Study on 3D Reconstruction of Plant Root Phenotype Based on X-CT Technique

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Abstract. The change of the global climate in recent years influences the adaptability of plant roots to the soil environment. Detecting the plant roots in the original soil environment without destroying and moving them and analyzing, processing and reconstructing the root image requires the improvement of technology. Firstly, to conduct the in-situ non-destructive measurement of the root system in soil, this paper investigates and studies the three-dimensional imaging of plant root phenotype using X-CT technology. Secondly, to examine the feasibility of the segmentation methods applied in medical image analysis in root CT images, the experiments of segmentation using fuzzy clustering of CT images were designed. The segmentation results of root features obtained from 10, 30 and 50 times clustering algorithms for the in-situ root CT images are analyzed with the FCM (Fuzzy C-Means) algorithm. The experimental results show that the traditional medical image segmentation method does not produce a good segmentation effect in this particular environment.

Keywords: In situ non-destructive measurement · X-CT tomography · Fuzzy clustering segmentation · FCM algorithm

1 Introduction

The root system is an important organ for plants to obtain nutrients and water. Due to the invisible opacity of the root system in soil, it is difficult to observe and study the underground part of plants [1], this makes the research on the above-ground part of the plant far more than the underground part. In the early days of plant root research, the existing methods of observing plant roots can be divided into two categories [2], one is a destructive method and the other is a non-destructive method. At that time, limited by soil media and imaging technology under plants, researchers often adopted destructive sampling methods, including container method, tube loading method, nail

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plate method, air culture method, mesh bag method, etc. Non-destructive methods as opposed to destructive methods, such as underground root chamber method, isotope tracer method, etc. [3]. In 2017, the French Academy of Agricultural Sciences, with the help of the high-throughput plant phenotyping platform, RhizoTube, a high-throughput micro root window measurement system for plant root phenotype. Automatic, high-throughput and noninvasive long-term root growth monitoring of plant root phenotype was realized [4]. While these methods guarantee the complete measurement of plant roots, they are all based on the study of plant root characteristics under an ideal environment, but still cannot reach the original growth environment of plants in reality. The disadvantages lie in the following aspects. Firstly, the cultivation of transplanted seeds cannot completely restore the original growth environment of plants; Secondly, when the root system of a plant is taken out for contact measurement, the roots with a too-small diameter around it will break, which will damage the accuracy of the final measurement; Thirdly, the observation and measurement of the root system are not complete and it can only be measured locally. With the advancement of medical imaging technology in recent years, the imaging methods of root nondestructive measurement are mainly divided into two types: one is based on nuclear magnetic resonance (NMR) imaging [5] and the other is based on X-CT imaging. Because the principle of NMR technology in hydrogen resonance degree impact will be limited by the influence of water in the soil, the energy released by the complex medium in the soil will affect the determination of the position and type of the nucleus, making its imaging resolution lower [6].

This paper investigates and studies a series of principles and methods for 3D imaging of plant root phenotypes based on X-CT [7]. To achieve unified in situ non-destructive measurements of different complex plant root systems. Firstly, it is necessary to conduct high-precision non-destructive imaging of roots in soil media based on a kind of high-resolution X-CT imaging equipment. The principle of fuzzy clustering image segmentation is studied in this paper [8–10] and the FCM algorithm [11–13] was used to perform clustering operations on CT images of the root in situ for 10, 30 and 50 times. It can be found from the segmentation result diagram of the obtained root features that FCM algorithm of fuzzy clustering segmentation can perform an iterative operation on the CT image of the in-situ root system, however, it is difficult to achieve satisfactory results for CT images of the root in situ with more noise and artifacts using traditional medical segmentation methods.

2 Systematic Research Route

The research technology route of three-dimensional imaging of plant root phenotype based on X-CT technology is shown in the following figure (Fig. 1):

The main research contents of this paper include: The X-CT technique was used to conduct three-dimensional imaging of the root phenotype in the soil. The feasibility of applying the fuzzy clustering algorithm commonly used in the medical image to the CT image of the root in situ was also explored.

