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REVIEW OF ROBOTIC TECHNOLOGY FOR STRAWBERRY PRODUCTION

S. G. Defterli, Y. Shi, Y. Xu, R. Ehsani

ABSTRACT. *With an increasing world population in need of food and a limited amount of land for cultivation, higher efficiency in agricultural production, especially fruits and vegetables, is increasingly required. The success of agricultural production in the marketplace depends on its quality and cost. The cost of labor for crop production, harvesting, and post-harvesting operations is a major portion of the overall production cost, especially for specialty crops such as strawberry. As a result, a multitude of automation technologies involving semi-autonomous and autonomous robots have been utilized, with an aim of minimizing labor costs and operation time to achieve a considerable improvement in farming efficiency and economic performance. Research and technologies for weed control, harvesting, hauling, sorting, grading, and/or packing have been generally reviewed for fruits and vegetables, yet no review has been conducted thus far specifically for robotic technology being used in strawberry production. In this article, studies on strawberry robotics and their associated automation technologies are reviewed in terms of mechanical subsystems (e.g., traveling unit, handling unit, storage unit) and electronic subsystems (e.g., sensors, computer, communication, and control). Additionally, robotic technologies being used in different stages in strawberry production operations are reviewed. The robot designs for strawberry management are also categorized in terms of purpose and environment.*

Keywords. *Robotics, Strawberry, Strawberry robots.*

Fruit and vegetable growers are always aiming to reduce their production costs, a high percentage of which comes from intensive and time-consuming labor such as in-season field scouting for biotic and abiotic stresses and pests, harvesting, and post-harvesting processing. With technological advances in sensing and control, robotics have provided and will continue to provide a great opportunity to significantly improve the production efficiency and increase the profit margin of agricultural products.

Between 1983 and 2014, at least 33 review articles were published covering a wide range of topics related to robotic technologies used in different agricultural applications. Robots used in general agricultural products are covered by reviews such as Grift et al. (2008), Hajjaj and Sahari (2014), Suprem et al. (2013), and Yaghoubi et al. (2013). Reviews on robots used in specific vegetables or crops are

also available, such as harvesting robots for oranges (Sanders, 2005) and sensing devices in hay crops (Marcotte et al., 1999). Kondo et al. (1996) reviewed different harvesting robots that have been studied in Japan. Some articles reviewed specific robotic technologies that have been applied to farming activities, such as spectral analysis approaches (Scotford and Miller, 2005; Sankaran et al., 2010), computer vision (Milella et al., 2006), guidance and navigation (Shalal et al., 2013), and sensors (Rovira-Más, 2010). Also, review papers have been published for different farming activities, such as weed control (Slaughter et al., 2008) and harvesting (Bac et al., 2014; Li et al., 2011). Table 1 shows a non-exhaustive list of the review papers that are publically accessible. It is worth noting that there are eight review papers which are listed in multiple categories.

Strawberries are one of the most consumed fruits all over the world. Fresh strawberry production increased from 143.335 million kg in 1970 to 1097.239 million kg in 2012, while the deflated grower price dropped from US \$1.8673 to US \$1.7328 per kg at the same time (Economic Research Service, 2013). The major contributor to the high cost of strawberry production is the labor cost, especially during harvesting and packaging (Feng et al., 2012a, 2012b). In addition to the aim of reducing the high cost of production via robotic technologies, strawberries have some unique growth tendencies; therefore many operations can be easily automated. Firstly, the size of the strawberry plant is relatively small as compared with fruits such as apples and citrus. Thus, they can be easily reached by relatively smaller or less expensive robots in both greenhouses and

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Table 1. Review articles about automation and robotic technologies applied in agricultural production.

Categories		References
Agricultural products	General products	Marchant and Moncester (1990); Edan (1995); Cox (2002); Zhang et al. (2002); Belforte et al. (2006); Pedersen et al. (2006); Grift et al. (2008); Suprem et al. (2013); Yaghoubi et al. (2013); Hajjaj and Sahari (2014)
	Specific products	Marcotte et al. (1999); Sanders (2005); Scotford and Miller (2005)
Farming activities	Harvesting	Tillett (1993); Kondo et al. (1996); Dampney et al. (1998); Sanders (2005); Li et al. (2011); Chiu et al. (2013); Rodriguez et al. (2013); Bac et al. (2014)
	Weed control	Zwiggelaar (1998); Lamb and Brown (2001); Blasco et al. (2002); Thorp and Tian (2004); Slaughter et al. (2008)
Robotic technologies	Computer vision	Blasco et al. (2002); Milella et al. (2006); Scotford and Miller (2005); Sankaran et al. (2010)
	Guidance navigation	Jahns (1983); Li et al. (2009b); Shalal et al. (2013)
	Sensors	Tillett (1991); Dampney et al. (1998); Zwiggelaar (1998); Marcotte et al. (1999); Lamb and Brown (2001); Reyns et al. (2002); Thorp and Tian (2004); Rovira-Más (2010)

fields. Secondly, matured strawberries are red, and can be easily detected using low-cost vision systems. Handling strawberries may be a bit challenging as compared with fruits like apples. Strawberry fruits are easily damaged and so most of the picking techniques in robotics attempt to grab the stems to avoid damaging the strawberry fruits.

To improve the profit margin for strawberry growers, many researchers around the world have developed robotic technologies to assist in a variety of operations, such as harvesting, sorting, packing, and disease detection, either in greenhouses or in open fields. In the United States, several projects related to robots for strawberry have been recently funded by the National Institute of Food and Agriculture through the Special Crop Research Initiative and the National Robotic Initiative programs (National Institute of Food and Agriculture, 2011). However, to the best knowledge of the authors, there has not been any review written that specifically discusses the status of the robotic technologies that have been developed, utilized, and/or are being developed for strawberry production.

This study provides a review and comparison of the current robotic or automation technologies applied in strawberry production with the aim of offering guides and references for readers to build their own automation systems for strawberry or other delicate specialty crops. A non-exhaustive list of different technologies used in strawberry production from 1998 to 2014 is presented and discussed. The article is organized into four sections. In the “Robot Category” section, studies in strawberry robotics are categorized according to their purposes and working environments. In the “Strawberry Production Operations” section, autonomous technologies used in different strawberry production operations are discussed, including planting, in-season management, harvesting, sorting/packaging and post-harvesting quality detection. In the section “Mechanical and Electronic System,” mechanical design of the travelling unit, handling mechanism, storing unit and electronic system components such as sensors, as well as computer, communication and control devices used in strawberry robotics studies are discussed. In the “Conclusions and Future Research Directions” section, conclusions are given for the current status of strawberry robotic studies and several future research directions are proposed so that efficient and more profitable autonomous operations can be achieved in the production of strawberries.

ROBOT CATEGORY

The strawberry production routine starts with preparation of the soil except in the case of hydroponic systems. The preparation, distribution, size and number of rows (in open field) or benches (in greenhouses or tunnels) precede the planting of the seedlings. Designs of robots for strawberry applications may differ in many aspects according to their working environment and objectives. In strawberry production throughout the world, the United States has a leading market share (28% of world production in 2010) followed by Turkey and Spain (Wu et al., 2012). The cultivation environments implemented in different countries are varied, such as greenhouses and tunnels in Netherlands and Belgium, greenhouse table top culture and hydroponic systems in Japan and South Korea, and open fields in California and many other places (Takeda, 1999). Although harvesting is considered a major task of robotic technologies in strawberry production, sorting, hauling, packing, weed control, and stress detection have also been studied. These robotic technologies from around the world are categorized for the different operations in strawberry agriculture.

Strawberry robots can be categorized by the functions of its subsystems which are directly in contact with targets such as strawberries, stems, leaves, or weeds in any strawberry production process. In harvesting robots, the main objective is to grip mature strawberries without causing damage and the handling system is designed according to this functionality (Kondo et al., 2005; Hayashi et al., 2010a, 2010b, 2012; Feng et al., 2012a, 2012b; Dimeas et al., 2014). In packaging and some strawberry harvesting robots, an end-effector is designed to apply suction to fruits (Hayashi et al., 2010a, 2010b, 2011b); while in disease detection robots, an end-effector will be used to cut diseased leaves and put them in containers (Xu et al., 2014). For weed control, autonomous robots are being designed to perform in-field operations and weed/blossom removal which is executed by end-effectors using mostly mechanical approaches (National Robotics Engineering Center, 2014).

Additionally, strawberry robots can be categorized according to their working environment. Most of the harvesting and packing/sorting robots are designed to work in greenhouses or specially organized plots. In many greenhouse harvesting operations, rail systems were used to guide the robot between rows (Kondo et al., 2005; Hayashi et al., 2010a, 2010b; Nagasaki et al., 2010, 2013); while a

few other harvesting robots were self-guided (Feng et al., 2012a, 2012b). For strawberry sorting/packaging in greenhouses, the robot is typically fixed while a belt conveyor brings the fruits in front of the robot (Hayashi et al., 2011b; Yamamoto et al., 2012). Some challenges involved in designing robots for commercial orchards can be mitigated if the field is well-organized. For example, Agrobot has collected strawberries along the side of strawberry plant rows in the field and then they are packed by human operators (Agrobot, n.d.; Bolda, 2012). Secondly, semi-autonomous and autonomous robots have been developed or are currently under development for strawberry field operations. For example, the commercially available, so-called all-electric strawberry harvesters are semi-autonomous vehicles: harvesting and packaging operations are done by human operators and the vehicle is automatically driven in-field (“Tektu T-100 Strawberry Harvester,” 2010.). In another study, the robot is an autonomous tractor-type vehicle, consisting of automated subsystems for detecting, picking, and transporting strawberries (AZoRobotics, n.d.). Studies on harvesting-aid robots which aim to transport harvested and packed strawberries on its container from a worker’s current location to a loading area have been reported (Scheiner, 2013; UC Davis College of Engineering, 2014; USDA-REEIS, 2014). One robot which is currently under development is aimed specifically at commercial strawberry field applications (Xu et al., 2014). In a future project planned in Brazil, a simulated environment was created in a software, in which unmanned aerial vehicles (UAVs) are used for the inspection of strawberry plants in field (Rieder et al., 2014).

Forty-four studies on robots for strawberry found in the literature are summarized in table 2, categorized by the working environment and the task(s) they carry out.

Weed control and disease detection throughout the strawberry production season are vital procedures affecting the quantity and quality of crops. In addition, these operations are more challenging in field as compared to greenhouse environments. Although state-of-the-art detection sensor development is a hot-button issue, there are only a few robots that have been developed or are under development specifically for such important strawberry operations. There are current studies in detection and removal of weeds (Blasco et al., 2002; Slaughter et al., 2008); however only one robot is under development specifically for use in strawberry fields (National Robotics Engineering Center, 2014). For irrigation, nutrient supply and chemical spraying operations, there are a few automated greenhouse systems (CMW Horticulture, n.d.). Harvesting robots have been intensively studied since this operation requires most of the labor effort. In sorting/packing operations, machine vision systems and image processing algorithms have the potential for more precise solutions than human eyes. There are more greenhouse robots being developed than field robots due to the controlled environment and well-organized indoor structure. Therefore, much research needs to be focused on robots that can work in real strawberry fields. The

Table 2. Categories of the studies using strawberry robotics (developed or under development) in publicly-available literature.

