

論文内容の要旨

Agriculture, despite being one of the most important fields for humanity as it provides food resources, hasn't been affected by automation as other fields. The common trend for last several decades is to automate every single process where it is possible. Rapid advances in computer technology and control systems make it possible for automation of almost anything, starting from such mundane tasks as cleaning to seemingly difficult technological tasks such as building bridges. Automation in general is relatively easy in a well-defined or controlled environment. Agriculture, however, is neither. Agriculture could be defined as partially controlled environment as it is possible to define almost all parameters except for some important ones. For example, plants can be planted in known locations, but the place where plants will grow fruits can't be predicted or controlled with high accuracy. These and other reasons complicate automation of the harvesting process and is one of the main reasons why automatic harvesting robots still haven't reached the commercial production phase.

For the last few decades researchers all over the world have been trying to develop automatic harvesting robots for various fruits and crops. The main focus, of course, is on the major vegetables, such as tomatoes, bell peppers and cucumbers, and fruits, such as strawberries and grapes. For several years researchers in KUT have been trying to develop an automatic harvesting robot for Japanese green pepper, locally known as pīman (ピーマン), automatic harvesting. Japanese green pepper is smaller than bell peppers with average weight of approx. 40g (measurement obtained from commercially available specimens), and is one of the major vegetables in Japan. According to Ministry of Agriculture, Forestry and Fisheries of Japan collected statistical data for fiscal year of 2013 (Heisei 25), from 41 officially recognized major vegetable Green pepper is in 28th place in terms of the planted area (3360ha) and in 21st place in terms of the total production (145 300t). Kochi prefecture is the third largest Green pepper producer in Japan with 141ha of planted area and 13 000t (8.95% of all Japan production) of total production. In Kochi prefecture Green pepper compared to other vegetables is in 7th place in terms of planted area and in 5th place in terms of total production, making it an important income sources for the local farmers.

The first green pepper automatic harvesting robot prototype was developed by S. Kitamura and K. Oka and later improved by S. Bachche and K. Oka. The latest version of the robot prototype consisted of a 7 DOF robotic arm which was mounted on a mobile platform. All electronics were mounted in the mobile platform and consisted of central computer, power controller and motor controllers. The target recognition was performed by using two CCD IR cameras in stereo configuration for and an additional camera mounted on the end effector of the robotic arm. The end effector consisted of a scissor system that could perform the cutting and gripping tasks with a single movement. The prototype had many flaws, both in terms of mechanical development and actual functionality. For example, it didn't have means of moving itself in greenhouse as the mobile platform had no motor for motion. Also, it had to be connected to an external power source via power cable as no battery was mounted on the platform during the development period. Despite the fact that the algorithm for target recognition was already mostly developed by previous researchers, the performance of the harvester prototype still wasn't acceptable.

There are several reasons that complicate automatic harvesting of the green pepper and have been the main target of the continuous research. First of all, the detection of a target is not a trivial task due to the great similarity between color of fruits and the surrounding environment. The previous research performed by S. Bachche concluded that the HSV color space can be used to detect green pepper fruits in night time by using artificial lighting and by using an IR96 infra-red filter during day time. The acquired performance for both of these methods varied from 70 – 90% depending on the level of occlusions and illumination conditions. In this research however it was found that the best approach would be to perform the harvesting strictly during nighttime to avoid changing illumination conditions. Changing illumination is one of the main reasons for failure of target recognition as usage of global threshold values for segmentation is complicated and prone to errors. Unfortunately none of these methods allows for stem position detection, which is necessary for the used cutter system. The usual method in such case would be to analyze the shape of the target segment and to assume that the stem is along the longest major axis of the smallest possible ellipse that can be fitted on the target segment in the image. This method doesn't deal with cases when the fruit in question is occluded, thus the major axis can be in direction unrelated to the fruit direction, and when the fruit is tilted in direction towards or away from the camera. The second situation would lead to a stem position closer or farther away

from the robot than the fruit itself, and would complicate the harvesting.

Green pepper has a rather thick stem, which together with dense foliage are the main reasons for often slantwise growth of the fruits. The chosen end-effector is well suited for the automatic harvesting of green pepper as it doesn't need to grasp the fruit itself, just the stem of the fruit. The scissor-pincer system is capable of cutting and secure grasping of a fruit with a single motion and the V shape of the cutter allows for an error in the lateral direction of the stem position calculation.

