博 士 論 文 の 要 約

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学 位 論 文 題 名

Development of a Harvesting Robot for Heavy-weight Crop

（重量作物のための収穫ロボットの開発）

## I. Introduction

The agriculture industry has faced different undeniable challenges including low self-sufficiency in food, age distribution of farmers, declining farming population and time-consuming for training new farmers. The heavy-weight crops such as pumpkin, watermelon, melon, and cabbage have remarkable market value in Japan. However, the number of farmers keeps decreasing in this fields because of physical fatigue of farmers and labor shortage. Current harvester is not properly designed in aspect of precision and carefulness. Current technology causes the damage of crop and declining in market value. The robot technology is a potential answer aiming to solve these issues. However, most of developed agricultural robot was focused on the small-sized and light-weight crops. In this study, the development procedure and performance evaluation of a specifically designed a harvesting robot for heavy-weight crops (HRHC system) were presented. The HRHC system includes a robotic arm (RA), an end-effector (EE) and a controlling unit (CU).

## II. Design and manufacture of robotic arm

The development procedure of a robotic arm for farm use was conducted by considering limitations caused by agricultural complex conditions with limited workspace and payload. The aims of this chapter were to develop an applicable low-cost robotic arm for farm use, and evaluate the performance. The components of the robotic arm were designed and simulated by using Solidworks software with standard design processes. A four degrees of freedom (DOF) structure with serial links was selected due to its simplicity in structure and cost-efficiency. The joints torque, Payload Per Weight (PPW), repeatability and other parameters were calculated. The average PPW of the developed RA and current industrial robotic arms were 0.2 and 0.084, respectively. The analysis showed that designed workspace volume, front access and harvesting area of the RA were $8.024 \times 10^9\ mm^3$, $3.518 \times 10^6\ mm^2$, and $808\ mm$, respectively. The results indicated that the selected DOF could be an adequate structure which can support an optimum workspace volume and covered surface for harvesting.

## III. Characterization of physical properties of pumpkin

The pumpkin verities of JEJEJ, TC2A, Hokutokou, Sukuna, Kikusui, and Ebisu were experimented. Three kinds of experimentations were conducted including general physical properties for investigating the pumpkin orientation and possible harvesting methodologies, compression strength test for measuring the yield force ($F_{ct}$), and bending-shear test for measuring the yield force to cut the stem. The orientation angle of stem in pure situation ($\theta_{PSO}$) and lift situation ($\theta_{LSO}$) was measured. The results showed that the average pumpkin's lift weight was 26% more than pumpkin's pure weight. After lift, the $\theta_{LSO}$ of all of specimens was changed to the range of $-90^\circ < \theta_{LSO} < +90^\circ$ due to the applied force from stem connections. The combination of lifting technique with pumpkin parametrization simplified the harvesting algorithm of the robot. The minimum cutting period has been achieved when the single angles blade with $60^{\circ}$ (S-60) was used. The minimum stress value to cut the stems was 2.84, 3.3, and 2.01 $N/_{mm^2}$ for JEJEJ, TC2A and Hokutokou, respectively. These results indicated that the S-60 was the appropriated blade to harvest the mentioned varieties of pumpkin with minimum time-consumption and stress.

## IV. Design and manufacture of end-effector and controlling system

Development of an EE with a unique harvesting methodology based on the properties of pumpkin was presented. The components of the EE were designed by using Solidworks software; dynamically simulated in SAM software; and after several modifications, the final components were manufactured and assembled. The EE contains five fingers designed to grasp and harvest heavy-weight crops with the diameter of 170 to 500 mm by a sustainable force distribution. The maximum stress values of final design were $6.2 \times 10^7$ and $7.8 \times 10^7\ N/m^2$ in the opened and closed mode, respectively. The results proved that the fingers components have enough capability under the maximum payload of the system, and the designed EE can harvest the mentioned varieties of pumpkin because the range of radius, volume and mass can cover the extracted physical parameter of pumpkins. The controlling unit (CU) of HRHC system (based on a PLC system) consists of a PC, a position board, amplifiers, servo motors, switching unit and emergency switches. The PC sends the commands to the servo motor and switch unit via position board and optical cables. The controlling algorithm was developed by using Denavit and Hartenberg (D-H) method in forward kinematics and inverse kinematics calculations. The experiment results indicated that the CU and developed algorithm could control the system properly.

## V. Field experimentations of harvesting robot for heavy-weight crops

The performance of the HRHC system were evaluated in terms of harvesting success rate (HSR), cycle time (CT), damage rate (DR), working space (WS), accuracy (Ac), repeatability (Rp) and control resolution (CR). The HRHC system had HSR, DR, average CT, and full CT of 92%, 0%, 42.4s and 53s, respectively. The final workspace parameters of modified system including the workspace volume, harvesting surface and harvesting length were $5.662 \times 10^9\ mm^3$, $2.86 \times 10^6\ mm^2$, and $800\ mm$, respectively. The results showed that average Ac in x and y directions, and Rp were 10.91, 9.52, and 12.74 mm, respectively. The CR in *x* and *z* directions were $1 \pm 0.075$ and $1 \pm 0.025\ mm$, respectively. These results indicated that the system had enough CR, Ac, and Rp for harvesting pumpkins. The HS of HRHC system (100%) was higher than overall average HS of previous studies 66% (40–86%). The experiments results were satisfied with the required performance. And, it was concluded that the HRHC system was applicable to harvest pumpkin in the field.

## VI. Conclusion

In this study, the HRHC system was designed, modified and evaluated under various conditions and environments. Physical properties of pumpkin as a target crop were taken under various conditions, and the characterization of the properties was performed. The evaluation of system showed that the HSR, CT, DR, WS, Ac, Rp and CR of the HRHC system met the performance requirements. Considering all process of design, simulation, manufacture, modification and characterization, it was concluded that the developed HRHC system was effective for harvesting heavy-weight crops.