References	Purpose ^a	Environment ^a
Arima et al. (2001, 2003); Cui et al. (2013); Dimeas et al. (2014); Feng et al. (2012a, 2012b); Hayashi et al. (2009, 2010a, 2010b, 2012, 2013, 2014a); Kim et al. (2008); Kondo et al. (1998, 2005); Leonard et al. (2013); Nagasaki et al. (2013); Rajendra et al. (2009, 2011); Saenz et al. (2013); Takeshita et al. (2010); Tarrío et al. (2006); Yamamoto et al. (2008, 2009, 2014); Xie and Zhang (2006); Xu et al. (2013); Zhang et al. (2005)	H	G
Guo et al. (2008)	H & S	G
Hayashi et al. (2011b)	P	G
Hayashi et al. (2014b) [mobile harvesting robot; stationary harvesting robot, packing robot]	H & P	G
Rieder et al. (2014) ^b ; Xu et al. (2014) ^b	D	F
Yamamoto et al. (2012)	P & S	G
Xu and Zhao (2010)	S	G
Agrobot (n.d.); Bolda (2012)		
Busch and Palk (2011); AZoRobotics (n.d.) “Tektu T100 Strawberry Harvester” (2010)	H	F
National Robotics Engineering Center (2014) ^b	W	F
Scheiner (2013)		
UC Davis College of Engineering, (2014)	TR	F
USDA-REEIS (2014)		
Nagasaki et al. (2010); Saitoh et al. (2010)	TR	G
Hayashi et al. (2011a)		

^a “W,” “D,” “H,” “TR,” “S,” and “P” are used to represent “weed control,” “disease detection,” “harvesting,” “transporting,” “sorting,” and “packing” in the purpose category, respectively. “F” and “G” are used to indicate the working environment of robots as either “field” or “greenhouse.”

^b The robot is either planned to be developed or currently under development.

automation technologies are needed for all operations in strawberry agriculture in order to have efficiency resulting in accelerated production.

STRAWBERRY PRODUCTION OPERATIONS PLANTING

Traditional open field strawberry production requires precision bed shaping before planting to provide a basis for guidance of subsequent operations. This is usually done by a pan-type bed shaper or a spool bed shaper mounted on the rear of a rotary tiller (LSU College of Agriculture Center, 2014). Heavy-duty plastic mulch is laid with or after the bed shaping. Drip tapes for irrigation and fertilizing purposes are placed under the mulch using a specialized machine. During planting, a tractor punches holes at certain intervals on the mulch, and small strawberry plants are manually placed into the holes by workers riding behind the tractor. Although little research can be found for strawberry pre-planting preparation and planting, these are relatively highly-automated operations in commercial open field strawberry production.

IN-SEASON MANAGEMENT

Several research projects have examined the sensing technologies to facilitate strawberry in-season management.

These mainly included monitoring strawberry plant growth parameters, detecting stress and disease, and predicting yield. The commonly used ground-based or aerial-based sensors were multi-spectrometers or multispectral cameras (MS), hyper-spectrometers or hyperspectral cameras (HS), infrared thermometers or thermal cameras (TH), and chlorophyll fluorimeters (CF).

Often, stress and disease alter plant pigmentation, water content, and cell structure, which result in a change in the spectral reflectance of the plant. Because of this phenomenon, the spectral reflectance information can be used in-season to detect plant stress and disease (Fraulo et al., 2009; Wang et al., 2012), and later correlated with the final yield to establish yield prediction models (Misaghi et al., 2004; Li et al., 2009a). Many of these studies resulted in good accuracies or high correlations. For instance, an average accuracy of 81% was achieved for the classification of different levels of severity of two-spotted spider mite damage using spectral reflectance sensing (Fraulo et al., 2009). The accuracy of strawberry yield prediction by reflectance was reported to be between 46% and 61% by Li et al. (2009a) and 94% by Misaghi et al. (2004). Hyperspectral sensors measure the spectral reflectance of objects in tens to hundreds of narrow spectral bands depending on the specific application; while multispectral sensors measure the spectral reflectance of objects at a few (usually three to six) wide spectral bands. Infrared thermal sensors can be used to detect temperature or water stress of strawberries (Penuelas et al., 1991; Mannini and Anconelli, 1993; Grant et al., 2012) based on the fact that objects with different temperatures emit a different amount of radiation in the long wave infrared range. The average leaf temperature difference between water-stressed and non-stressed plants was negatively correlated with average measured stomatal conductance with a correlation r of -0.602 (Grant et al., 2012). Non-stressed plants were found to be about 3°C cooler than the stressed plants before re-irrigation (Penuelas et al., 1991). The difference between leaf and air temperatures correlated well with the maximum evapotranspiration ($R^2 = 0.79$), the soil moisture ($R^2 = 0.58$), and the yield ($R^2 = 0.79$) (Mannini and Anconelli, 1993).

Chlorophyll fluorescence is the fluorescence emission by plant chlorophyll molecules and is an indicator of plant physiology, such as water and chilling stresses in strawberries (Khanizadeh and DeEll, 2001; Razavi et al., 2008). Sunlight easily interferes with fluorescence measurement so its outdoor applications are more challenging. For a networked disease detecting robot pair which is currently under development (Xu et al., 2014), a multi-spectral camera and webcams are planned to work together to detect diseased leaves. It is worth mentioning that there is also some web-based software employed for the identification of strawberry diseases by comparing symptoms with pictures in a database (Pertot et al., 2012). This approach, however, has not been applied on strawberry robots. A summary of these applications is shown under the category of in-season management as shown in figure 1a.

HARVESTING

Though the majority of strawberry harvesting is still conducted manually in open field production, much research and product development has occurred on strawberry harvesting robotics, especially for greenhouse production. Various strawberry harvesting robots developed thus far follow a similar workflow, detecting mature fruits, locating desired fruit position, approaching each one, suctioning and pulling off the fruit or locating its peduncle followed by a hold and cut (Kondo et al., 2005; Yamamoto et al., 2009; Hayashi et al., 2010a, 2010b, 2012; Rajendra et al., 2009, 2011; Feng et al., 2012a, 2012b). Whether or not a strawberry is mature can be decided by calculating the ratio of the area covered by red pixels over non-red pixels in the strawberry image. If the calculated percentage exceeds a certain threshold value, the target fruit was defined as mature enough to be harvested by robots (Feng et al., 2012a, 2012b; Rajendra et al., 2009). Therefore, instruments used in strawberry harvesting robots usually obtain color and shape information from RGB cameras (“color”) and/or range cameras (“range”). The cameras used in these applications are mainly stereo-vision or binocular cameras.

The success rate of the onboard vision systems and their algorithms in harvesting robots is determined by both fruit maturity detection and position and orientation detection of the fruit or peduncle. The success rate in fruit color recognition was 83.4% in a study conducted by Yamamoto et al. (2009). In Cui et al. (2013), the vision system of harvesting robot was able to achieve a 93.6% success rate in detecting the ripe strawberries. The ripeness assessed by machine vision system had good correlations with human assessments—an R^2 of 0.956 for Amaotome variety and an R^2 of 0.821 for Beni-hoppe variety (Hayashi et al., 2010b). Fruit and peduncle detection accuracies are detailed in table 5 in the Electronics System section. Considering both the fruit/peduncle position/orientation and the maturity level detection success rates, in an annual hill top harvesting robot, the efficiency in harvesting was 83.2% with an operation time for a single fruit of 16.6 s (Cui et al., 2013). The harvesting robot for an elevated-through culture in a greenhouse had an 86% success rate with an average harvesting time of 31.3 s (Feng et al., 2012a, 2012b). In Hayashi et al. (2012), the third (fourth) prototype of the robot had an operation success rate of 60% to 65.6% (52.6%), and a harvesting time of 8.8 s (6.3 s), respectively.

The sharp distinction of colors between the mature strawberry fruits and other parts of the plant can facilitate the detection process. Most of the strawberry harvesting robots have used digital RGB cameras with CCD or CMOS imaging sensors to seek red color in successive image frames on-the-go [Arima et al., 2001; Tarrío et al., 2006; Guo et al., 2008; Hayashi et al., 2009, 2010a, 2010b, 2012, 2014a, 2014b (mobile harvesting robot); Rajendra et al., 2009, 2011; Takeshita et al., 2010; Feng et al., 2012a, 2012b; Cui et al., 2013]. CCD digital cameras provide high quality imagery, but they are expensive. CMOS digital cameras usually cost much less and provide images with acceptable quality.

