
Post-fusion standard deviation S	0.046					

6.4 Long-distance data transmission based on cyclic iteration method

6.4.1 Value of parameter h and amplification factor k

Because the strength of the signal depends on its step value h and the number of FOD processing iterations, the original data were processed for the first iteration through differential results with h = 0.005, v = 0.5, and $x \in$ [0.27, 0.42]. Before and after the iterations, the applied parameters were the same as those in the mathematical model. The various data points before the iterations are presented in Table 4.

By combining the FOD operator shown in Equation (45) with the data processing model, the data shown in Table 9 were processed by the first FOD operator iteration to obtain the values shown in Table 10. The amplification coefficient and data accuracy before the iterations were essentially equal between the data after iterative processing by the FOD operator, thus verifying the correctness of the above assertion regarding the relationship between the accuracy and amplification coefficient in the data processing and the FOD parameters. When v = 0.5 and h = 0.005, the amplification factor K = 2.078 for the data before and after the iteration of the FOD operator.

Table 8. Summary of Experimental Data when h = 0.005 (%)

Sensor No.	1#	2#	3#	4#	5#	6#
Pre-iterative data $\overline{E}_i$	10.702	10.904	10.940	10.624	16.071	16.065
Pre-iteration mean E	10.74					
Standard deviation S	0.27	0.40	0.31	0.30	0.42	0.32
Data after iteration $E^{0.5}$	16.061	16.068	16.063	16.063	16.069	16.064
Standard deviation after iteration S	0.046					
Amplification factor K	2.078					

6.4.2 Values of amplification factor K and number of iterations m

Based on the above analysis of FOD theory, we have concluded that FOD operators have the function of amplifying the measured values of information data, and the amplification coefficient K is only related to the range of fractional order v and influence factor x ∈ $[a, b]$, and is not related to the detection accuracy S. Based on the calculation results of step value h = 0.005 when ensuring the accuracy of information data detection S_G = 0.05, combined with the Table 2, it can be concluded that the amplification coefficient K = 2.078 of the information data in the case after the fractional differentiation process. m is the number of FOD processing iterations for data. To satisfy the amplification factor K_G set by the detection system, it is necessary to satisfy the following Equations:

$$\begin{cases} K = 2.078^m \\ 9.25 \le 2.078^m < 2.078^{m+1} \end{cases} \tag{47}$$

By solving for parameter m in Equation (47), we can see that under the above detection conditions, when the FOD operator steps h = 0.005, the number of FOD processing cycles m = 3. The amplification coefficient of the detection signal K = 8.97, which satisfies the set system requirements.

6.5 Experimental Results and Their Analysis

According to the above research results, it can be concluded that when the fractional order v = 0.5, and the step size h = 0.005, the detection accuracy of the information data in Table 1 is 0.046 after the experimental data are processed by fractional order differentiation, as shown in Table 9. The amplification coefficient of the information data is 8.97 after 3 times processing by the fractional-order differentiation operator, from which we can see that the detected information data can completely meet the detection target set by the system.

Table 9. Summary of Final Processing Results of Experimental Data (%)

Sensor No.	1#	2#	3#	4#	5#	6#
Average value $\overline{E}_i$	10.702	10.904	10.94	10.624	16.071	16.065
Standard deviation S_i	0.27	0.40	0.31	0.30	0.42	0.32
Final detection value $E_i^{0.5}$	73.649	73.683	73.656	73.656	73.690	73.663
Standard deviation before treatment	0.1146		Standard deviation after treatment		0.046	
Final amplification factor K	8.97					

Because the experimental site in this study was located in a structural space more than 500m underground, it was a harsh experimental environment. The experiments were conducted by simplifying the calculation steps and selecting typical parameter values to analyze and process the experimental data. In practical applications, the corresponding fractional order *v* can be selected based on the data characteristics, and the detection system can arbitrarily achieve the detection distances and data accuracies by adjusting the step value *h* and processing number *m* of the FOD operator.

7 Conclusion

Fractional-order calculus theory was applied to the detection of information data in complex environments. by analyzing the characteristics of the generate information in complex environments and the signal amplitude and frequency characteristics after fractional differentiation algorithm processing to meet the needs of improving the quality of information data. The fractional calculus theory is successfully applied to the field of information data detection. The application experiments prove that the method described in this paper has the following characteristics:

(1) Successfully applied fractional calculus theory to the fusion processing of information data, achieving the detection technology for multiple types of high-quality information data in complex environments.

(2) Based on the spectral characteristics of fractional order differential operators, high-precision detection technology for information data in complex environments is achieved by adjusting the parameter fractional order *v* and step size *h* in the fractional order differential operators.

(3) By adjusting the frequency *m* of FOD for information data fusion processing, enhancing the strength of the information signal to improve its anti-interference ability, and compensating for the energy loss of the signal during transmission, the remote transmission technology of information data has been achieved.

(4) The complex environmental information detection system combines high-precision detection methods with long-distance transmission methods to achieve information data detection technology for setting attribute targets.

Therefore, the algorithm used in this paper can successfully solve the problems existing in the current omplex environment information detection methods.

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