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学位論文題目	An End-to-End System Using Artificial Intelligence (AI) and Augmented Reality (AR) to Support Table Grape Cultivation （人工知能(AI)と拡張現実(AR)を用いたぶどう栽培支援）
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学位論文内容の要旨

Trimming the inflorescence and thinning the berries are two critical processes in table grape cultivation. This is because bunch compactness, bunch shape, and berry size, which are controlled mainly by these two tasks, all have a significant impact on the market value of table grape production. The inflorescence trimming and berry thinning should be carried out during appropriate period and farmers have limited time to complete the tasks. Especially in case of berry thinning, the appropriate time period is 2-3 weeks and it overlaps with raining season during which the berries grow quickly and the bunches soon become densely packed and it becomes impossible to do thinning without hurting the neighborhood berries. Since berry thinning requires high skill and is the key task to decide the final shape of the grape bunch, the size and quality of each berry, which has a dominant impact on market value, instead of getting help from part-time farmers, the farmers have to perform berry thinning tasks by themselves. Consequently, one skilled farmer usually needs to thin berries for more than 3000 bunches each season. Therefore, the technologies for supporting skilled farmer to perform the task more efficiently or enabling part time farmers perform the task with least training are urgently required by the table grape industry.

This dissertation addresses the challenging issues in applying state-of-the-art Artificial Intelligence (AI) and Augmented Reality (AR) technology to assist inflorescence trimming and berry thinning tasks in table grape cultivation. An end-to-end approach was implemented by considering the whole process from preparing data, training Deep Neural Network(DNN) models, deploying DNN models on the server, selecting the appropriate AR device for farmers, and designing the user interface for showing the relevant information to farmers. Image augmentation technique has been designed to tackle the difficulty of collecting sufficient images for training a DNN model generalized to detect grape berries with high accuracy under various unconstrained capturing environment. Experiments have been conducted to select and fine tune the state-of-the-art DNN models for the particular tasks. Novel post-processing techniques have been proposed to fulfill the requirement for each task. A server-site approach is adopted to make the DNN model capable of working with various devices and reducing the computation on edge devices such as mobile phones and smart glasses. Furthermore, the user experience has been taken into consideration in visualizing the predicted results to farmers in adherence with the intent of empower the farmer and do not disturb the regular tasks. The proposed end-to-end supporting system consists of an AI server and an Optical See-Through Head-Mounted Display (OSTHMD). Images are captured with the cameras installed on OSTHMD and sent to the AI server via pocket WiFi. The AI server accounts for intensive prediction computing then sends the results back to OSTHMD, showing the results and instructions to the farmer. This dissertation presents three main technologies for constituting such grape cultivation supporting system. The first is an automatic inflorescence measurement technology for supporting the inflorescence trimming task. The second is the automatic berry counting technology for supporting the berry thinning task. The third is the technology for automatically identifying berry to be removed for berry thinning task.

In most cases, only 20%–30% of an inflorescence is required to produce a bunch of grapes, and the ideal length varying by grape variety. Trimming inflorescences efficiently requires a farmer to accurately assess their length using their eyes, which is difficult for inexperienced farmers. While one to two weeks is the optimal time for inflorescence trimming, grape growers can significantly benefit from automated inflorescence measuring operates on a wearable device. The proposed novel end-to-end inflorescence measurement technology enables farmers to accomplish table grape trimming efficiently. It uses 2D images of the trimming scene only without requiring extra calibrators or high sophisticated preprocess, such as the existing methods based on 3D model reconstruction. The experiment results demonstrate that the proposed approach could reach an accuracy of 88.02% in inflorescence measurement and the inference time are fast enough for real-world working circumstances. An OSTHMD was employed to capture images and guide farmers without obstructing their trimming tasks. An interview to the farmers who used the proposed technology indicates that they are satisfied with the visualization design and that it aided them in intuitively comprehending the current and target lengths. As a result, the proposed system could significantly improve inflorescence trimming operations, and according to several farmers, the proposed system transformed a laborious process into a delightful one.

Berry thinning is a critical step in table grape cultivation. It is a necessary procedure for eliminating undesirable berries and provide sufficient space for remaining berries to grow into ideal size and taste. Karoglan et al. discovered that combining bunch and berry thinning increased mean cluster weight, total phenols, flavan-3-ols, anthocyanins, and a variety of other phenolic chemicals. The number of berries in the bunch is the essential criterion in the berry thinning task, and the optimal berry count range vary by the table grape variety. On the other side, counting berries during berry thinning takes time for both expert and novice farmers, and it is especially difficult for novice farmers. The proposed novel end-to-end berry number prediction technology succeeded in predicting the numbers of berries in the operating bunch accurately by making use of the state-of-the-art deep learning technology. Since a DNN model requires massive training data, a novel data augmentation technique simulating the thinning process is proposed to create a customed grape dataset for gaining a good instance segmentation result. To focus on the working bunch only and avoid detecting surrounding bunches, the structure of the state-of-the-art instance segmentation model is modified to integrate the location feature. The proposed location-sensitive Hybrid Task Cascade (HTC) model can also be applied for other object detection problems that require detecting a particular object from an image comprised of multiple objects of similar features. A set of features, together with their extraction algorithms, is designed for predicting the number of berries in a bunch (3D counting) using the berries detected on a single 2D image. Experiments results show that the proposed the average prediction error is below ±2.5 berries, which is considered to be smaller enough for being used for supporting real thinning task.