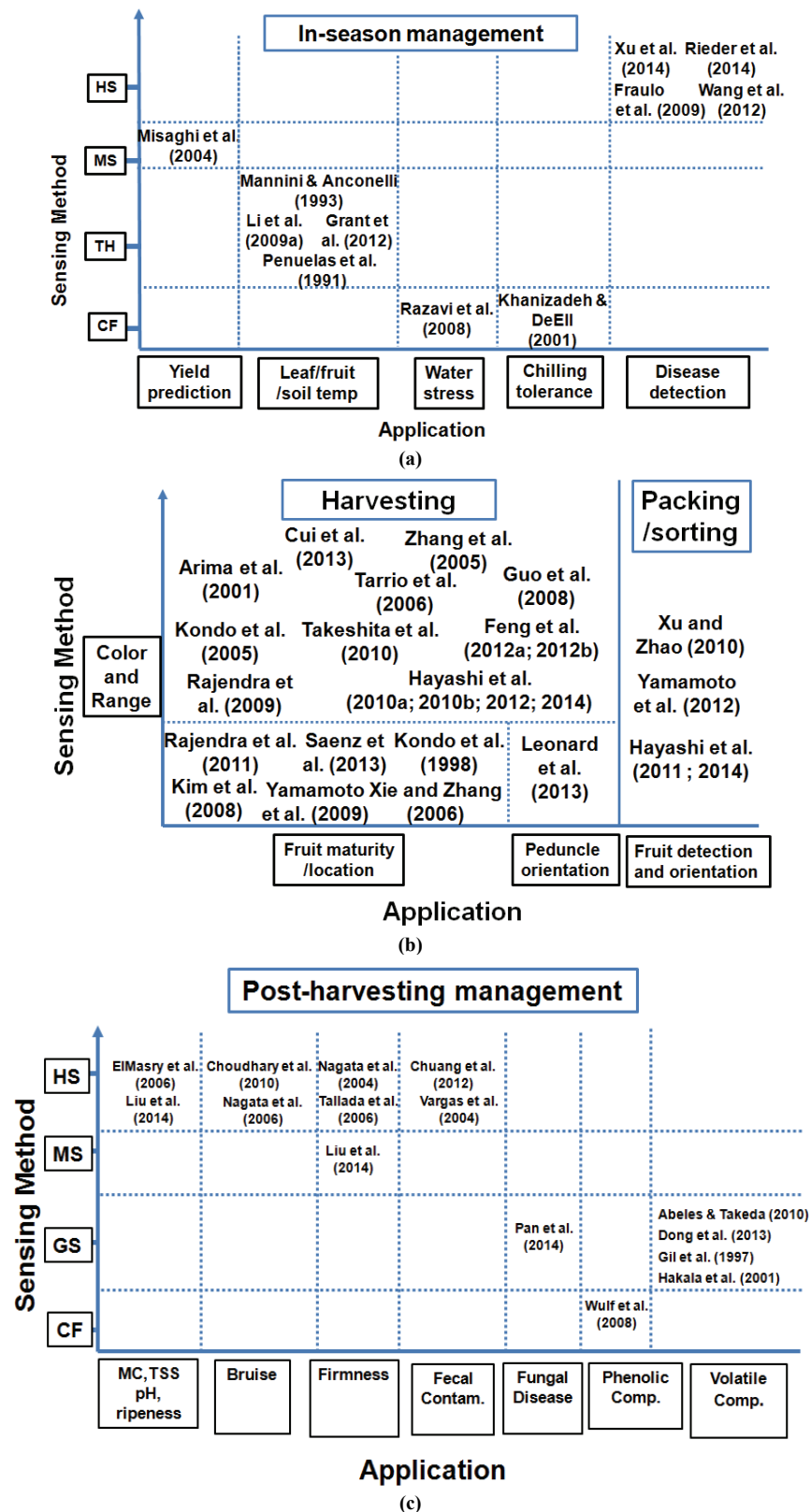


Figure 1. Sensing and analysis methods used in strawberry management operations. HS, MS, GS, TH, and CF represent hyper-spectrometers, multi-spectrometers, gas sensors, thermal cameras, and chlorophyll fluorimeters, respectively.

Algorithms have been developed in RGB (Zhang et al., 2005; Xie and Zhang, 2006; Yamamoto et al., 2009, 2014; Takeshita et al., 2010; Cui et al., 2013), HSI (Rajendra et al., 2009; Hayashi et al., 2010b, 2014a; Feng et al.,

2012a, 2012b), HSV (Rajendra et al., 2011), or OHTA color spaces. OHTA is an algorithm developed by Ohta et al. (1980) to assess the maturity level which is efficient when the background color is white or black (Guo et al.,

2008). In order to minimize the shading effect and create a uniform illumination for better image quality, white LED arrays have been installed to assist RGB cameras (Kondo et al., 2005; Yamamoto et al., 2009, 2014; Hayashi et al., 2010a, 2010b, 2012, 2014a; Rajendra et al., 2009, 2011; Feng et al., 2012a, 2012b). Stereo-vision cameras consisting of two RGB cameras are the most common type of sensors used by strawberry robots to locate the detected mature fruits in 3D coordinates (Kondo et al., 2005; Yamamoto et al., 2009, 2014; Hayashi et al., 2010a, 2010b, 2012, 2014a; Rajendra et al., 2009, 2011; Feng et al., 2012a, 2012b). Range images are formed by triangulating the images taken from the left and right cameras. In greenhouses, due to the constrained, organized and controlled environment, algorithms of the vision system of the robots can handle the detection of strawberry position and stem detection easily compared to field robots. In some greenhouse robotic studies, the erosion-labeling-dilatation method has been implemented for separating the views of closely adjacent strawberries (Yamamoto et al., 2014). In other studies the Canny edge detection method has been used for stem edge detection and the HOG/SVM method has been used for individual fruit detection in a bunch of strawberries with a success rate of 80% (Xu et al., 2013). In field robotics, any variations in the outside environment such as lighting, humidity, and wind may happen during the operation of the robot and the orientation and location of strawberries on the plant bed can exist in any combination. These uncertainties in field conditions require image processing algorithms to be robust for any unpredictable situation.

In other cases, robots picked fruits at their peduncles with the assistance of RGB cameras and photoelectric proximity sensors (Kondo et al., 2005; Hayashi et al., 2009, 2010a, 2010b, 2012, 2014a; Rajendra et al., 2009; Feng et al., 2012a, 2012b; Cui et al., 2013). Various image processing algorithms were also adopted in order to locate the grip points of a strawberry or its peduncle. The contour and structural frame of a fruit can be detected to form rectangles in the image of the strawberry, and then the one that contains the peduncle can be chosen according to the fruit geometry (Leonard et al., 2013). Peduncles could also be detected by converting the RGB values to OHTA color space (Guo et al., 2008). Strawberries were differentiated from leaves using segmentation in the HSV space (Feng et al., 2012a, 2012b). Each segmented fruit was divided into several row sections with constant height, and the center of the highest row section was selected as the picking point (Feng et al., 2012a, 2012b). Successful detection of peduncle orientation is also important for the peduncle gripping of end-effectors. The detected orientation of the peduncle guided the end-effector to rotate at corresponding angles making use of the rotational DOF of its wrist joint (Takeshita et al., 2010). Hayashi et al. (2012) reported an accuracy of 60% in detecting strawberry peduncles. With the exception of the above techniques, photoelectric proximity sensors were generally used to ensure the presence of a fruit (Hayashi et al., 2010a, 2010b, 2012, 2014a). A summary of these applications is provided under the harvesting category in figure 1b.

SORTING AND PACKAGING

In open fields, harvesting and packing operations are conducted simultaneously. In California, empty harvesting boxes are usually provided by vehicles to pickers and afterwards filled boxes are collected and transferred to loading locations. Some countries, such as Japan and Korea, require grading operations in order for the strawberries to be sold on the markets. The major task in automatic packing and sorting strawberries is to convey fruits from containers to pack and then align them according to their shapes. It is common practice that both RGB cameras and photoelectric sensors are used in this process for shape, range, or existence detection. For example, the RGB camera mounted on one manipulator decides which fruit to pick up first from the container and the best point at which to suction it up; while the RGB camera mounted on the other manipulator is in charge of picking up each strawberry and placing it in the packing trays (Hayashi et al., 2011b; Yamamoto et al., 2012). Photoelectric sensors were also installed on both the conveyor belt and the manipulator to detect fruit presence (Yamamoto et al., 2012). Hayashi et al. [2014b (packing robot)] developed a system to pick up the harvested strawberries from their container box and place the fruits on a conveyor belt by a suction-type manipulator. The orientation of each strawberry was detected by combining the center points of the major red and green areas in order to rotate the end-effector so that it could align itself for suctioning the strawberries in a proper way [Hayashi et al., 2014b (packing robot)]. In an automatic grading system developed by Xu and Zhao (2010), the strawberries were placed on conveyor belt manually, but the sorting and manipulating of the strawberries was done automatically. Two photoelectric sensors confirmed the strawberry presence on the belt, then images were taken for grading; lastly the gripper placed the graded strawberry within its classified box (Xu and Zhao, 2010). Some of the packing/sorting applications are listed in figure 1b.

The success rate of a sorting or packing robot depends on its machine vision hardware and algorithms. The packing robot in Hayashi et al. (2011b) had a packing success rate of 95% via a suctioning type end-effector with a certain height and alignment, and the time required to pick the strawberry from the conveyor belt and place it in a designated container was 8.9 s. In Yamamoto et al. (2012), the success rate including both the packing unit and the supply unit was 97.3%. It took the robot 4.5 to 4.6 s to grip a strawberry from the container and place it on the conveyor belt, and another 5.7 to 6.4 s for the robot to take a strawberry from the conveyor belt and place it into the tray. Similarly, in Hayashi et al. [2014b (packing robot)], the system had a success rate of 98% for its supply unit and 99.3% for its packing unit with an overall operation time of 7.3 s. The accuracy of the color evaluation and diameter categorization were 88.8% and 90%, respectively, and it took less than 3 s to sort each strawberry (Xu and Zhao, 2010).

POST-HARVESTING QUALITY DETECTION

Hyperspectral, multispectral, and fluorescence sensors have been used in strawberry post-harvesting quality

detection. The major parameters include moisture content (MC) (ElMasry et al., 2006; Liu et al., 2014), total soluble solids (TSS) content (ElMasry et al., 2006; Liu et al., 2014), acidity (pH) (ElMasry et al., 2006; Liu et al., 2014), ripeness (ElMasry et al., 2006), bruise areas (Nagata et al., 2006; Choudhary et al., 2010), firmness (Nagata et al., 2004; Tallada et al., 2006; Liu et al., 2014), and certain compounds (Wulf et al., 2008). Those sensors were also used for detection of post-harvesting disease, insects, or contamination (Vargas et al., 2004; Chuang et al., 2012; Pan et al., 2014). Another type of non-destructive sensor frequently used in post-harvesting fruit storage is the gas sensor (“GS”). They are used for monitoring volatile compounds such as C₂H₄ which is usually correlated with the fruit quality during storage (Gil et al., 1997; Abeles and Takeda, 1990; Hakala et al., 2001; Dong et al., 2013). The correlation coefficient for predicting the MC in ElMasry et al. (2006) was 0.87, for predicting the TSS content in Liu et al. (2014) was about 0.83. The accuracies for detecting bruised areas were between 84.6% and 86.7% in Nagata et al. (2006) and 100% in Choudhary et al. (2010). The correlation coefficients for predicting firmness were 0.784 in Nagata et al. (2004), 0.786 in Tallada et al. (2006), and 0.94 in Liu et al. (2014). The accuracy in detecting pathogenic fungal disease was 96.6% as shown in Pan et al. (2014).

A group of post-harvesting applications is shown under the category of post-harvesting management in figure 1c. All of the robotic technology studies in strawberry production listed under in-season management, harvesting, sorting, packing and post-harvesting management categories are shown in figure 1.

MECHANICAL AND ELECTRONIC SYSTEMS

MECHANICAL SYSTEM

Traveling Platform

Strawberry robots need to effectively travel throughout their working areas to reach all plants. Different mechanisms and drive systems have been utilized to achieve their translational and rotational motions, which can be grouped into the following four categories: stationary robot systems, moving bench and stationary robot combination systems, mobile robot systems, and moving bench and mobile robot combination systems. Compared to traditional cultivation, moveable bench systems provide benefits in strawberry production such as increased indoor area utilization, efficient use of sunlight and strawberry yield productivity (Hayashi et al., 2011a). Movable bench culture used with robots in strawberry greenhouses can be categorized into moveable hanging beds (Hayashi et al., 2010a) and circulating moveable beds (Saitoh et al., 2010). Combined systems are composed of either a mobile robot and moveable hanging bed system (Nagasaki et al., 2013) or a stationary robot and circulating moveable bed system (Hayashi et al., 2014a).

