博 士(農 学) 傅 隆 生

学 位 論 文 題 名

A methodology for efficient harvesting and grading of haskap berry, and its application on blueberry harvesting

(効率的なハスカップ収穫・選別手法の開発およびブルーベリー収穫への応用)

学位論文内容の要旨

In this research, a system which can harvest haskap berries and blueberries and a methodology which can grade the harvested haskap berries were developed. The system was aimed to replace the conventional hand picking for harvesting haskap berries and blueberries in Japan. The methodology of grading was the first step for developing a future automatic berry grading system which could replace current hand sorting. The main propose is to improve the productivity of the farm owners by accomplishing this agricultural task with smaller number of labors and lower cost to encourage more farmers to plant berries, especially the being appreciated local haskap berries. In addition, ageing in agricultural societies in developed countries is becoming a serious problem that needs to be solved by automating physically-tiring and dangerous tasks as well as repetitive tasks which do not require special skills.

In order to improve the harvesting efficiency of haskap berries with minimal added cost, three new harvesting systems were developed by making use of items that are usually available in farm sheds or easily found in the market. In 2008, haskap berries were separated by picking and dropping method, collected by a modified umbrella, and cleaned by sieving fruit by mesh nets in water. In 2009, haskap berries were separated by striking the fruit branches with a hand-hold plastic pipe, collected by a plastic net container, and cleaned by blowing foreign materials with an electric fan. In 2010, haskap berries were separated by vibrating the fruit branches with a special designed metal hock which is linked to a modified jigsaw, collected by a portable tarp catch, and still cleaned by blowing with an electric fan. Among them, the new harvesting system developed in 2010 was selected as the optimal way. It could separate 19.4 kg or clean 22.9 kg haskap berries in one hour, reached the total harvesting efficiency of 10.4 kg/h which is seven times than that of the conventional hand picking (1.5 kg/h). Moreover, it could reduce the average cost for harvesting haskap berries from 483 yen/kg of the conventional hand picking to 78 yen/kg based on a rough estimate. However, it increased damaged fruit rate from 2.7% of the conventional hand picking to 3.8%, and required additional grading for classifying large unripe and damaged fruit from the sound haskap berries.

Since the skin colors of the unripe haskap berries (green or red) are different from that of sound ripe berries (blue), and damaged berries have the presences of defects but none in sound ripe berries. All of them thus were supposed to be able to be distinguished from each other by using color imaging analysis. All the samples were divided into five groups based on the skin's color features: 'nondefective', 'damaged' (including 'scarred', 'insect damaged', and 'broken'), 'shrunk', 'unripe (red)', and 'unripe (green)'. In order to reduce the cost of using controlled lighting, images of all samples in Red, Green, and Blue (RGB) were acquired at outside noon shade. Since it is uncontrolled lighting condition, directly obtained RGB components are varied with lighting change. Therefore, a relatively stable color model HSI (Hue, Saturation, and Intensity) which decouples the intensity component from the color information was adapted. And the procedure for classification is as followed. Firstly, by analyzing the hue values distribution which was obtained by sampling pixels from the 'nondefective' fruit, the color of haskap berries was found near 212° in hue value. The same method was used to investigate the optimal background color by testing the fourteen common color sheets that available in the market. One of them No.11 with the hue value around 29° was selected as the background to hold haskap berries. Then, with the threshold computed by Otsu's algorithm in the red channel, the fruit were segmented from the background successfully. Lastly, three parameters, average and standard deviation of hue component, and average of saturation component, were chosen as the best descriptions for each haskap berry. Based on that, three canonical functions obtained by using forward stepwise discriminant analysis were able to classify 'nondefective', 'damaged', 'unripe (red)', 'shrunk', and 'unripe (green)' haskap berries at success rates of 95.1%, 81.5%, 85.0%, 88.9%, and 100%, respectively. However, around 15% 'damaged' were misclassified into the 'nondefective' berries. Nevertheless, this study indicated that it is possible to classify the unripe and damaged fruit from the sound berries under noon shade according to their color features by using imaging analysis with a RGB color camera.