To verify the practicality of the proposed system in actual viticultural settings, the table grape field in Yamanashi prefecture, Japan, was selected to experiment with the proposed system during the entire annual cultivation process in season 2021. Participants including 1 skilled farmer and 6 people who have no experience of grape cultivation at all were invited to perform the tasks with the 6 naïve farmers using the supporting system while the skilled farmer didn't. The experiment showed that the proposed system enables unskilled farmers to perform inflorescence trimming and berry thinning efficiently and accurately. The unskilled farmers can become to be familiar with the proposed system very fast. For inflorescence trimming tasks, they can perform better than the target time and even faster than professional farmers. The berry thinning task is more challenging than the inflorescence trimming task. Unskilled farmers can thin the berry faster when they get used to the system and tends to reach the target time. Nevertheless, it is impressive that unskilled farmers can perform the tasks without training. As the results, the average quality score of harvested table grapes grown by unskilled farmers using the proposed system was 8.18 % higher than that by skilled farmers, which demonstrates that the proposed AI model can prevent human error to determine which berry should be removed.

論文審査結果の要旨

山梨県はブドウの生産量が日本一であるともに、熟練した生産者により品質の高いブドウが生産されており、国内のみならず海外からも高い評価を受けている。こうした高品質のブドウを生産するためには、生産段階において様々な栽培管理作業が必要であるが、なかでも果（花）房管理の良否は、外観・品質に直接影響する重要な作業である。経験豊富な生産者は、房づくり（開花期に花の長さを調整する作業）や摘粒（多すぎる粒を間引く作業）といった管理を長年の経験から適切に行っており、こうした「匠の技」が高品質ブドウの生産を支えている。一方、新規就農者や雇用労働者（援農なども含む）などは経験が少なく、このような熟練者の技を伝承する必要がある。しかし、果樹作は「年１作のため技術習得の機会が少なく」、「農繁期の限られた期間に作業が集中するため個々に十分な指導が行き届かない」などの制約があり、スムーズな技術の伝承が困難なことが大きな課題となっている。

このような地域の課題を解決するために、本研究では最先端の深層学習技術（AI）と拡張現実（AR）技術を応用し、ブドウ栽培に房づくりと摘粒作業を支援する技術を開発した。この技術は、高品質ブドウを生産するために重要な栽培管理である「房づくり」と「摘粒」作業において、スマートグラスで作業者が視野に捉えた果（花）房の画像をサーバに転送し、AI で解析した適切な作業指示をスマートグラスの視野内にリアルタイムに投影することで、新規就農者や雇用労働者に匠の技を伝承し、高品質なブドウの生産をサポートすることができる。

房づくり作業では、花穂の先から一定の長さを残し、残りの花をすべて切り落とす必要がある。熟練者は目視で長さをある程度判断することができるが、新規就農者には難しい。本学位論文で提案する技術では、最新の深層学習モデルに独自に設計した画像解析アルゴリズムを組み合わせ、穂先からの長さを自動測定することを可能にした。実験では、穂先からの軸長の計測誤差を±0.2mm以下に抑えられることを確認した。

一方、摘粒作業では、房に含まれる粒数は摘粒作業における重要な基準であり、粒数のカウントは熟練者にとっても時間のかかる作業である。本研究では深層学習と回帰モデルを組み合わせることで、作業中の房の１枚の 2D 画像から 3D 房に含まれている粒数を推定する技術を開発した。作業中の房のみに着目し、その周囲の房を検出しないよう、最新の領域分割モデルの構造を改良し、位置情報を統合した。提案手法の平均予測誤差は±2.5 粒以下であり、農業従事者より実際の摘粒作業支援に十分利用可能であるとの評価を得た。また、新規就農者には摘粒対象の判別が困難である。本研究では、摘粒対象と周囲の粒との位置関係の特徴を獲得しやすくさせる Attention Forcing

機構を提案し、摘粒対象推定問題を画像分類問題に差し替えて、摘粒対象を推定する技術を開発した。その予測精度は88.02%に達している。

本研究では実際のブドウ畑において、熟練者及び提案の支援技術を用いた一般参加者により栽培したブドウの品質を評価する実験を行った。その結果、提案技術を用いることで、熟練者よりも8.18%高い品質の達成という優れた結果が得られた。この理由として、AI モデルはノイズを排除したうえで良好な学習データに適合させることができ、人為的なミスを防ぐことできるため、より安定した作業結果つながるが挙げられる。

本学位論文の研究成果は、国際会議録及び国際学術誌に掲載されたほか、計 3 点の特許出願も果たしている。多くのメディアにも採り上げられ、全国的に大きな注目を集め、地域の発展にも寄与することができた。

博士論文審査要綱に基づき最終試験を実施した。提出された博士論文および公聴会における発表の内容に関連し、研究背景、概念規定、アルゴリズム設計、実装方法、評価実験の妥当性と信頼性、論文構成、情報学的価値などに関する質疑を行い、論文提出者の見識を問うた。その結果、試問の内容において妥当な解答が得られたこと、並びに発表論文の基準を満たすものであったことから、博士論文審査委員会は博士に相応しい学力と見識を有するものとして認め、最終試験を合格とした。