Mapping Yield and Quality using the Mobile Fruit Grading Robot

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Localised crop output measurement is the principal requirement in determining profit on a spatially variable basis. Quality of agricultural products immediately affects the market value. Therefore, quality maps should be obtained as well as yield map. In this research, a database of spatial yield and quality information was created for sweet pepper by using the mobile fruit grading robot. Then a real-time mapping method was developed from the database. Three hundred and seventy-two sweet pepper fruits harvested from 300 plants were utilised for the experiment in laboratory. Information such as plant location, harvesting time, fruit index (number of fruits from a plant), fruit size, colour, shape, defects and grade also mass was obtained. Based on these information sources, a database was established to create both a yield map and a quality map. Results indicated that the database is adequate to represent the spatial variability of yield and quality in a field as yield and quality maps, the developed mapping program is effective and practical, and that the system can be applied in real time.

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1. Introduction

Precision agriculture, an emerging and important technology for improving farm profitability, utilises detailed site-specific information within agricultural fields to manage input decisions on a spatially variable basis (National Research Council, 1997). Advances in technologies such as global positioning systems (GPS), geographic information systems (GIS) and remote sensing have created the possibility to assess the spatial variability present in the field and manage it with appropriate site-specific practices.

Spatial yield variability in a field is the focus of many studies for the purpose of making yield maps. Yield monitors or sensors incorporating GPS are utilised to create yield maps (Pringle et al., 2003; Kaho et al., 2003; Dobermann et al., 2003). Schueller et al. (1999) reported low-cost yield mapping in hand-harvested citrus. Also, real-time crop yield mapping has become increasingly popular (Pierce et al., 1997).

One of the most significant factors that affect the marketable value of crops is quality information, but it has not received enough attention as compared to yield. Especially for fruit crops, the quality of fruits immediately influences the market price and producer benefits. Therefore, if the spatial quality information in a field can be collected as yield information, crop health, insect or disease conditions can be available, so that the crops can be managed site-specifically applying proper doses of fertilisers and pesticides, then investment can be optimised and the effect to the environment reduced (Giles & Downey, 2003).

In Japan, the scale of a farm is about 1-5 ha, and agriculture is mostly a second occupation for farmers. Moreover, farmers are over 65 yr old on the average. Further, major concerns for farmers are how to enhance consumers confidence in the food supply, how to increase production efficiency and how to get/train their successors. Japanese farmers are seeking solutions for such complex problems, leading them to look at the potential application of precision farming to small-scale farms (Shibusawa, 1999, 2000, 2001). Shibusawa (2003) has developed the concept of a Japanese precision farming model, where ‘community-based precision
farming is accompanied by the well-organised knowledge of farmers and a technology platform. The technology platform provides three key technologies: mapping techniques, variable-rate techniques and decision support systems which take into account rural constraints. The best linkage between the farmers’ knowledge and the technology platform would produce information-oriented fields and information-added products that encourage multi-functions in agriculture, creating new value-chains in the agro-production-consumption system. For information-oriented fields, information collection and management are key tasks in precision farming. Also, in order to produce food with safety and reliability, information-added product/food chain traceability is becoming one of the effective approaches (EFSA, 2000; EU, 2002; Shibusawa, 2003). The concept of information-added agricultural products, especially high class fruits, are classified with identity and information (i.e. harvesting time and location, quality, etc.) added to them. Moreover, for fruit production system appraisal, both input and output data are necessary to be considered, and the quality information is as important as quantity for output data. Therefore, collecting data of spatial quality, yield, and harvest time of fruit and vegetables is a high-ranked task for Japanese farmers.

However, quality information has more parameters than yield information. According to Kondo and Ting (1998), for fruit crops, quality commonly includes outer parameters (size, colour, shape, surface texture and mass), inner parameters (sweetness, acidity or inner diseases) and freshness. Although outer and inner quality information can be collected by an automatic grading system in a factory (Ishii et al., 2003), once fruits are inside a facility it is difficult for a fruit grading system to collect information such as harvesting time for freshness and harvesting location for mapping, because producers often mix their fruit together without any information about where and when the fruits were collected. Therefore, the collection of spatial information of fields and plants and the management of the information for the Japanese precision farming model has been considered as an emergency issue in Japan. In a former study (Qiao et al., 2004a), a mobile fruit grading robot for sweet pepper was developed to fulfill this purpose. This mobile grading robot can travel in the field and grade fruits on the go, as a result, fruit quality information, harvesting time and location can be acquired 

The objectives of this paper are to create a database of yield and quality information by using the mobile fruit grading robot, and to develop a method to accomplish mapping for yield and quality spatial variability of sweet pepper.