Stationary Robot Systems

In strawberry packing and/or grading robots, the harvested strawberries are transported on belt conveyors while the robot is stationary (Xu and Zhao, 2010; Yamamoto et al., 2012). Mobility of the robot is not required for sorting and packing operations due to conveyor belts that bring the fruits in front of working station, i.e. sorting or packing robot [Hayashi et al., 2011b, 2014b (packing robot)].

Moving Bench and Stationary Robot Combination Systems

In a recently developed traveling system in a greenhouse, one of the two harvesting robots was motionless while the bench unit moved [Hayashi et al., 2014b (stationary harvesting robot)] on a rail system. The benches had a circulating motion by constrained by the rail system in the greenhouse and they came in front of the stationary harvesting robot for the harvesting operation [Hayashi et al., 2014b (stationary harvesting robot)]. In another study, the longitudinal and lateral transmitting units are driven by electric motors so that benches gain mobility by help of these transmitting units (Yamamoto et al., 2009). The manipulator grabbed the fruit after detection of mature strawberries when the plant benches reached the front of robot.

Mobile Robot Systems

Four-wheel-drive mobile robots have been used in strawberry cultivation tasks in greenhouses. They usually carry manipulators, end-effectors, vision units, and storage units. Feng et al. (2012a, 2012b) studied a mobile robot which moved between the rows of table-top cultured strawberry plants in greenhouses to harvest them. Arima et al. (2003) has studied a strawberry harvesting robot that worked under table-top culture benches, which is a suitable layout for the simplification of the robotic operations. The location and orientation of the robot simplified detecting and reaching the target strawberries from inside the row rather than from the aisle side. In other studies with table-top plants, harvesting robots moved between fixed rows of plants on benches using rail systems (Kondo et al., 2005; Rajendra et al., 2009). The other one of the two harvesting robots mentioned in Hayashi et al. [2014b (mobile harvesting robot)] moved on a rail system along and across benches. For annual hilltop culture, a wheeled robot was developed to travel over the top of the strawberry plants while harvesting (Cui et al., 2013).

There are several field robots that have been under development for strawberry orchards. In a recently funded USDA project (Scheiner, 2013; UC Davis College of Engineering, 2014; USDA-REEIS, 2014); a four-wheeled mobile robot was being developed to deliver the harvested and packaged strawberries to a central location in order to increase harvesting efficiency in field operations by reducing time loss and labor workload. In Xu et al. (2014), a mobile robot was designed to travel over strawberry rows and to work in cooperation with an unmanned aerial vehicle (UAV) for close-range disease detection. In the Agrobot design, a customized tractor was developed for autonomous harvesting of a strawberry field while the

packaging of the harvested strawberries was done by a human operator (Agrobot, n.d.; Bolda, 2012). The autonomous tractor moved through the strawberry field to pick up the strawberries with its manipulator arm located at the bottom of the vehicle (AZoRobotics, n.d.).

Moving Bench and Mobile Robot Combination Systems

In some strawberry robotic designs, both the robots and the benches move to improve performance and efficiency. For example, in Nagasaki et al. (2013), strawberry plants were in movable hanging beds while the harvesting robot moved on a rail system within the greenhouse. Hayashi et al. (2013) designed a hanging bench system which automatically adjusted to provide room so that the robot could move through and across the plant rows.

Hayashi et al. (2010a, 2012) constructed an X-Y table on a rail system for the motion of a harvesting robot in a greenhouse, in which there were three stationary and three movable strawberry benches. The distance between the movable strawberry benches was adjustable to incorporate the movement of the robot (Hayashi et al., 2010a, 2012).

In table 3, the strawberry robots discussed in the publically accessible literature are categorized according to their travelling platforms as described above.

In the mechanical design of strawberry robotics, the preferred mobility method depends on the required functionality of the robots and the operating environment. In field conditions, mostly wheeled robots are desired and employed; while travelling platforms, either robots or plant benches, are mostly used in greenhouses in order to gain mobility by help of a rail structure. From the functionality perspective, weed control, disease detection and transportation robots mostly are movable; on the other hand for sorting/packing and sometimes harvesting operations, robots often do not have to be itinerant.

Handling Mechanism

Manipulator Design

Manipulators in strawberry robotics are responsible for guiding task-specified end-effectors to reach strawberries, leaves, soil, or weeds. The degrees of freedom (DOF) of a manipulator depend on its motion requirement and can be classified according to their joint types as rotational, translational, and translational-rotational.

In manipulator arm designs, usually four to seven DOFs were achieved via revolute joints; each of them having one rotational DOF along a single axis. In Hayashi et al.

(2010a), a 5-DOF articulated-type manipulator having only revolute joints was studied for harvesting strawberries. In cylindrical-type robot design, the wrist joint where the end-effector is connected was a revolute joint along only one rotation axis and the platform which carried the vision system together with handling system moved by sliding joints along two axes (Hayashi et al., 2010a). In another study, the harvesting robot was a mobile autonomous vehicle, which traveled between the strawberry benches with the manipulator affixed to the top of the vehicle (Feng et al., 2012a, 2012b). The articulated manipulator arm had six DOFs, and its working space encloses the locations of the strawberries hanging from benches on both sides of the aisle (Feng et al., 2012a, 2012b). Also, in hydroponic greenhouse harvesting, an industrial robotic arm such as a PUMA type manipulator arm with four DOFs was utilized (Saenz et al., 2013).

To reach strawberries, weeds, or leaves, translational DOFs might also be needed. Prismatic joints would be useful to slide the end-effector to the strawberries. An XYZ-table (i.e., a Cartesian manipulator) was used in the handling mechanism of the supply unit to take harvested strawberries from a box container and put them on a conveyor belt [Yamamoto et al., 2012; Hayashi et al., 2014b (packing robot)]. In a recently developed grading robot, one translational DOF was used to manipulate the strawberries moving on the conveyor belt according to their dimensions and shape (Xu and Zhao, 2010).

Some strawberry robots use both rotational and translational joints in their manipulator designs. Yamamoto et al. (2008, 2009, 2014) designed a stationary robot with a 7-DOF manipulator arm with a prismatic joint end-effector to perform harvesting tasks. Also, a harvesting robot with a 7-DOF articulated manipulator arm together with a sliding end-effector was developed in order to grab and pull strawberries (Takeshita et al., 2010). In a strawberry harvesting study, the robot's cylindrical manipulator was designed with two translational DOF and one rotational DOF (Hayashi et al., 2009, 2010a, 2010b). It translated along both upward-downward and forward-backward directions. It also had one revolute joint at the bottom to rotate the entire handling unit in order to put the harvested strawberry into the container (Hayashi et al., 2010a, 2010b). For the enhanced version of this robot, another DOF was added as a rotary joint of the end-effectors, allowing it to rotate to certain angular positions (Hayashi et al., 2012). Hayashi et al. [2011b, 2014b (packing robot)]

Table 3. Categories of the travelling systems used in robotic studies on strawberry.

Category	References
Stationary robot	Xu and Zhao (2010); Hayashi et al. (2011b, 2014b [packing robot]); Yamamoto et al. (2012)
Combined moving bench and stationary robot	Kondo et al. (1998); Yamamoto et al. (2009, 2014); Takeshita et al. (2010); Hayashi et al. [2014b (stationary harvesting robot)]
Mobile robot	Agrobot (n.d.); AZoRobotics (n.d.); "Tektu T-100 Strawberry Harvester," (2010); Arima et al. (2001, 2003); Kondo et al. (2005); Tarrio et al. (2006); Guo et al. (2008); Kim et al. (2008); Yamamoto et al. (2008) Hayashi et al. (2010b, 2011a); Saitoh et al. (2010); Busch and Palk (2011); Bolda (2012); Cui et al. (2013); Feng et al. (2012a, 2012b); Saenz et al. (2013); Scheiner, (2013); UC Davis College of Engineering (2014); Rajendra et al. (2009, 2011); Rieder et al. (2014) ^[a] ; National Robotics Engineering Center (2014); Xu et al. (2014) ^[a]
Combined moving bench and mobile robot	Hayashi et al. [2009, 2010a, 2012, 2013, 2014a, 2014b (mobile harvesting robot)]; Nagasaki et al. (2010, 2013)

^[a] The robot is either planned to be developed or currently under development.

developed sorting and packaging robots for strawberries which consisted of a XYZ-table mechanism (i.e. a Cartesian manipulator) with a rotational wrist joint connected to the end-effector, and a vacuum system used to pick up fruits from the belt conveyor and place them into the designated trays. In field operation of a disease detection robot, an XYZ-table connected with a 3-DOF manipulator arm was designed as a 6-DOF handling mechanism to approach the diseased leaves of strawberry plants, cut them off, and then place the samples into containers (Xu et al., 2014).

Figure 2 provides a non-exhaustive summary of manipulator designs in strawberry robots shown in publically accessible literature.

The handling unit of a robot is the subsystem which reaches strawberries. The accessibility of the handling mechanism is an important factor to be considered in design of the manipulators such as link lengths and joint types. The workspace of the robot, location and orientation of the strawberry plants, approach direction of the robots, and mechanical construction of the robot itself define the number of joints and type of degrees of freedom needed in handling mechanisms.

For weed control and close-range disease detection operations in fields, the mechanical structure of the robot is designed to approach the plants from the top. The handling mechanism of these robots has both translational and rotational degrees of freedom to reach the plants on the ground. In harvesting operations, depending on the robots' approach direction to the strawberry plants, both translational and rotational degrees of freedom are also employed to guarantee the accessibility of the handling mechanism. In greenhouse procedures, the type of bench culture affects the workspace of the handling mechanism, so manipulators may have only rotational joints or both rotational and translational joints. In field harvesting robots, the uncertainty in the location of the strawberry fruit

on the plants requires various configurations of the handling mechanism to get successful results for each attempt. To this purpose, both rotational and translational degrees of freedom have been utilized in manipulators. Due to simplicity of the process in sorting/packing robots, translational degrees of freedom are sufficient to place the strawberries coming in line by the help of conveyor belts to designated trays.

End-Effector Design

The end-effector is the last link of the handling unit, and is in direct contact with strawberries. To the best knowledge of the authors, five methods have been used in designing the end-effectors of strawberry robots: peduncle holding-cutting, strawberry grasping-pulling, strawberry suctioning-cutting, strawberry suctioning-pulling and strawberry suctioning.