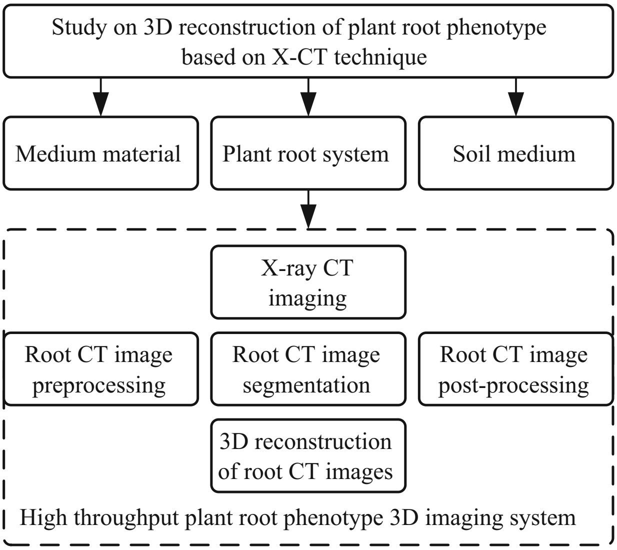

Fig. 1. Research technology roadmap

3 Study on Root Phenotypes with High Throughput

In the past two years, with the rapid development of plant phenotype, high-throughput detection technology has been gradually optimized and applied in the field of plant phenotype detection. For example, the visible light high-throughput optical imaging instrument with relatively high wavelength can be used for non-contact imaging of plant leaf area, seed morphology, spike type, root system and other physical structures. There are also transmission images of subsurface parts of plants using non-visible light with wavelengths between 100 μm and 500 μm [14]. The investigation found that the purpose of high-throughput plant phenotype detection is to better study the genotypes and genetic traits of plants in the next step and build a front-end plant phenotype database. Based on the characteristics of high throughput technology, such as high yield or output per unit time, and combined with the research route in this paper, the research on root phenotype detection of high-throughput plants can be further divided into three parts. Firstly, high-throughput plant root phenotype X-CT imaging system; Secondly, CT image data analysis of plant root phenotype with high throughput; Thirdly, 3D reconstruction of CT images of high-throughput plant root phenotypes.

With the rapid development of deep learning and machine vision research [15], it has brought the possibility of development to the data analysis of high-throughput root phenotypic CT images and the 3D reconstruction of high-throughput CT images. Plant phenotypic omics is an interdisciplinary subject, image processing for the obtained large number of CT images of the root system in situ has also gradually crossed into the field of computer [16]. Based on the analysis of CT image data analysis of high-throughput plant roots, there are few types of research at home and abroad.

Due to the limitations of the research and development of a high-throughput root CT image imaging system, high-throughput root CT image processing will remain the bottleneck of the new development of plant root phenotype for a long time to come. The high-throughput X-CT plant root phenotypic imaging system only completed the collection of root phenotypic data. As an intermediary link, how to analyze the root characteristics from the huge root image database obtained. The phenotypic classification obtained through image analysis further understands the morphological structure and functional process of plants, and it can find out useful information for plant phenotyping. That's all that matters.

4 X-Ray CT Imaging

4.1 Linear Attenuation Coefficient

In recent years, with the development of imaging technology in the medical field, X-CT has established an unshakable position as a high-performance non-destructive diagnostic technology in the medical field. X-CT has not only brought unprecedented revolutionary influence in the field of medicine, but also been successfully applied in many fields such as industrial nondestructive testing, geophysical resource exploration and botanical determination [17]. Preliminary studies at home and abroad show that it is feasible to use X-CT to image plant roots.

X-ray CT imaging is different from traditional X-ray imaging. For the complex spatial structures of plant roots that block and cross each other, traditional X-ray imaging cannot achieve the effect, but CT imaging technology can solve this problem.

As can be seen from Fig. 2, X-CT imaging uses x-rays to create a tomography image of an object's interior, Since some of the X-ray attenuations occurs when the X-ray penetrates the object, X-CT imaging is essentially the imaging of linear attenuation coefficient, the ultimate goal of CT image reconstruction is to solve the μ value of each voxel (Fig. 3).

