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学 位 論 文 題 目	Study in Features of Plants Based on Quantitative Analysis of Non-numerical Properties
論 文 審 査 委 員	主　査　教授　石黒　真木夫 教授　田村　義保 助教授　瀧澤　由美 教授　渡辺　正勝 主任研究官　岩田　洋佳（(独）農業・生物系特定産業技術研究機構）

Recently, as a result of development of biotechnology, especially of genome marker technology, acquisition of genomic information became easier. Investigation of the relationships between creatures' macro-traits and genome information is becoming an important theme for biologists. On the other hand, inexpensive digital cameras made it easy to get digital images of living things. Accordingly, investigation of the relationships between creatures' shape and genome information is becoming an important theme for biologists. In order to do this, the quantitative measurements of shapes are necessary. In this research, we propose a new method for quantitative evaluation of shapes.

In 1982, a quantitative evaluation method for shapes of plants by using elliptic Fourier descriptors (EFDs) proposed by Kuhl and Giardina. Since then many researches began to use Fourier descriptors to do quantitative evaluation of shapes of plants. For examples, Furuta *et. al.* analyzed leaves of soybean, Ohsawa *et. al.* did analysis of seeds of buckwheat, Iwata et al. analyzed shape of roots of Japanese radish and leaves of citrus and so on.

Though EFDs has many merits, it has the fault that only closed curves can be well described. In the evaluation of shapes of the plants, it is sometimes necessary to evaluate shapes with open curves. Results of analyzing partial contour are more meaningful than that of analyzing whole contour in some cases. Moreover, when the targeted plant's organ has got the insect damage or has been cut artificially, the complete contour is not able to obtain. So the evaluation of parts of contours is important. In 1984, Uesaka proposed P-type Fourier descriptors (PFDs). PFDs is not only applicable to closed curves but also to open curves. Since PFDs can be applied to the description of open curve, it is considered that the method based on PFDs can extend the range of application of shape analysis based on EFDs and become one of the effective quantitative evaluation techniques for plant organ shapes. P-type Fourier descriptor was applied to the author distinction of the Ukiyoe. But application for the quantitative evaluation of plant's shapes is not found. Our research is the first one in which plant organ's shapes is analyzed with the aid of PFDs and principal components analysis (PCA).

In our research, we analyze tips of lotus's petals and blades of citrus as samples for our new method. Petals of lotus had been cut into several parts in order to make them flat, so that we can easily digitize their contours. Outlines of petal are not closed, and so the quantitative evaluation method that based on EFDs cannot be applicable sufficiently.

From fragmented lotus petals, which were obtained by cutting each bowl-shaped petal into four or five fragments, we extracted the contour of the tip part of petal and delineated the contour shape using PFDs up to 8th order. The first principal component of PFDs accounted for 50% of the total variation, and the cumulative contribution of the first five components reached 80%. The shape variation explained by each principal component could be visualized by inverse Fourier

transformation. The 1st and 2nd components were good measures of sharpness and asymmetricity of the tip part of petal, respectively. The 3rd and 4th components explained the features of the apex of the tip part. We assessed shape variations within a flower based on petals of two varieties, and found that a systematic variation in the 1st principal component. As results of ANOVA, the varietal effect was significant at the 0.1% level in the 1st and 3rd principal components, indicating that the shape characteristics accounted for by these components reflected the among-variety variation well. The varietal mean of these two components showed continuous distribution, indicating that it is difficult to grade these shape characteristics. We conducted the variety classification based on principal component scores of PFDs using support vector machine. The rate of correct classification of 7 varieties was estimated as high as 85% by leave-one-out cross-validation.

Our results indicated that PCA of PFDs extracts the independent shape characteristics of petal of sacred lotus and these characteristics are efficiently used in the classification of sacred lotus varieties.

In research of blades of citrus, blades of several varieties of citrus were used to verify whether our method is useful or not. In this research, total 6 varieties citrus were divided into 2 sets (setA and setB), each set has 5 varieties. The blade shapes of setA are similar to each other. On the other hand, in setB the blade shape of Poncirus is very differ to other 4 varieties' blade shape. The highest recognition rate ratio reached 70.4% and 82.2% respectively for setA and setB. We also found that the PFDs principal components of Poncirus are very different with PFDs principal components of the other varieties. It indicates that these principal components of PFDs can also evaluate the plant organ, whose shapes are very differing to each other.