Peduncle Holding and Cutting

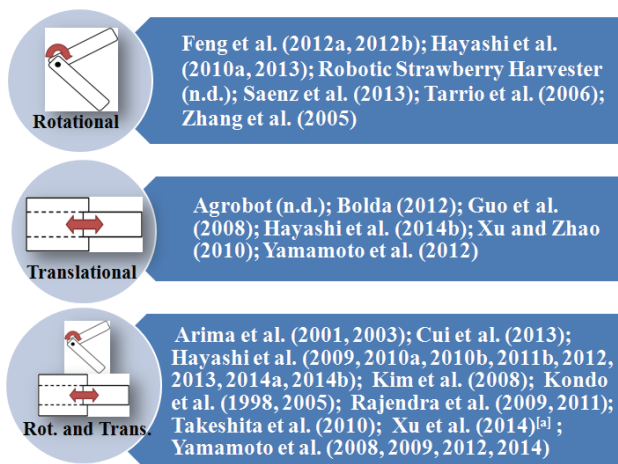
Strawberry is a delicate fruit and any automation process should avoid damaging the fruits. Especially for strawberry harvesting robots, fruits should be handled without bruising them, which can happen when separating a strawberry from its peduncle. For this purpose, an end-effector was designed to grip peduncles with finger-type holders and cut it with a sharp blade (Cui et al., 2013; Hayashi et al., 2010a, 2010b, 2012) or scissors (Guo et al., 2008; Tarrío et al., 2006). In a disease detection robot, in order to grip the diseased leaf from its peduncle, the end-effector was designed as both a holder and a cutter (Xu et al., 2014).

Strawberry Grasping and Pulling

An end-effector was designed by mimicking an experienced human operator's mild grabbing of strawberries (Dimeas et al., 2014). Its design consisted of three fingers coated with a soft material and driven by one motor, with each finger a mechanism having three revolute joints and one prismatic joint. Some experiments were performed to measure the pulling forces required to remove strawberries by grabbing them without damaging or touching the peduncle (Dimeas et al., 2014).

Strawberry Suctioning and Cutting

After approaching the target fruit, the end-effector of the harvesting robot used its suction head to grab the mature strawberry as well as two fingers at the top of the suction head to hold the peduncle. Hayashi et al. [2009, 2010a, 2010b, 2014b (mobile harvesting robot)] studied harvesting robots that cut the peduncle with the sharp edge of the end-effector fingers or in other harvesting robot designs, an electrically-heated cylindrical thin metal rod was used for this process after suctioning (Feng et al., 2012a, 2012b). In Takeshita et al. (2010), in addition to a suction pipe, the end-effector had two fingers at the upper side responsible for grabbing the peduncle and two fingers at the bottom side to cut it. Using both suctioning and cutting methods, the harvesting success rate could be increased because the position detection error could be reduced by the suctioning (Hayashi et al., 2010b).



^[a] The robot is either planned to be developed or currently under development.

Figure 2. Manipulator categories of robotic studies on strawberry according to their joint types.

Strawberry Suctioning and Pulling

In some studies, peduncles were considered unnecessary parts after harvesting since they could scratch fruits during packaging. For example, in Yamamoto et al. (2008, 2014), the end-effector consisted of a suction pipe, air nozzles, two clutching plates, and an up-down slider. Firstly, the suction pipe grabbed the target strawberry from its bottom and the plates enclosed it at the top. To remove the fruit from its peduncle easily, the fruit was pulled along certain angular directions by the slider (Yamamoto et al., 2008, 2014).

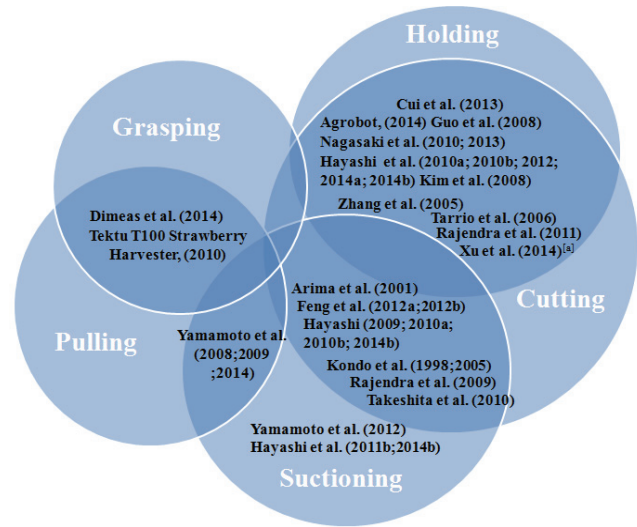
Strawberry Suctioning Only

In this method, air under a vacuum is used to hold strawberries. Suction type end-effectors were often used in sorting and packaging robots to remove strawberries from belt conveyors. The strawberries entering conveyor belts are in random orientations. In order to grip successfully, each strawberry should be suctioned from its top; thus rotational freedom at the wrist joint is needed so that the end-effector can align itself along the fruit inclination [Hayashi et al., 2011b, 2014b (packing robot)]. After handling strawberries, the air was released into the suction tube to place the fruits in trays (Yamamoto et al., 2012). This method provides simplicity in an end-effector mechanical design since only a tubular structure and vacuum are needed to grasp the harvested fruit; also, it provides easy handling of the strawberries without any damage during operation. Figure 3 categorizes end-effectors in strawberry robots as discussed earlier.

The design of an end-effector, which directly touches strawberries, is inspired from the purpose of the robots. In harvesting robots, the robots pick strawberries from their peduncles or sometimes they are directly in contact with the fruit itself. If the peduncle of strawberry or leaf is the location to be handled, the hold and cut method (Cui et al., 2013; Hayashi et al., 2010a, 2010b, 2012) is generally used; if the fruit is the target, grasping (Dimeas et al., 2014), pulling, or suctioning [Hayashi et al., 2011b, 2014b (packing robot)] are usual end-effector designs of strawberry robotics. The grasping and pulling technique is not generally preferred in harvesting robots due to its high possibility of damaging the fruit, so in these studies continuous force feedback during grasping is required. In sorting/packing robots, the suctioning method is used in end-effector design since the harvested strawberries come in front of the robot by a conveyor belt and an easy and innocuous handling method is achieved by suctioning only.

Storage Unit

After harvesting, sorting, and grading strawberries or removing diseased leaves, the next step is to store them. One storage method is to put them into trays (Kondo et al., 2005; Takeshita et al., 2010) or drop them randomly on belt conveyors (Cui et al., 2013; Guo et al., 2008), and the other way is to place them in organized, pocketed containers (Hayashi et al., 2010b). Trays may be customized and transported by conveyor belts or simply they can be boxes delivered by humans. For example, in one strawberry harvesting robot study, there was a container box to collect dropped fruits and a separate storage unit consisting of



[a] The robot is either planned to be developed or currently under development.

Figure 3. Categories of end-effector used in studies on strawberry robotics according to their method.

pocketed trays travelling on a conveyor belt (Hayashi et al., 2010b). Feng et al. (2012a, 2012b) and Yamamoto et al. (2008) designed autonomous mobile vehicles for strawberry harvesting in greenhouses where the storing unit was a medium-size container located next to the arm. After the manipulator arm harvested the strawberries, it randomly placed fruits into the container box, and when the container was fully loaded, it was manually replaced (Feng et al., 2012a, 2012b).

Specialized storing units have also been designed (Hayashi et al., 2011b, 2014b; Yamamoto et al., 2012). For instance, Hayashi et al. (2011b) developed a packing robot with four conveyor belts: one on the top of robot bringing the harvested strawberries from storing units to the XYZ table-type manipulator in order to be placed into the corresponding containers, and the other three conveyor belts on the bottom side of the XYZ table-type manipulator to carry and move the trays for strawberries to be placed in. Both Hayashi et al. [2014b (packing robot)] and Yamamoto et al. (2012) used a manipulator, a storing unit, and a vision system. The manipulator selected the randomly oriented strawberries from the container box and put them on the conveyor belt, which then transferred the fruits to the packing unit.

For strawberry delivery, a mobile robot is being designed to load harvested strawberry packages into a carton, which is later unloaded (Scheiner, 2013; UC Davis College of Engineering, 2014; USDA-REEIS, 2014). This mobile vehicle has a sloped metal plate at its top, which has almost the same dimensions as that of the container. In the strawberry disease detection robot (Xu et al., 2014), the containers are located on the inside of the left wall frame of the robot. After detected leaves are cut, they will be put in the small plastic containers, in order, using the manipulator (Xu et al., 2014).

The storage unit is not a critical subsystem for most strawberry robots except those used for packaging and/or

transporting. This unit can be designed as a random container box such as in harvesting and disease detection robots, or designated trays driven by a conveyor system in fully automated harvesting or packing robots. The presence of a storage unit in strawberry robotics also depends on whether it is a fully automated or partially automated robot. For partially automated robots, human labor can take the responsibility for storing; on the other hand, fully automated strawberry robots have a system for organized placement of the strawberries into the defined trays and they have a conveyor belt system to transport them.

ELECTRONIC SYSTEM

Sensors

In strawberry robotic studies, benches, rails (Hayashi et al., 2010a, 2010b) or wheel-drive systems (Feng et al., 2012a, 2012b; Xu et al., 2014) need to be guided to perform assigned tasks in greenhouses or fields. Navigation sensors, such as GPS, ultrasonic sensors, visual sensors, photoelectric sensors, fiber optic sensors, limit switches, or cameras, are needed to acquire the physical information on strawberries, leaves, and/or robots such as their position, velocity, acceleration, and pose.

Limit Switches

In many greenhouse systems, strawberry harvesting robots are designed to move on rails, in which the translational motion is restricted and there is no need to control the direction of movement except the backward and forward motions. In one study, the robot moved with a step displacement at a constant velocity after the strawberries were harvested from the detected region (Nagasaki et al., 2013). When the robot arrived at the end of one row, it touched the limit switch. Under different switching conditions, the robot would either continue to harvest the other side of the row or go to the next row (Nagasaki et al., 2013). In circulating-type moving bench systems, longitudinal and lateral motion was required for the motion of the plant benches in a greenhouse and a lateral transmitting system had two limit switches to prevent any deviation in the conveying system (Hayashi et al., 2011a). In a strawberry grading system, the manipulator had only one DOF translational motion along a sliding rod at the top of the conveyor belt, and at the end points of the sliding rod there were limit switches (Xu and Zhao, 2010). When the manipulator touched the limit switch at one end of the sliding rod, it changed direction to other side of the sliding axis (Xu and Zhao, 2010).

Ultrasonic Sensors

Ultrasonic sensors use sound waves to find the distances between robots and obstacles. In Feng et al. (2012a, 2012b), three sensors located on both sides of a vehicle body were used to measure the distance between the plant bench row and the vehicle to prevent any deviation from the route. For a disease detection robot, a total of eight ultrasonic sensors located inside and outside of the vehicle were used to avoid collision with strawberry beds, to prevent any damage to plants and to detect obstacles in the

route of the vehicle motion (Xu et al., 2014). The accuracy of the sensors used was 3 mm, and they had a range of 2 to 400 cm (Xu et al., 2014).