Known from Lambert's law in physics [18], when the monochromatic wiring harness passes through an object of uniform density, the energy of the wiring harness is weakened by the interaction between the atoms of the material. The weakening degree is related to the thickness and absorption coefficient or composition of the material. It can be expressed by the following formula:

$$I = I_0 e^{-\mu d} \tag{1}$$

Where I_0 is the intensity of incident X-ray; I is the ray intensity transmitted after passing through an object of uniform density; μ is the linear coefficient of matter to this wavelength; d is the path length through the object of uniform density; e is the natural logarithmic base. We can see from the formula, the μ value is related to the X-ray energy, the atomic coefficient and density of the substance, the larger d or μ, the smaller I can be deduced, that is the greater the attenuation of X-rays. From the conditions of lambert's law [19], X-rays penetrate objects of uniform density. For soils with complex structures, the formula still needs to be transformed (Fig. 4).

Suppose the object is divided into equal-length segments, each of length d, and d is small enough, assume that the density and attenuation coefficient of each segment are uniform, and the incident intensity of the first segment of X-ray with length d is I_0,

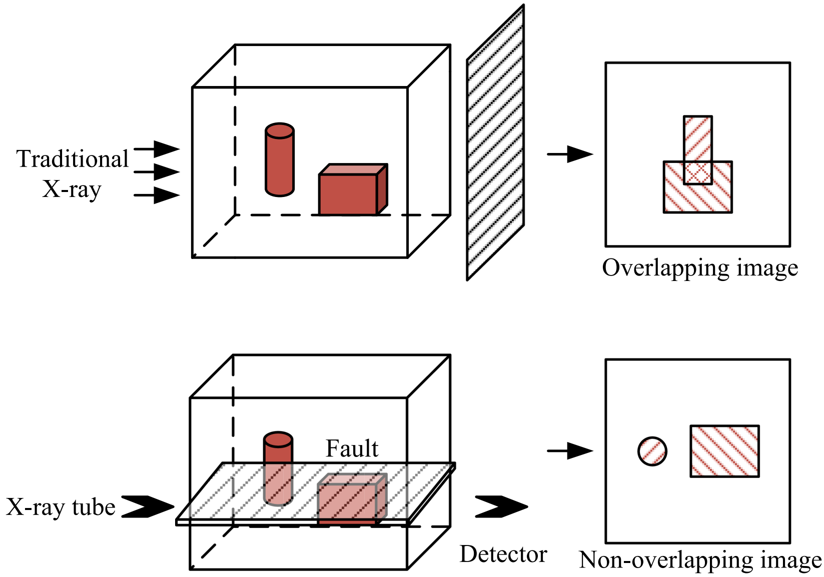

Fig. 2. Comparison of traditional X-ray and X-CT imaging

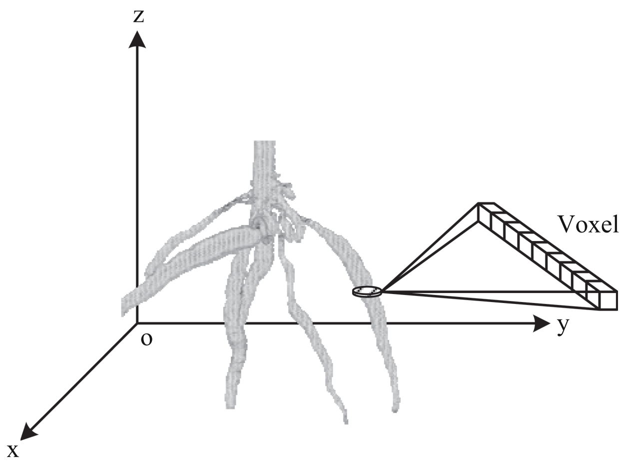

Fig. 3. Root spatial voxel

According to formula (1), the X-ray intensity I_1 of the first transmission can be obtained. According to the principle of calculus, there are:

$$I_n = I_0 e^{-(\mu_1 d + \mu_2 d + \ldots + \mu_n d)} \tag{2}$$

The transformation formula (2) that we can get:

$$\mu_1 + \mu_2 + \ldots + \mu_n = \frac{1}{d} \ln \frac{I_0}{I_n} \tag{3}$$

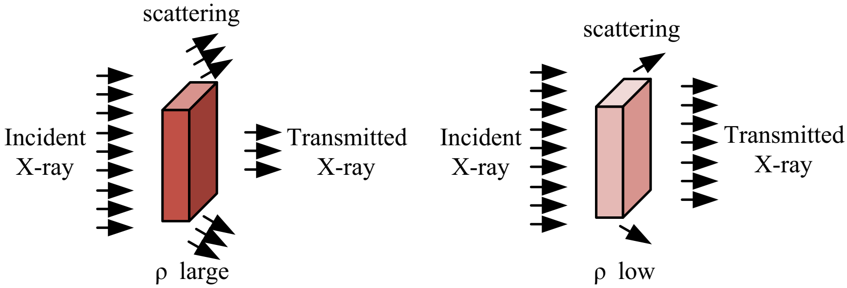

Fig. 4. The effect of density on X-ray attenuation

Therefore, under the premise that d, I_0 and I_n are known, the projection equations in multiple directions must be established to calculate the values of μ.

4.2 CT Number

In CT applications, the linear attenuation coefficient μ is not very descriptive and depends to a large extent on the X-ray spectral energy. Therefore, the CT number needs to be calculated relative to the attenuation of water. The data set generated by CT imaging technology is usually composed of CT values, it is defined as the X-ray attenuation coefficient of an object minus the water X-ray attenuation coefficient divided by the water attenuation coefficient and then multiplied by 1000. The unit of the result is expressed in Hounsfield.

$$CT_{number} = \frac{\mu_{material} - \mu_{water}}{\mu_{water}} \times 1000 \tag{4}$$

In formula (4) μ is the attenuation coefficient of X-ray, by definition, the CT number of air is -1000, the CT number of water is 0. Materials with an X-ray attenuation coefficient greater than water have positive CT value, while those with an X-ray attenuation coefficient less than water have negative CT value. When performing X-ray tomography, X-rays can make the voxels in each tomography scan to generate a CT value. This small

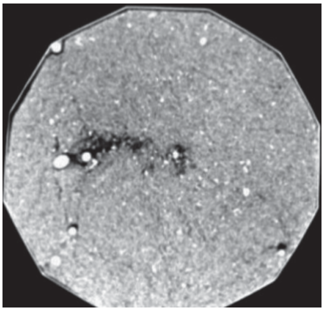

Fig. 5. CT image of in situ root system

space is regarded as a cube and 3D image data after the X-CT scan. The following figure shows the tomographic image data obtained by X-CT imaging (Fig. 5):

5 Root Image Segmentation

5.1 Image Feature

Among the data obtained from the three-dimensional imaging of plant root phenotypes based on X-CT technology, root analysis is a critical and hot CT image processing problem that needs to be accurately solved. Root image segmentation is also regarded as an important pre-processing link before three-dimensional root reconstruction. The central idea is to determine whether a specific voxel in the image space is "root" or "non-root". Unlike the micro-root window technology of transplanting seeds cultivated or visualized in a transparent nutrient base, which can identify the root imaging from the visible image. The root CT image is intended to be segmented from other substances (water, air, small stones, etc.) taking root features out is regarded as a technical problem in CT image processing. Because in the CT image, the root and some non-root matter will have overlapping CT numbers, in this process, the image segmentation methods involved in feature extraction are diverse and varied. Therefore, a root segmentation method suitable for the in-situ root CT image should be found.

5.2 Fuzzy Clustering Image Segmentation

The CT image segmentation of the root system is based on the difference in grayscale, texture, color and spatial characteristics of the root system in the soil medium. It benefits from the mature medical CT technology used in the imaging. After investigation and research, it is found that the clustering segmentation method is suitable for the segmentation and processing of medical images, which can well describe the fuzziness and uncertainty in general CT images.