However, there was one more category haskap berries, overripe berries, were left in the group 'nondefective' since their color appearance is similar to the sound ripe berries and thus could not be detected from them by the RGB color imaging analysis. The problem is that the overripe berries can be extremely damaged or broken with its juice leaking out. It may not bad at the time of harvesting but may be unacceptable when they reach the consumer. Therefore, a novel technique, hyperspectral imaging, was employed for distinguishing overripe berries from ripe berries of haskap. It included two parts, i.e., removing background from fruit and discrimination between overripe and ripe haskap berries. Both of them can be divided into pixel-based discrimination and object-based discrimination.

From sample pixels of fruit and background, it was found that intensities of fruit pixels at the *NIR* wavelength region were higher than that at the *RED*, while intensities of background pixels were high at *RED*. Therefore, the value of the intensity at 751 nm divided by the intensity at 671 nm of each pixel was calculated for removing background. Then, spatial processing was applied to identify each entire fruit object. And it reached the success rate of 90%. For discrimination between overripe and ripe haskap berries, the sample pixels could be discriminated correctly in 70.5% using three wavebands at 751 nm, 420 nm and 857 nm. And the success rate of fruit objects discrimination was only 65.8% which is not high. Therefore, a future improvement is to erode the fruit object area for eliminating the fruit edge area where most pixels had been misclassified by the pixel discriminate model. Nevertheless, it showed the potential of overripe berries identification using hyperspectral imaging analysis.

The new harvesting system not only for haskap, but also had been test on blueberry. The harvesting experiment for blueberry in Yoichi Orchard reached a rate of 19.7 kg/h with the harvesting system 3 (2010), while that of the conventional hand picking is 2.8 kg/h. However, this new system also harvested 20% unripe blueberries. Therefore, it was necessary to investigate the suitable vibrating speed of the experimental jigsaw, and this speed should separate more ripe while less unripe fruit with the shortest time. A high-speed camera was employed to record separating process of blueberries by the jigsaw. Then, details of the harvesting process were collected by replaying recorded videos in a slow motion. After that, statistical analysis was used to determine the suitable vibrating speed and vibrating time. It was found that the best setting of the jigsaw was dial 2 with the vibrating speed of 1670 cpm to vibrate each branch around 1 s. In that case, it could separate 78% ripe blueberries while only 17% unripe blueberries.

In 2011, the new harvesting system (2010) was applied in a commercialized blueberry farm. Since blueberries in this business oriented farm were more productive, the harvesting efficiency was increased to around 30 kg/h, and it is ten times than that of the conventional hand picking (3.0 kg/h) in this farm. However, it harvested much more unripe blueberries which would burden on grading. Grading efficiency was dropped to 2.4 kg/h from 3.5 kg/h on the fruit of conventional hand picking. Nevertheless, the total cost for harvesting 1 kg blueberries was reduced 21% from ¥433 to ¥344. Moreover, the new harvesting system could save field working time thus increase production that had been lost every year due to lack of handpicking workers and raining during harvesting season. In all, this new harvesting system by vibrating blueberries with a modified jigsaw is already adopted by this farm. Although they still handpick blueberries in the early harvesting stage where few ripe fruits, they will use the vibrating system to harvest them in later stage when all or most blueberries are ripe.

Finally, it can be said that, a harvesting system, which not only harvested haskap berries and blueberries efficiently but also reduced cost, was developed by making use of items commonly available in the farm sheds or easily found in the market. A grading methodology, which successfully classified unripe and damaged haskap berries from sound ripe haskap berries using RGB color imaging analysis and identified overripe haskap berries using hyperspectral imaging analysis, was also developed.

学位論文審査の要旨

主　査　教　授　柴　田　洋　一
副　査　教　授　木　村　俊　範
副　査　准教授　片　岡　　崇
副　査　講　師　岡　本　博　史

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本論文は6章からなり，図64，表25，文献71を含む122頁の英文論文であり，別に参考論文2編が付されている。

本研究では，ハスカップ・ブルーベリーの収穫システム，およびハスカップを選別するための手法を開発した。本研究は従来，日本において行われている手摘み法からの置換を目指した。本研究の主目的はハスカップおよびブルーベリー栽培における収穫・選別作業の能率を向上させることである。そしてこれにより，必要な労働力およびコストの低減を目指している。加えて，現在日本では農業従事者の高齢化が深刻な問題となっており，過度の肉体労働や危険な仕事を回避するためにも，本研究の手法は有効である。