Global Positioning System (GPS)

To date, GPS has not been widely used mainly due to the fact that most of the strawberry robots have been built for greenhouse applications. In Xu et al. (2014), the strawberry disease detection ground and aerial robots moved across fields and GPS was used to determine the current position, velocity, and acceleration information. Also, it is mentioned in (Rieder et al., 2014) that GPS will soon be used in ground robots or aerial vehicles.

Fiber Optic and Photoelectric Sensors

These sensors can be used to confirm harvested strawberries or detect the presence of peduncles, after which the robot controller guides the corresponding subsystems such as conveyor belts in the case of packing robots [Hayashi et al., 2014b (packing robot)] or manipulators in the case of harvesting robots (Hayashi et al., 2010b). These sensors use light beams to identify the presence of objects and to find the distance (Frigyes et al., n.d.; "Construction and Principles," 2009). In strawberry harvesting robots, a photoelectric sensor is usually mounted close to the end-effector to verify the presence of harvested fruits (Hayashi et al., 2009, 2010b). There are three types of photoelectric sensors: transmission, reflection, and diffusion (Frigyes et al., n.d.; "Construction and Principles," 2009). Hayashi et al. (2012) used a transmission-type photoelectric sensor in their third harvesting robot prototype, and it was replaced with a reflection-type sensor in their fourth version. In another robot study, a fiber optic sensor was mounted at the end-effector to detect strawberry peduncles during harvesting (Cui et al., 2013). In strawberry grading robots, two photoelectric sensors were attached at the top of the conveyor belt, and when the presence of the strawberry was detected, the vision system started to take images for the grading process (Xu and Zhao, 2010).

Cameras

Cameras have been used in almost all strawberry robots. Machine vision is used for, but is not limited to, finding strawberry coordinates, locating diseased leaves, and guiding vehicles. Different types of cameras have been used in machine vision units, including CCD (Hayashi et al., 2010a, 2010b, 2011b, 2014a), binocular (Feng et al., 2012a, 2012b), digital (Saenz et al., 2013), and VGA (Kondo et al., 2005). Hayashi et al. (2010b, 2014b) used at least two cameras to find the three-dimensional positions of fruit locations. In a grading robot, a CCD color camera was used for image processing to decide the class of strawberries. For peduncle detection, one more camera was needed to calculate its alignment (Hayashi et al., 2009, 2010b). For some harvesting robot studies, two color cameras were used for both strawberry and stem detection (Guo et al., 2008). For visual serving of the handling unit, one color camera with LEDs attached on the end-effector

of manipulator arm was used to get strawberry position feedback for the control system of a harvesting robot (Takeshita et al., 2010). Feng et al. (2012a, 2012b) utilized a binocular camera with a 1024(H) × 768(V) resolution and a 6 mm focal length, assembled on the manipulator for strawberry detection. In another study, a camera was used to create guidance paths in strawberry fields (Wang, 2010). In order to navigate a harvester, a laser beam source and a camera with a CMOS sensor were used together to detect the distance between the vehicle and the strawberry plant row (Busch and Palk, 2011). In a strawberry disease detection robot, eight mini web cameras with a CMOS sensor and 8 cm focal length were used to take pictures for guidance of the ground vehicle and detect the position of the diseased leaves in strawberry plants (Xu et al., 2014).

Pressure Sensors

In addition to fiber optic sensors, pressure sensors are also used for the detection of fruits. In a strawberry harvesting study, the robot's manipulator moved closer to the target fruit from the bottom side, and the end-effector carried a pressure sensor (Yamamoto et al., 2009). When the fruit touched the sensor, it provided the presence information to the robot before picking the fruit. In table 4 types of sensors involved in the hardware system of related strawberry robots are listed and in table 5, the detection rates and methods in image analysis are listed for strawberry robotics studies.

Development in sensor technologies has accelerated in the field of strawberry robotics. Improvements in vision and optical sensors such as cameras and fiber optic sensors provide precise and accurate results in machine vision systems of the robots. For navigation of strawberry robots, GPS, ultrasonic sensors, acceleration sensors and cameras are inevitable hardware components especially found in

field operations. In greenhouse applications, the navigation of the robot is generally restricted by a rail system and constant forward/backward motion steps, so limit switches are adequate and provide simplicity in navigation control algorithms.

Computer, Communication, and Control

In strawberry robotic studies, computers and communication are essential for many autonomous tasks, such as image processing (Hayashi et al., 2010b) and controlling of the robot manipulator, storing unit containers, and/or travelling unit (Hayashi et al., 2010a, 2011b; Nagasaki et al., 2013; Yamamoto et al., 2009). Some of the control hardware used for strawberry robots is listed in table 6.

In the control system of the strawberry robotics studies, utilization of either PC or PLC is closely linked with which subsystem of these robots is controlled. For example, in a machine vision subsystem for harvesting, sorting, packing, disease detection, weed control robots, a PC is used for the execution of the image processing algorithms due to the size requirement of the computer memory. Navigation and guidance of the robots is controlled by PC in field operations and PLC or PC in greenhouse applications. The manipulation subsystem can be controlled by either PC or PLC depending on the design of the control system.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Recently, a significant amount of research and development has been conducted in utilizing robotic and automation technologies to replace or augment humans in precision agriculture, particularly in the area of high-value, delicate fruit production such as strawberry. The ultimate goal of developing robots and associated technologies for strawberry production is to reduce the cost and beat the competition in

Table 4. Electronic hardware in navigation and guidance systems of strawberry robots.

References	Navigation Sensors	
Arima et al. (2001); Zhang et al. (2005)	1 CCD camera	
Busch and Palk (2011)	1 CMOS camera, laser	
Cui et al. (2013)	2 CCD cameras, fiber optic	
Feng et al. (2012a, 2012b)	Ultrasonic sensor, 1 binocular camera	
Guo et al. (2008)	2 CCD cameras, image capture card	
Hayashi et al. (2009, 2010a, 2010b, 2012, 2014a)	Photoelectric sensor, 3 CCD cameras	
Hayashi et al. (2011a)	3-axis acceleration sensor, 2 limit switches	
Hayashi et al. (2011b)	1 CCD camera, pressure sensor	
Hayashi et al. (2014b)	Mobile harvesting robot Packing robot Stationary harvesting robot	Photoelectric, 3 CCD cameras Photoelectric, 1 camera 1 Binocular camera
Kim et al. (2008)	2 CCD cameras, laser range finder	
Kondo et al. (1998)	1 CCD camera, photo interrupter	
Kondo et al. (2005)	3 VGA cameras, limit switch, photo interrupter	
Nagasaki et al. (2013)	Limit switch	
Rajendra et al. (2009; 2011)	Fiber optic sensor, 3 CCD cameras	
Rieder et al. (2014) ^[a]	Ultrasonic, 2 cameras, GPS, accelerometer, gyroscope	
Saenz et al. (2013); Takeshita et al. (2010)	1 Digital camera	
Saitoh et al. (2010)	3-axis acceleration sensor	
Tarrio et al. (2006)	2 CCD cameras, laser	
Wang (2010); Xie and Zhang, (2006)	RGB camera	
Xu and Zhao (2010)	Limit switch, photoelectric sensor, 1 CCD camera	
Xu et al. (2013)	2 CMOS color cameras	
Xu et al. (2014) ^[a]	GPS, 8 digital cameras, ultrasonic sensor	
Yamamoto et al. (2009, 2014)	Stereo vision sensor, pressure sensor, limit switch, 2 cameras	
Yamamoto et al. (2012)	Photoelectric, 1 CMOS camera	

^[a] The robot is either planned to be developed or currently under development.

Table 5. Detection accuracies in some strawberry harvesting and packing robots.

Reference	Success Rate or Error Values in Detection		Method ^[a]
	Peduncle	Fruit	
Feng et al. (2012a, 2012b)		Error in position detection: < 4.6 mm	HSI
Cui et al. (2013)	70.8%		RGB
Guo et al. (2008)	93%		OHTA
Hayashi et al. (2010b)	~60%	~55.34%	HSI
Hayashi et al. (2011b)		Error in orientation detection: 5.3° Standard deviation: 4.2°	RGB
Hayashi et al. (2012)	~70%		
Hayashi et al. (2014b)	~97.7% (harvesting robot)	~57% (harvesting robot)	
Kondo et al. (2005)	90% (54 peduncles were visible out of 60 fully detected strawberries)	60%	
Leonard et al. (2013)	94% stem detection success		
Rajendra et al. (2009)	Ranges from an average of 85.66% to 0% according to their visibility in surrounding environment.		HSI
Takeshita et al. (2010)	Mean error in the inclination detection: 0.5° Standard deviation: 0.3°		RGB
Xu and Zhao (2010)		Size detection error < 5% Color detection success > 90%	RGB
Xu et al. (2013)	Root mean square error in Z-direction: 1.96 mm	80%	HSV
Yamamoto et al. (2009, 2014)		89%	RGB
Yamamoto et al. (2012)		99.2%	HSV
Zhang et al. (2005)		Error in CG location detection < 3 mm	RGB

^[a] HIS: Hue –Intensity –Saturation, RGB : Red –Green –Blue, HSV: Hue – Saturation -Value

the global market through more efficient and low-cost field operations in disease/stress detection, yield prediction, and automated harvesting, delivering, sorting, and packing.

Many papers have been published describing robotic technologies used for strawberries in either greenhouse or fields. To help potential readers, growers, or researchers to gain an overall picture of the state-of-the-art strawberry robotic technologies, this study summarized and compared different designs in terms of the strawberry robot category, mechanical subsystem, and electronic subsystem. In each category, the related studies are summarized in tables or figures. The scientific payload has been extensively reviewed since this subsystem is a crucial component determining whether or not a strawberry robot can successfully meet its performance needs.

Although significant progress has been achieved in developing robots for different strawberry farming tasks, there are many challenging issues to be addressed before the benefits of autonomous robots can be fully realized. Here, a few possible future research directions are discussed.

First, most strawberry robots developed to date are for greenhouse applications rather than field operations. An organized and controlled environment, such as a greenhouse, can significantly mitigate the difficulties involved in autonomous robotic tasks such as image processing, vehicle motion guidance and control, and manipulator and end-effector controls. However, it is a lot more challenging when those technologies are transferred to typical commercial farms. The terrain may be wet and

Table 6. Computer and communication components used in strawberry robotics studies.