2. Materials and methods

2.1. Mobile fruit grading robot

Figure 1 shows the structure of the prototype grading robot and associated software. The hardware includes: the mobile mechanism, which travels across the field ditch carrying the other parts and fruit containers; a two-dimensional Cartesian manipulator for moving an end-effector; an end-effector for grasping the stem of the pepper fruit, moving the fruit through the machine vision system and loading it into a container; a grading unit composed of an electric balance to weigh the mass of the fruits and a machine vision system to grade fruits by image processing; and three personal computers (PC1, PC2 and PC3). The first computer (PC1) controls the mobile mechanism, manipulator, end-effector and electric balance, and is installed with two software packages as shown in Fig. 1(c). The other two computers (PC2 and PC3) are used for the machine vision system and have three software packages. A local network was used for data transmission between the computers.

A view of the grading robot prototype and the scheme of machine vision system are shown in Fig. 2. The machine vision system consisted of five charge coupled device (CCD) cameras, which can take five images, four from the sides and one from the top of the fruit; and nine direct lights, which provide uniform light in constant luminous intensity and colour perception (Qiao et al., 2004a).

Sweet peppers are widely consumed fruit vegetable in the world and with variable colour also irregular shape; hence, sweet pepper was selected as experimental materials. For grading sweet pepper fruits by the machine vision system, grading algorithms were developed by Qiao et al. (2004b). The algorithm can successfully
estimate size, sort colour, classify shape, detect bruises or scar tissue and predict the mass of the pepper fruits.

2.2. Database of fruit yield and quality

The grading robot not only can grade fruits but also has the potential to collect spatial yield and quality information. In this research, a database was created to save and apply the information. There are two types of file storage in the database: a bitmap file for images of fruits and a text file for features and harvesting time of fruits and plant location. The left side of Fig. 3 presents the flow chart of the grading robot operation and the right side gives the database of the spatial yield and quality information collected. The flow chart shows that when a plant is located by the grading robot, the plant location data is sent to the database. Then, the end-effector accesses a fruit harvested by an operator; meanwhile, the harvesting time (in fact, it is accessing time of the end-effector) and a unique index of the fruit are recorded in the database. In the next step, the fruit moves through the machine vision system, five images
including four side views and one top view of the fruit being acquired and at the same time, the images are saved in the database. After that, the features of each view including size, colour, shape and defects are extracted by image processing, and these features are transmitted and saved to PC1 for the next step to integrate the five image aspects to represent the whole property of the fruit. After image integration, the features of the fruit are obtained, and the fruit is sorted according to the grading standards. The information is also saved in the database. Finally, the sorted fruit is loaded into a suitable container while its mass is weighed. However, if there are any more fruits on that plant, the robot continues to access the next one, otherwise it will move to the next plant. By this means, the database created to include the yield and quality information, harvesting time and plant location can be used to map the yield and quality in the field.

In the experiment, the location of each plant was determined by using position of the plant itself, since the distance of each plant was fixed (i.e. 0-45 m).

2.3. Experimental area

Sweet pepper was utilised for the experiment. The materials were picked up from Yasato town in Ibaraki Prefecture, Japan on 16th July 2003. The total area of the sweet pepper field was of 1125 m² with about 1500 plants. The width between the rows was 0.75 m and the distance between the plants was 0.45 m. Commonly, the farmer sprays chemicals on each plant or gives uniform fertiliser as an average dose. According to the local regulations for agricultural products (Yasato, 2003a), during the 6 months harvesting season, farmers can only use chemicals for disease or insect control less than eight times; also fertiliser is applied at the beginning of the harvesting season. As a result, reduction of chemicals and effective usage of fertiliser become an important point for reducing costs of products and limiting environmental effects.