Blurring is a fundamental feature of most medical imaging. It is difficult to make a short-term breakthrough in the research of imaging equipment in the early stage and there is no set of imaging equipment that can fully apply to the high resolution and high resolution of plant roots at the present stage, so the CT images have an artifact, noise, and fuzzy root boundary. FCM algorithm has been widely used in medical image segmentation [20].

6 FCM Algorithm

In the fuzzy clustering algorithm, the FCM algorithm is also known as the fuzzy c-means algorithm, which is an improved algorithm compared with the traditional algorithm [21]. It divides all the pixels in the image into y fuzzy groups. For each fuzzy group, the clustering center of each group of pixels is solved. Through continuous iteration, the objective function is minimized. The objective function is:

$$J(a, b) = \sum_{i=1}^{m} \sum_{j=1}^{n} \mu_i(x_j)^k \left\| x_j - b_i \right\|^2 \tag{5}$$

In the formula, $\mu_i(x_j)^k$ represents the membership function of the j-th pixel to the i-th category. Satisfy $0 \leq \mu_i(x_j)^k \leq 1$, b_i is used to represent the clustering center of class i, we can get the Euclidean distance $\|x_j - b_i\|^2$. It is also a similar measure of the algorithm.

In the FCM algorithm, $\sum_{i=1}^{m} u_i(x_j)^k = 1$, which is expressed as the membership degree of each cluster center is 1. In this case, the minimum value of Eq. (5) is solved. The iterative and fuzzy operations are used to solve the cluster center value to complete the fuzzy classification of the collected image data.

The specific steps of the FCM algorithm are shown in the figure below (Fig. 6):

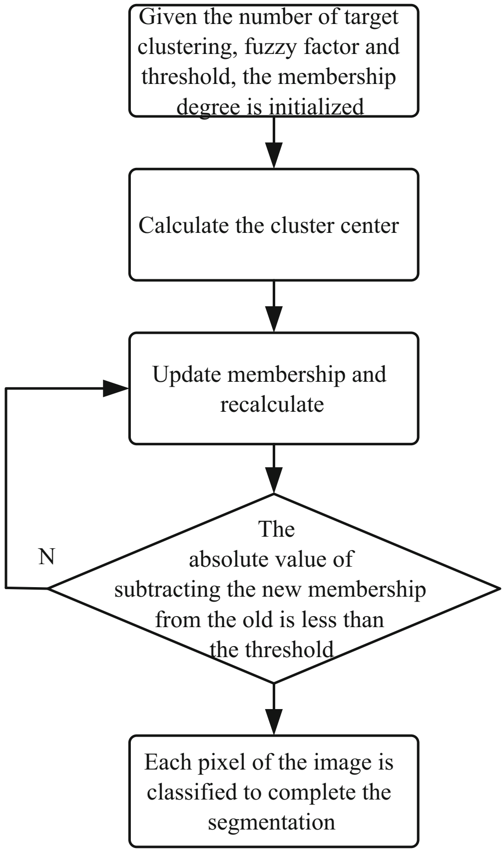

Fig. 6. FCM algorithm step flow

7 Analysis and Discussion

In situ CT tomography of plant roots was performed, as shown in Fig. 7:

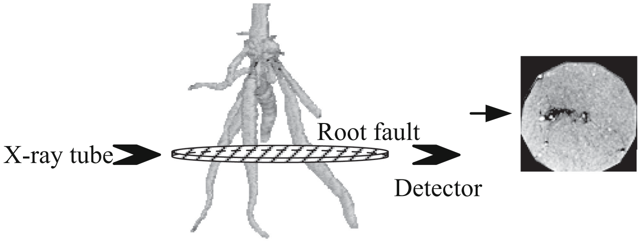

Fig. 7. Root CT imaging

We perform N = 10 times, N = 30 times, and N = 50 fuzzy operations on the obtained in situ root CT images by MATLAB R2017a, the obtained segmentation map is:

In this figure, a, d and g are CT images of the root in situ. b, e and h are the clustering results of the FCM algorithm 10, 30 and 50 times respectively. c, f and i are the results of the FCM algorithm 10, 30 and 50 times respectively.