Reference	Computer ^[a]	Communication ^[b]	Some Control Functionalities
Cui et al. (2013)	PC and PLC		Robot motion control, image processing, handling unit control
Dimeas et al. (2014)	PC	USB	Motor control
Feng et al. (2012a, 2012b)	PC or PLC	RS232	Fruit detection, vehicle navigation, manipulator control
Guo et al. (2008)	PC		Image processing
Hayashi et al. (2010a, 2014a)	PLC	Remote DIO Digital I/O pins	Travelling table control, robot control
Hayashi et al. (2010b)	PC		Vision processing
Hayashi et al. (2011a)	PC and PLC		Movable bench control
Hayashi et al. (2011b)	PC	RS232C DIO board IEEE1394 Interface	End-effector control, suctioning and conveyor belt control, lighting and vision control
Hayashi et al. (2012)	PC and PLC	Wireless Adapter Digital I/O Ports	Moving platform control, manipulator, end-effector, vision system, storage unit control
Hayashi et al. (2013)	PC and PLC	Wireless Adapter	Motor control, position sensing, travelling system control
Hayashi et al. (2014b)	PC		Supply unit and packing unit control
Nagasaki et al. (2013)	PLC		Bench system control
Saenz et al. (2013)	PC	USB	Image processing, structure analysis, camera calibration, graphical interface and data acquisition
Yamamoto et al. (2009)	PC		Movable bench control, harvesting control and machine vision

^[a] PC and PLC refer to the personal computer and programmable logic controller, respectively.

^[b] In Communication column, the ports/interfaces for the connection in between the hardware of the strawberry robots and in the functionality column, the operations to be controlled by PC or PLCs of robots are listed.

soft; the lighting conditions are not always ideal for vision/imaging; and the onboard components may vibrate significantly during motion causing prior calibrations to be inaccurate. Strawberry robots in fields need to be aware of the environment and avoid collisions with humans, other vehicles, and rocks (Edan et al., 2009). Additionally, from an agronomy perspective, strawberries grown in greenhouses are already trained in the sense that the fruits hang down and have less interference with leaves (Hayashi et al., 2010b). In field operations, engineers may need to collaborate more with agronomists to find a novel way to grow strawberries in a similar pattern.

Second, improving the adaptability of robots considering different strawberry field environments, requirements, and constraints is a challenging task. For example, strawberry ground robots should be flexible for organized or rough surroundings, different times of operation, and sandy or wet terrain. Also, the robot should be easily scaled up and down for different field configurations with various strawberry plant dimensions.

Third, the operation of a strawberry robot needs to be straightforward for a typical grower or producer. A grower will not be able to gain benefits from a non-user-friendly design. The simplicity of mechanical, electrical, and software subsystems in robots will help growers in both operation process and maintenance. For instance, a graphical user interface should be provided, which allows growers to enter some basic parameters of the operation or environment updates into software functions. All of the electronic devices in robots should be easily calibrated by even a non-technical person, and most parts should be off-the-shelf components so they can be easily replaced or renewed when needed.

Fourth, as has been reviewed, the scientific payload and its associated algorithms/software are crucial for the success of strawberry robots. Most of the scientific payloads are cameras, either thermal, RGB, or multispectral sensors, and many current image processing algorithms cannot achieve reliable, real-time performance. However, to fully utilize the autonomous capability of robots, decisions need to be made in each step after fusing all sensor information obtained from electronic hardware, in real-time and *in-situ*. For example, the imaging or video processing algorithm heavily depends on lighting conditions and calibration quality. In order to compete with human inspection and speed, the accuracy and reliability of these sensors and algorithms need to be high for each subsystem of the robot. Additionally, in-season stress management and yield estimate of strawberry is an important topic and should be further investigated.

Finally, robotic technology has attracted more and more attention. Several companies, such as Agrobot, have initiated their commercial strawberry robot products (Agrobot, n.d.; Bolda, 2012). For commercialization, the vital concerns include, but are not limited to, the cost, reliability, and maintenance of robots. High cost can be one of the reasons that producers want to avoid robot technology. As mentioned in Schmoldt (2012), growers worry that robotic technologies may lead to the loss of jobs. However as agricultural robotics matures enough for in-

field strawberry operations, growers may start to reconsider the potential reduction of labor intensive jobs in exchange for an increase in their competitiveness in the global market by reducing costs and enhancing product quality and quantity.

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REFERENCES

- Abeles, F. B., & Takeda, F. (1990). Cellulose activity and ethylene in ripening strawberry and apple fruits. *Scientia Horticulturae*, 42(4), 269-275. [http://dx.doi.org/10.1016/0304-4238\(90\)90050-O](http://dx.doi.org/10.1016/0304-4238(90)90050-O)
- Agrobot (n.d.) Agrobot strawberry harvesters. Huelva, Spain: Agrobot. Retrieved from <http://www.agrobot.com/products.html>
- Arima, S., Kondo, N., Yagi, Y., Monta, M., & Yoshida, Y. (2001). Harvesting robot for strawberry grown on table top culture, 1: Harvesting robot using 5-DOF manipulator [in Japanese with English abstract]. *J. Soc. High Tech. Agric.*, 13(3), 159-166. <http://dx.doi.org/10.2525/jshita.13.159>
- Arima, S., Monta, M., Namba, K., Yoshida, Y., & Kondo, N. (2003). Harvesting robot for strawberry grown on table top culture, 2: Harvesting robot with a suspended manipulator under cultivation bed [in Japanese with English abstract]. *J. Soc. High Tech. Agric.*, 15(3), 162-168. <http://dx.doi.org/10.2525/jshita.15.162>
- AZoRobotic. (n.d.). Robotic strawberry harvester from robotic harvesting, LLC. Chesire, UK: AZoNetwork. Retrieved from <http://www.azorobotics.com/equipment-details.aspx?EquipID=304>
- Bac, C. W., van Henten, E. J., Hemming, J., & Edan, Y. (2014). Harvesting robots for high-value crops: State-of-the-art review and challenges ahead. *J. Field Robotics*, 31(6), 888-911. <http://dx.doi.org/10.1002/rob.21525>
- Belforte, G., Gay, P., & Aimonino, D. R. (2006). Robotics for improving quality, safety and productivity in intensive agriculture: Challenges and opportunities. In L. K. Huat (Ed.), *Industrial robotics: Programming, simulation and applications* (pp. 667-690). Berlin, Germany: Verlag. <http://dx.doi.org/10.5772/4923>
- Blasco, J., Aleixos, N., Roger, J. M., Rabatel, G., & Moltó, E. (2002). Robotic weed control using machine vision. *Biosyst. Eng.*, 83(2), 149-157. <http://dx.doi.org/10.1006/bioe.2002.0109>
- Bolda, M. (2012). Robotic strawberry harvester on the move. Retrieved from http://ucanr.edu/blogs/strawberries_caneberries/index.cfm?tagname=Agrobot
- Busch, A., & Palk, P. (2011). An image processing approach to distance estimation for automated strawberry harvesting. In M. Kamel, & A. Campilho (Ed.), *Int. Conf. on Image Proc. and Recognition* (pp. 389-396). Berlin, Germany: Springer-Verlag. http://dx.doi.org/10.1007/978-3-642-21596-4_39
- Chiu, Y., Chen, S., & Lin, J. (2013). Study of an autonomous fruit picking robot systems in greenhouses. *Eng. Agric., Environ. Food*, 6(3), 92-98. [http://dx.10.1016/S1881-8366\(13\)80017-1](http://dx.10.1016/S1881-8366(13)80017-1)
- Choudhary, R., Paliwal, J., Nanyam, Y., & Gupta, L. (2010). Near infrared hyper spectral imaging for nondestructive measurement of strawberry quality. ASABE Paper No. 1008745. St. Joseph, MI: ASABE.