最小のコスト追加でハスカップの収穫能率を向上させるために，3つの新しい収穫システムを開発した。2008年，両手で払い落とす方法でハスカップ果実を収穫して下に置いた傘で集め，メッシュネットと水を用いた手法により葉，枝などの異物を除去した。2009年，プラスティックパイプを用いて枝をたたくことにより果実を落下させ，収穫した。異物の除去は送風ファンを用いた。2010年，ジグソーを改造したハンディ型振動式収穫機を開発した。

北海道大学余市果樹園のハスカップ圃場において検証実験を行った結果，これら3つのシステムの中で，2010年に開発した振動式収穫機の結果がもっとも良かった。このシステムにより1時間当たり19.4 kgの収穫，および22.9 kgの異物除去が可能となり，トータルの作業能率は10.4 kg/hとなった。これは従来の手摘み法（1.5 kg/h）に比べて7倍である。また，コストを計算したところ，従来法では483円/kgであったのに対して，振動式収穫では78円/kgとなり，大幅な低コスト化を実現できた。

また，開発した振動式収穫機をブルーベリー収穫作業にも適用した。北海道大学余市果樹園のブルーベリー実験圃場にて収穫実験を行った結果，作業能率は手摘みによる従来法が2.8 kg/hであったのに対して，振動式収穫機では19.7 kg/hとなり，大幅な能率向上が確認された。しかし，振動数や振動時間によっては，適熟な果実だけでなく，多くの未熟果実も収穫してしまうことがあった。そこで，最適な振動数と振動時間を決定するための解析手法を考案した。高速度・高解像度カメラを用いた振動式収穫の解析により，ブルーベリーの場合，振動数1670 rpm，振動時間1秒が最適な振動設定であると判明した。

次に，この振動式収穫機を商業的果樹園における収穫作業に適用し，作業能率やコストを算出

した。この商業果樹園では，現状ではすべて手摘みにて収穫を行っており，その場合の収穫能率は3.0 kg/hであったが，本研究の振動式収穫機を用いることで作業能率は30 kg/hとなり，これは現行法の10倍であった。しかし，振動収穫を行うことで未熟果実の混入が増加したため，収穫後の選別作業において能率が従来法（3.5 kg/h）よりも低下した（2.4 kg/h）。以上の結果から，収穫と選別を合わせた総合的なコストを試算したところ，従来法が433円/kgであったのに対し，本研究の手法では344円/kgとなり，およそ20 %のコスト低減が実現した。

振動式収穫機の導入により大幅な収穫能率の向上が実現した一方で，未熟果実の混入増加により選別能率の低下が課題となった。また，未熟果実だけでなく，損傷果実，虫食い果実，過熟果実などについても作業者の目視による手作業選別が行われているのが現状である。そこで，本研究では画像解析技術を応用した自動選別手法についても検討した。

ハスカップ果実を対象とした選別において，未熟，損傷，虫食いのものについては可視カラー画像処理を応用した判別手法を開発した。分析の結果，色相の平均・標準偏差および彩度の標準偏差を組み合わせた判別式を用いることで最も良い判別精度が得られ，その場合の判別成功率は88.5 %であった。

しかし，過熟果実についてはその表色が正常果実とほぼ同様であるため，可視カラー画像処理による手法を用いるのは困難である。そこで，ハイパースペクトル画像解析手法を用いた詳細な分光スペクトル分析を行い，過熟果と正常果の判別を行った。判別実験の結果，751，420，857 nmの3波長バンドの組み合わせた判別式が最適となり，判別成功率は72.9 %となった。これは必ずしも高い判別精度とは言えないが，人間の目視による判別はほとんど不可能であることを考えれば，十分に意味のあるものと考えられる。

以上，本研究ではハスカップおよびブルーベリー収穫・選別のための省力化技術を開発，検証した。収穫作業の省力化技術として，市販ジグソーを改造した手持ち型振動式収穫機を開発し，大幅な作業能率向上およびコスト低減を実証した。また，選別作業の省力化技術として，可視カラー画像処理およびハイパースペクトル画像処理を応用した，未熟，過熟，損傷，虫食い果実の判別手法を開発した。これらの技術を活用することにより，日本のベリー栽培のような小規模果樹園においても小さな初期投資で効果的な省力化を実現できることが期待できる。よって、審査員一同は、傅隆生が博士（農学）の学位を受けるのに十分な資格を有するものと認めた。