It is widely recognized in the field of automatic harvesting that an additional sensing is required to deal with complicated cases when the visual cues alone doesn't provide the harvesting robot with the necessary information. The aim of this research was to develop novel methods for use in automatic harvesting of green pepper that would allow for improvement of the performance of the harvesting robot. The main question to answer was "How to detect the stem position if the visual information is unreliable?" Two general assumptions were made to base the research on, 1) only the cutting point is required for the cutter and 2) fruit position can be detected using the previously developed and verified method. In order to find the stem position a concept of pose estimation was used, which was proposed by K. Kapach et al. in the article "Computer vision for fruit harvesting robots – state of the art and challenges ahead". The concept was implemented by using model matching of a predefined model and the surface points of an actual green pepper fruit. The surface points were obtained by a LIDAR type laser range finder and the model matching was performed by Coherent Point Drift algorithm developed by Andriy Myronenko and Xubo Song. The hardware used for the developed method consists of a LIDAR laser range finder, an RGB USB webcam, a vertical slider, a LED array and the control electronics. The developed method calculates the orientation of a fruit in space and the position of the stem. This calculated stem position is supposed to be used by the harvesting robot to cut the found target pepper. Two experiments were performed to evaluate the developed method. First, the accuracy of the method was evaluated under the laboratory conditions by using a green pepper test object at a known inclination angle and stem position. A real green pepper fruit was positioned on a test platform and set to a known inclination angles using a 2DOF manipulator. Then the pose of the target in space and the stem position was calculated by using the developed method. The result of the calculation was compared to the set position to assess the error of the calculation. Secondly, a field testing was performed in a greenhouse on green

pepper fruits. A test rig was positioned in the greenhouse and the developed method was executed to acquire the result of pose estimation and stem position calculation algorithm. The result was then projected on the visual image to evaluate performance of the system.

It is recognized that the position of the stem calculated by the above described algorithm is a calculation and not actual stem position detection. Therefore means to verify that the stem is in the cutting position must be implemented. For this reason a touch sensor was developed, based on piezo effect. The sensor consists of two piezo stack actuators and a particular shape contact tip, which are all mounted together on the base of the cutter. The sensor works as follows: one of the actuators is being driven by a sine wave in one of the resonant frequencies while the other actuator generates a charge due to this motion. The contact tip acts as a mechanical coupling between the actuators and also as an additional mass. The resonant frequency of any mechanical system depends on the stiffness and mass properties of the system. In this case, whenever some object, such as a stem, touches the contact tip of the sensor, the mass and the stiffness properties are changed and consequently also the frequency response of the sensor. The shift of the resonant frequency causes the amount of charge generated by the second actuator to change. The change of the generated charge is then detected by the signal processing unit. As the change of the properties is directly dependent on the mass properties of the touching object, the touch between the sensor and a leaf is not detected due to the relatively small mass and stiffness change of the system. The position of the sensor allows a detection of a stem between the cutter blades but also makes it impossible for bigger objects such as fruit itself to touch the sensor. Several tests were performed to evaluate the performance of the developed sensor. First, the frequency response was measured to find the driving frequency. Secondly, each of the found major resonant frequencies was tested for stability in an extended time measurement to evaluate the quality of the frequency. The most promising frequency was used as the driving frequency for all remaining tests. The following tests were sensitivity test, movement test and field testing. The sensitivity test was designed to evaluate the sensitivity of the sensor by pushing a pinpoint force to various parts of the sensing tip with a known force, which was measured by a dial tension gauge. The result was then compared to the force required to push a green pepper stem in a greenhouse. The movement test was designed to analyze the effect of the movement of a manipulator on the sensor output. The experiment was performed by attaching the sensor to a manipulator and moving the manipulator

randomly while recording the sensor output. Then the result was compared to the measurement of a static sensor to assess the impact of the movement. Lastly, the field testing was performed by using the sensor in a greenhouse. The sensor was attached to a manipulator, which was moved manually, and a physical contact was made between the sensing tip and a green pepper stem while recording the output. This experiment was performed for two reasons. First, it was necessary to verify that a contact with a green pepper stem changes the physical properties significantly enough to affect the reading of the sensor. Secondly, the amplitude of the sensor output change was examined to decide on the detection threshold value.

Incompatibility between the hardware used for the pose estimation algorithm and the hardware of the previous green pepper automatic harvesting robot revealed a necessity for a new harvesting robot design. As a result, a new monorail type harvesting robot was designed. This design uses a single rail to move around a greenhouse thus solving the harvester positioning and movement problems. It also has vertical slider implemented separately from the working manipulator and works fully on batteries. The batteries are charged by noncontact inductive power supply, which allows for fully automatic operation. The developed harvesting robot is currently at the assembling stage and is not yet fully tested although some parts have been tested separately.

The dissertation is constructed as follows. First, a literature review on automatic harvesting is given with the focus on methods used for target detection and grasping/detachment technologies. The state-of-art situation both in methodology and in hardware development is presented to demonstrate current achievements and obstacles to overcome. Afterwards, the problems addressed by the current dissertation are explained together with the used methodology to solve them. A full description in great detail is given for all three of the above described developed systems and the tests performed, each in its own section. The results of performed tests are analyzed thoroughly and the implications of certain results are explained. Future work and improvement options are discussed in the end to outline the path for future researchers.