The schematic experimental area is presented in Fig 4. A part of the field with 300 plants (6 lines by 50 rows) was selected, and a local coordinate was established as shown in the figure.

2.4. Materials

Three hundred and seventy-two fruits of the sweet pepper variety of ‘Tosahikari’ were harvested from the experimental area and used in this experiment. According to the local grading standards (Yasato, 2003b), sweet pepper is classified into three grades. Grade A corresponds to uniform colour and good shape (shape A), no bruises or insect injuries; grade B includes pepper fruits with good shape (shape A) but with limited defects, fruits with only shape deformation (shape B) as well as fruits with shape deformation (shape B) also limited

![Fig. 4. Schematic of experimental area](image)

![Fig. 5. Flowchart of drawing map in real time](image)
defects; and grade C, of sub-standard quality categorised by the lack of specific colour, presence of too many bruises or injuries and also with significant distorted shape. For the defects of the pepper fruits, the grading standard indicates three main unacceptable colours: ‘red parts’, ‘black parts’ and ‘white parts’ on the surface of green pepper fruit; also bruises and scars.

In this experiment, the pepper fruits were picked up and their identity (from which plant) were recorded in the field, and then the harvested pepper fruits were transported to laboratory for experiment. In the laboratory, the mobile grading operations were reproduced by the robot, the pepper fruits were graded one by one as if a farmer was working with the robot in the field.

2.5. Real-time mapping method

2.5.1. Data representation

As the data of each individual plant can be obtained by the mobile fruit grading robot, there is no need for interpolation or modelling to map this information, only to design which information should be mapped. In this experiment, the distribution of both number and mass of fruits per plant was mapped as yield information and the distribution of shape, defect and grade of harvested fruits were described as quality information map.

2.5.2. Mapping programme

For mapping the spatial yield and quality data, a mapping class was developed using Microsoft VC++6.0. The mapping class consists of five functions: determine unit size; get coordinates; read data; select colour panel and draw map. Figure 5 shows the flowchart of drawing map in real time. The first step is to determine the unit size of one mapping unit in a map. As the mapping window has a limited size (512 pixels in width and 480 pixels in height), the mapping unit size should be determined first to ensure that the whole map can be shown within the window. The default unit size is 10 pixels in width by 15 pixels in height and the user can change it by inputting the number of lines and rows of

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**Fig. 6.** Yield maps for sweet pepper: (a) number of fruits picked; (b) average mass of fruits; and (c) total mass of fruits
plants. The second step is to obtain coordinates of the plant location from the database, and later a mapping unit would be drawn following the coordinates. The third step is to read data of yield or quality from the database in preparation to map it. And then there is a condition, if it does not get data; it means the database has not the data of the plant yet. As a result the program will go to the end. If data is available, the program continues to the next step to select the colour panel to represent the different levels of the data. In this research, the data level was decided by the local sweet pepper grade standards and each level of data corresponded to a colour panel. The last step is to draw map, which paints a unit of the map using the selected colour in the corresponding location. Iterations of the program continue until all units are completed. For drawing the map there are two options. One is drawing a unit immediately after the fruits of one plant are graded; the other is drawing all the units when the grading task is finished.

3. Results and discussion

3.1. Yield map

Although sweet pepper production has a long harvesting season and the total yield should be the aggregated output of all data collected through the season, in this experiment only one time output data was used to create the maps. The yield map of data obtained on 16th July, 2003 is shown in Fig. 6, where Fig. 6(a) shows the number of fruits picked up from each plant. The white area shows the location of plants with no output on that day, the blue area represents the level of grade A, the red area represents the level of grade B(1), and the black area represents the level of grade B(2). The last option is to draw all the units when the grading task is finished.