We got the results that our method can recognize differences of shapes among varieties with high recognition rate. Because the leafstalk and the blade can be thought as different organs, so we evaluate not whole outline of leaf but its blade quantitatively, We wish that this analysis would help us to find some new features related to shapes of leaves.

In our research, the software was developed. It can help us to evaluate shape of plant's organs with PFDs and PCA. Our analysis results indicate that PCA of PFDs can extract independent characteristics of shapes from petals of sacred lotus and blades of citrus. Principal component scores of P-type Fourier descriptors from plant organ were used for discriminate analysis. We hope that our research will promote the improvement of automatic classification of plants.

I assembled several programs developed for this research into package software. I expect that my research of automatic classification and genetic analysis based on the quantitative analysis of shapes of plant's organs will be able to profit agriculture and biology in near future.

論文の審査結果の要旨

(論文審査結果)

審査委員会は鄭澤宇氏の提出論文について口頭試問を含む審査を行い、当該論文が学位授与に値する水準のものであるとの結論を得た。詳細は以下の通り。

(論文の構成と概要)

1章:Introduction

課題の位置付けおよび歴史的経緯のまとめ。

2章:Image analysis of digital photos

画像データ、輪郭抽出法などのその解析の手法およびP型フーリエ変換について解説し、これらの組み合わせによって構成される2次元曲線形状解析ソフトを提案。

3章:Quantitative Evaluation of lotus's petal shape

提案した方法によって、ハスの花弁の先端部分の形状の品種依存性、ひとつの花のなかの花弁の位置の効果、同じ品種の花の花弁の平均的形状などが求められることを示した。

4章:Cultivar Identification of Lotus with Tip Contour of Petal

ハスの花弁の先端部分による品種分類にあたっては、花弁の幾何的特徴と色の組み合わせより、提案した方法によって抽出した形状の特徴の方が有効であることを示した。

5章:Quantitative Evaluation of Leaf Shape and Classification of Citrus Variety

柑橘類の品種分類にあたって、提案した方法によって抽出した葉の形状の特徴が使えることを示した。

6章:Conclusions

まとめおよび今後への展望。

(注)論文は英語で書かれている。

(論文の評価)

本論文は植物器官の形態から情報を抽出するための手法と適用に関する研究の成果を述べている。植物器官の形態形状は、一般に遺伝子のみではなく、環境や、また遺伝子と環境の相互作用(GE 交互作用)を通して決定されるためにばらつきが大きく、形態からの情報抽出には大きな困難が伴う。従来、たとえば、形態による植物の分類は、専門家が対象物を目視し、その経験によってなされていた。形態情報を数値化して統計的手法を用いることもなされていたが、閉曲線の解析に適して楕円フーリエ記述子が用いられていた。鄭氏は、植物の形態の研究にあたって外形の一部分の解析が必要になる場合があり、そのためには開曲線の解析が重要になることに着目し

・　デジタル写真から画像処理の方法により輪郭線を抽出する

・抽出した輪郭線をP型フーリエ記述子を用いて情報圧縮する

・P型記述子の主成分分析を行うことにより形態の特徴を抽出する

・主成分得点を用い、SVM（サポートベクターマシーン）等の手法により判別を行う

という一連の手法を連結させることを発案し種々の応用の可能性を示した。

鄭氏が可能性を示した方向は植物の形態にもとづく自動分類あるいは、形態と遺伝情報との関係を調べる方法につながるものであり、今後交配等による遺伝実験や，複数環境における実験等を通して，十分に評価されるべきものである。

・　以上を総合して、鄭氏の論文で提案された方法の個々の要素手法は既存のものであるが，独創的な組み合わせによって構成された方法はデジタルイメージからの輪郭抽出から解析と分類までの機能を、使いやすい、将来の生物学的応用への広い可能性を秘めたソフトウェアとしてまとめたものとしての価値が認められる．結果の主要部分が論文として育種学会誌に掲載予定（印刷中）であり、方法の有用性は証明されているものと考える。