According to the transverse comparison in Fig. 8, it is found that fuzzy clustering segmentation based on CT images of in-situ roots can segment the characteristics of plant roots within a certain fuzzy threshold, but some problems of the complex structure of soil medium are also exposed. For example, there may be uneven density distribution in the soil, resulting in different imaging grays or grays consistent with plant edge root systems, another example is the effect of a little air and moisture in the soil on the imaging results, however, it is undeniable that fuzzy clustering segmentation can be applied to CT image segmentation of root in situ through the segmentation results of the relatively thick upper root.

From the vertical comparison in Fig. 8, it can be seen that the processing diagram generated by multiple fuzzy clustering segmentation still fails to separate root characteristics to a large extent. The gap between the processed segmentation results is getting smaller and smaller, which exposes the problem of basic imaging equipment. There is no imaging equipment exclusive to in-situ CT images based on plant roots and this imaging is still solely dependent on medical imaging equipment. If we don't consider the imaging factor, we can't seem to get the desired segmentation map with root features by using only one segmentation method. At the same time, it is proved that the segmentation method cannot be single and limited in a specific complex environment.

Through the horizontal and vertical comparison of the results, it can be found that the FCM algorithm of fuzzy clustering segmentation can perform an iterative operation on CT images of in-situ roots, but it is difficult to achieve satisfactory results by using the traditional medical segmentation method for CT images of in-situ roots with more noise and artifacts.

In the in-situ CT image processing, after investigation and research, it is found that few segmentation methods are completely applicable to the in-situ root CT image and the traditional image segmentation methods are still used to realize the segmentation of CT image root features, which are specific to the in-situ root CT image segmentation methods that are rarely reported at home and abroad. The present research only improves and applies the mature method of medical CT image segmentation (fuzzy clustering

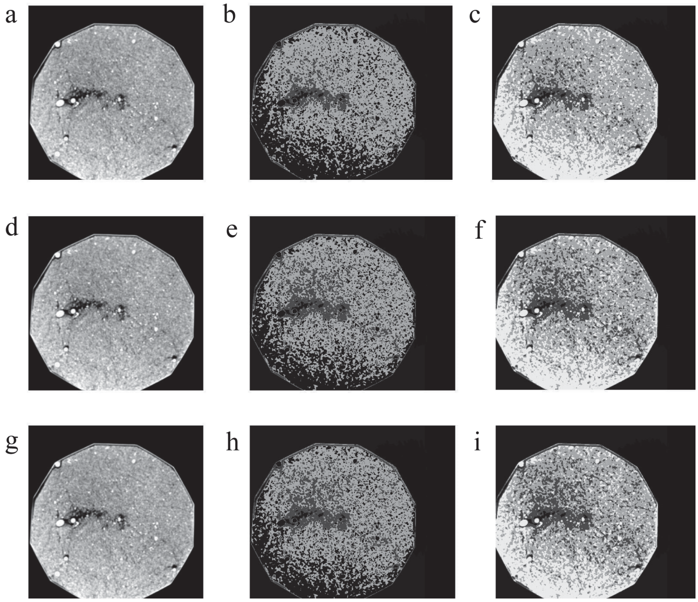

Fig. 8. Comparison of the number of fuzzy clustering segmentation operations for in situ root CT images

image segmentation). A CT image segmentation method based on in situ root system is urgently needed for the future research of root reconstruction and high throughput image processing.

8 Conclusion

This paper introduces the working principle of X-ray computed tomography, X-ray computed tomography technology was employed to reinforce the plant roots in situ nondestructive imaging, to obtain in situ root CT images, using medicine commonly used fuzzy clustering segmentation methods for feature extraction, through 10, 30, 50 times found that the results of the fuzzy arithmetic of single fuzzy clustering FCM segmentation algorithm can be implemented for in situ root feature extraction and segmentation of CT images, but not very good effect. To extract root characteristics accurately and with high quality, the segmentation algorithm of CT images of in-situ roots should be further optimized to make the data analysis of phenotypic images of high-throughput plants more accurate and stable in the future.

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