![Yield map](image)

Fig. 7. Quality maps for sweet pepper: (a) fruit shape based on local grade standards, where shape A is the best shape, shape B is worse than A but acceptable, and (1) and (2) indicates that a plant produces one or two more fruits in shape B; (b) fruit defects, where red and black fruits are unacceptable, limited bruises or white fruits are acceptable; and (c) fruit grades, where shape A without defects sorts to grade A, shape A or B with limited defects belongs to grade B, and misshaped or too defective fruits are grade C.
1 to 2 fruits per plant, the green area corresponds to 3 to 4 fruits per plant and the red area corresponds to the output with more than 5 fruits per plant. The map indicates that the number of fruits ranging from 0 to 10 m in X direction and from 0 m to 6 m in Y direction was lower than in the rest of the field. Also, the plants that were closest to the edge produced less fruits. Moreover, the number of no output plants on the right side is about half of that on the left side. The same results are shown in Fig. 6(b) and (c), the right side producing a higher yield than the left side in the maps. The reason for this occurrence may be due to edge effect caused on the left part located close to the road, but it could also be an isolated occurrence, and therefore more data needs to be collected to confirm this assumption.

3.2. Shape map

Figure 7(a) shows the shape of harvested fruits. The green colour means the shape of all the fruits picked up from that plant corresponds to shape A; the blue area indicates that only one fruit belonging to shape B was harvested and the rest belonged to shape A in each plant; and the red area shows there were more than two fruits corresponding to shape B and the rest belonged to shape A in each plant. As a result, all the fruits picked up from the experimental area on that day had a satisfactory shape. Among them, over 86% was classified as shape A.

3.3. Defect map

Figure 7(b) gives the distribution of defective fruits in the field. The green area means that the harvested fruits belong to the standard fruit category in that plant; the rest of the colours show those plants produced fruits with different defects. The orange colour represents the fruits with bruises or scars due to viruses or insects; the red colour shows green fruits with some red parts due to over ripening; and the black colour presents fruits with some black spots or some parts damaged by bacteria or soft rot disease; additionally, the yellow colour indicates a green fruit with white colour parts caused by sunscald or diseases (Mimura, 2002). As a result, the output information allowed the identification of total number of plants that produced defective fruits (14 plants) and the type of defects affecting each pepper fruit. It is evident that defects caused by bacteria, viruses or insects on the left side were higher than on the right side. The reason may be that the experimental area was close to the irrigation ditch and road where there was a weed buffer, possible lodging the damaging subjects, since damage in parts close to the edges were heavier than inside the field. Based on this information, suitable chemicals in proper amounts should be given to those plants or limited area. Therefore, the amount of chemicals can be reduced to save cost and concern the environment. However, in this experiment only one collection data was analysed, it is difficult to explain the phenomenon well; later, whole harvesting season data should be observed.

3.4. Grade map

Based on the local grading standards, grade A should be with shape A also no defects; grade B is shape A with limited defects, shape B or shape B with limited defects; grade C is allocated for sub-standard fruits with too many defects or misshaped. Figure 7(c) shows the grades of the fruits harvested on that day. This map implies that 82.8% fruits was sorted to grade A; 15.1% to grade B and 2.1% to sub-standard fruit in that day.

3.5. Database and the mapping system

The experimental results show that the created database could collect yield and quality information, harvesting time and plant location, and also the whole side views. The database was enough to present the spatial variability of yield and quality in a field. Six kinds of maps were produced using the database. Further, the database such as harvesting time and fruit views can be provided to consumers.

During the experiment, the time needed to make a map unit was of about 5 s from the moment a pepper fruit was fed into the end-effector until it was graded and loaded into a container. Within the 5 s, image processing needs only 0.4 s to extract the features of the pepper fruit, in addition the mapping time and data transmitting time, the total was less than 1 s. These results showed that the image processing program and the mapping class are effective and practical to produce the yield and quality maps. Also, the results implied that the yield and quality maps can be produced in real time while the fruits are graded in the field. On the other hand, the rest of the time of the 4 s was for moving the pepper by the mechanical system. Therefore, in the future, the function of the mechanical system needs to be improved.

4. Conclusions

A database of spatial yield and quality information was created using a prototype mobile fruit grading robot, and a real-time mapping method was developed. Using the database, both yield and quality maps could
be created in real time by the mapping class. Some 372 sweet pepper fruits from 300 plants were utilised for the experiment in laboratory, confirming that the database is adequate to map in real time the spatial variability of yield and quality in a field, and also that the mapping class is effective and practical. Moreover, the experiment results implied that the yield and quality maps can be produced in real time while the fruits are graded in the field. Further improvement is necessary to reduce the processing time for whole system.

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