- Chuang, Y., Yang, C., Kim, M. S., Delwiche, S. R., Lo, Y. M., Chen, S., & Chan, D. E. (2012). Inspection of fecal contamination on strawberries using line-scan LED-induced fluorescence imaging techniques. ASABE Paper No. 121337179. St. Joseph, MI: ASABE.
- CMW Horticulture Ltd. (n.d.). Retrieved from <http://www.cmwhorticulture.co.uk/>
- Construction and principles of operation of photoelectric sensors. (2009). Retrieved from http://files.pepperl-fuchs.com/selector_files/navi/productInfo/doct/doct1797a_eng.pdf
- Cox, S. (2002). Information technology: The global key to precision agriculture and sustainability. *Comput. Electron. Agric.*, 36(2-3), 93-111. [http://dx.10.1016/S0168-1699\(02\)00095-9](http://dx.10.1016/S0168-1699(02)00095-9)
- Cui, Y., Gejiyama, Y., Kobayashi, T., Hiyoshi, K., & Nagata, M. (2013). Study on cartesian-type strawberry-harvesting robot. *Sensor Letters*, 11(6-7), 1223-1228. <http://dx.10.1166/s1.2013.2949>
- Dampney, P. M. R., Bryson, R., Clark, W., Strang, M., & Smith, A. (1998). The use of sensor technologies in agricultural cropping systems: A scientific review and recommendations for cost effective developments. ADAS Contract Report, Review Report to Ministry of Agriculture, Fisheries and Food, U.K., Project Code CE 0140.
- Dimeas, F., Sako, D. V., Moulianitis, V. C., & Aspragathos, N. A. (2014). Design and fuzzy control of a robotic gripper for efficient strawberry harvesting. *Robotica*, 33(1), 1-14. <http://dx.doi.org/10.1017/S0263574714001155>
- Dong, D., Zhao, C., Zheng, W., Wang, W., Zhao, X., & Jiao, L. (2013). *Scientific Reports* 3(Article No: 2585). <http://dx.doi.org/10.1038/srep02585>
- Economic Research Service. (2013). U. S. strawberry industry (95003). Washington, D.C.: ERS-USDA. Retrieved from <http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1381>
- Edan, Y. (1995). Design of an autonomous agricultural robot. *Appl. Intelligence*, 5(1), 41-50. <http://dx.doi.org/10.1007/BF00872782>
- Edan, Y., Han, S., & Kondo, N. (2009). Automation in agriculture. In S. Y. Nof (Ed.), *Springer Handbook of Automation* (pp. 1095-1128). Berlin, Germany: Springer-Verlag. http://dx.doi.org/10.1007/978-3-540-78831-7_63
- ElMasry, G., Wang, N., ElSayed, A., & Ngadi, M. (2006). Hyper spectral imaging for nondestructive determination of some quality attributes for strawberry. *J. Food Eng.*, 81, 98-107. <http://dx.doi.org/10.1016/j.jfoodeng.2006.10.016>
- Feng, Q. C., Wang, X., Zheng, W. G., Qiu, Q., & Jiang, K. (2012b). A new strawberry harvesting robot for elevated-through culture. *Int. J. Agric. Biol. Eng.*, 5(2), 1-8. <http://dx.10.3965/j.ijabe.20120502.001>
- Feng, Q. C., Zheng, W. G., Qiu, Q., Jiang, K., & Guo, R. (2012a). Study on strawberry robotic harvesting system. *IEEE Int. Conf. Computer Sci. and Automation Eng.* (pp. 320-324). New York, NY: IEEE. <http://dx.doi.org/10.1109/CSAE.2012.6272606>
- Fraulo, A. B., Cohen, M., & Liburd, O. E. (2009). Visible/near infrared reflectance (VNIR) spectroscopy for detecting two spotted Spider mite (acari: tetranychidae) damage in strawberries. *Environ. Entomol.*, 38(1), 137-142. <http://dx.doi.org/10.1603/022.038.0117>
- Frigyes, G., Myers, E., & Allison, J. (n.d.). Fundamentals of photoelectric sensors. Retrieved from <http://www.automation.com/library/articles-white-papers/sensors-sensing-technologies/fundamentals-of-photoelectric-sensors>
- Gil, M. I., Holcroft, D. M., & Kader, A. A. (1997). Changes in strawberry anthocyanins and other polyphenols in response to carbon dioxide treatments. *J. Agric. and Food Chem.*, 45(5), 1662-1667. <http://dx.doi.org/10.1021/jf960675e>
- Grant, O. M., Davies, M. J., James, C. M., Johnson, A. W., Leinonen, I., & Simpson, D. W. (2012). Thermal imaging and carbon isotope composition indicate variation amongst strawberry (*fragaria x ananassa*) cultivars in stomatal conductance and water use efficiency. *Environ. Exp. Botany*, 76, 7-15. <http://dx.doi.org/10.1016/j.envexpbot.2011.09.013>
- Griff, T., Zhang, Q., Kondo, N., & Ting, K. C. (2008). A review of automation and robotics for bio-industry. *J. Biomechatronics Eng.*, 1(1), 37-54.
- Guo, F., Cao, Q., & Nagata, M. (2008). Fruit detachment and classification method for strawberry harvesting robot. *Int. J. Adv. Robotic Syst.*, 5(1), 41-48. <http://dx.doi.org/10.5772/5662>
- Hajjaj, S. S. H., & Sahari, K. S. M. (2014). Review of research in the area of agriculture mobile robots. *8th int. conf. on robotic, vision, signal process. and power appl., lecture notes in electrical eng.* 291, pp. 107-118. Springer Singapore. http://dx.doi.org/10.1007/978-981-4585-42-2_13
- Hakala, M., Ahro, M., Kauppinen, J., & Kallio, H. (2001). Determination of strawberry volatiles with low resolution gas phase FT-IR analyser. *European Food and Res. Tech.*, 212(4), 505-510. <http://dx.doi.org/10.1007/s002170000273>
- Hayashi, S., Saito, S., Iwasaki, Y., Yamamoto, S., Nagoya, T., & Kano, K. (2011a). Development of circulating-type movable bench system for strawberry cultivation. *Japan Agric. Res. Quarterly*, 45(3), 285 - 293. <http://dx.doi.org/10.6090/jarq.45.285>
- Hayashi, S., Shigematsu, K., Yamamoto, S., Kobayashi, K., Kohno, Y., Kamata, J., & Kurita, M. (2010b). Evaluation of a strawberry-harvesting robot in a field test. *Biosyst. Eng.*, 105(2), 160-171. <http://dx.doi.org/10.1016/j.biosystemseng.2009.09.011>
- Hayashi, S., Takahashi, K., Yamamoto, S., Saito, S., & Kameda, T. (2011b). Gentle handling of strawberries using a suction device. *Biosyst. Eng.*, 109(4), 348-356. <http://dx.doi.org/10.1016/j.biosystemseng.2011.04.014>
- Hayashi, S., Yamamoto, S., Saito, S., Ochiai, Y., Kamata, J., Kurita, M., & Yamamoto, K. (2014a). Field operation of a movable strawberry-harvesting robot using a travel platform. *Japan Agric. Res. Quarterly*, 48(3), 307-316. <http://dx.doi.org/10.6090/jarq.48.307>
- Hayashi, S., Yamamoto, S., Saito, S., Ochiai, Y., Kohno, Y., Nagasaki, Y., ... Yamashita, T. (2010a). Development of a travelling platform for a strawberry-harvesting robot. *Int. Conf. Agric. Eng. - AgEng 2010: Towards Environmental Technologies*, (p. 072). Aubiere, France: Cemagref.
- Hayashi, S., Yamamoto, S., Saito, S., Ochiai, Y., Kohno, Y., Yamamoto, K., Kurita, M. (2012). Development of a movable strawberry-harvesting robot using a travelling platform. *Proc. Int. Conf. Agric. Eng.* Valencia, Spain.
- Hayashi, S., Yamamoto, S., Saito, S., Ochiai, Y., Nagasaki, Y., & Kohno, Y. (2013). Structural environment suited to the operation of a strawberry-harvesting robot mounted on a travelling platform. *Eng. Agric., Environ. Food*, 6(1), 34-40. [http://dx.10.1016/S1881-8366\(13\)80015-8](http://dx.10.1016/S1881-8366(13)80015-8)
- Hayashi, S., Yamamoto, S., Shigematsu, K., Kobayashi, K., Kohno, Y., Kamata, J., & Kurita, M. (2009). Performance of movable-type harvesting robot for strawberries. (M. Dorais, Ed.) *ISHS Acta Horticulturae*, 893, 317-324.
- Hayashi, S., Yamamoto, S., Tsubota, S., Ochiai, Y., Kobayashi, K., Kamata, J., ... Rajendra, P. (2014b). Automation technologies for strawberry harvesting and packing operations in Japan. *J. Berry Res.*, 4(1), 19-27. <http://dx.10.3233/JBR-140065>

- Jahns, G. (1983). Automatic guidance in agriculture a review. ASAE Paper No. 83404. St. Joseph, MI: ASAE.
- Khanizadeh, S., & DeEll, J. (2001). Chlorophyll fluorescence: A new technique to screen for tolerance of strawberry flowers to spring frost. *Small Fruits Rev.*, 1(3), 61-67. http://dx.doi.org/10.1300/J301v01n03_06
- Kim, S. C., Han, G. S., Jung, S. C., Hai, L. T., & Hwang, H. (2008). Development of robotic harvest system for bench-type strawberry cultivation. *Proc. 4th Int. Symp. Machinery and Mechatronics Agric. and Biosyst. Eng.* Taichung, Taiwan: (BR-20 – BR-28).
- Kondo, N., Monta, M., & Arima, S. (1998). Strawberry harvesting robot on hydroponic system. *Proc. 3rd IFAC Artificial Intelligence in Agric.*, (pp. 181-186). Oxford, England: Elsevier.
- Kondo, N., Monta, M., & Fujiura, T. (1996). Fruit harvesting robots in Japan. *Adv. Space Res.*, 18(1-2), 181-184. [http://dx.doi.org/10.1016/0273-1177\(95\)00806-P](http://dx.doi.org/10.1016/0273-1177(95)00806-P)
- Kondo, N., Ninomiya, K., Hayashi, S., Ota, T., & Kubota, K. (2005). A new challenge of robot for harvesting strawberry grown on table top culture. ASAE Paper No: 053138. St. Joseph, MI: ASAE. <http://dx.doi.org/10.13031/2013.19110>
- Lamb, D. W., & Brown, R. B. (2001). Remote-sensing and mapping of weeds in crops: A review. *J. Agric. Eng. Res.*, 78(2), 117-125. <http://dx.doi.org/10.1006/jaer.2000.0630>
- Leonard, K., Strawbridge, R., Lindsay, D., Barata, R., Dawson, M., & Averion, L. (2013). Minimal geometric representation and strawberry stem detection. *13th Int. Conf. Computational Sci. and Appl.*, (pp. 144-149). <http://dx.doi.org/10.1109/ICCSA.2013.29>
- Li, H., Li, T., Gordon, R. J., Asiedu, S. K., & Hu, K. (2009a). Strawberry plant fruiting efficiency and its correlation with solar irradiance, temperature and reflectance water index variation. *Environ. Exp. Botany*, 68(2), 165-174. <http://dx.doi.org/10.1016/j.envexpbot.2009.12.001>
- Li, M., Imou, K., Wakabayashi, K., & Yokoyama, S. (2009b). Review of research on agricultural vehicle autonomous guidance. *Int. J. Agric. Biol. Eng.*, 2(3), 1-16. <http://dx.doi.org/10.3965/j.issn.1934-6344.2009.03.001-016>
- Li, P., Lee, S., & Hsu, H. Y. (2011). Review on fruit harvesting method for potential use of automatic fruit harvesting systems. *Procedia Eng.*, 23, 351- 366. <http://dx.doi.org/10.1016/j.proeng.2011.11.2514>
- Liu, C., Liu, W., Lu, X., Ma, F., Chen, W., Yang, J., & Zheng, L. (2014). Application of multispectral imaging to determine quality attributes and ripeness stage in strawberry fruit. *PLoS One*, 9(2), e87818. <http://dx.doi.org/10.1371/journal.pone.0087818>
- LSU College of Agriculture Center. (2014). Precision bed shaping for commercial vegetable production. Retrieved from http://www.lsuagcenter.com/en/crops_livestock/crops/vegetable_s/Precision+Bed+Shaping+for+Commercial+Vegetable+Production.htm
- Mannini, P., & Anconelli, S. (1993). Leaf temperature and water stress in strawberry. *Acta Horticulturae*, 345, 55-62. <http://dx.doi.org/10.17660/ActaHortic.1993.345.7>
- Marchant, J. A., & Moncaster, M. E. (1990). Robotics and automation in agriculture. *Outlook on Agric.*, 19(4), 221-228.
- Marcotte, D., Savoie, P., Martel, H., & Theriault, R. (1999). Precision agriculture for hay and forage crops: A review of sensors and potential applications. ASAE Paper No. 99-1049. St. Joseph, MI: ASAE.
- Milella, A., Reina, G., & Foglia, M. (2006). Computer vision technology for agricultural robotics. *Sensor Rev.*, 26(4), 290-300. <http://dx.doi.org/10.1108/02602280610692006>
- Misaghi, F., Dayyanidardashti, S., Mohammadi, K., & Ehsani, M. R. (2004). Application of artificial neural network and geostatistical methods in analyzing strawberry yield data. ASAE Paper No. 041147. St. Joseph, MI: ASAE. <http://dx.doi.org/10.13031/2013.16172>
- Nagasaki, Y., Hayashi, S., Kohno, Y., Kuroyanagi, T., Tanaka, H., & Nakamoto, Y. (2010). Development of a movable hanging-bed system for strawberry harvesting by a robot. *Proc. 5th Int. Symp. Machinery and Mechatronics Agric. Biosyst. Eng.*
- Nagasaki, Y., Hayashi, S., Nakamoto, Y., Kawashima, H., & Kohno, Y. (2013). Development of a table-top cultivation system for robot strawberry harvesting. *J. Agric. Res. Quarterly*, 47(2), 165-169. <http://dx.doi.org/10.6090/jarq.47.165>
- Nagata, M., Tallada, J. G., & Kobayashi, T. (2006). Bruise detection using NIR hyperspectral imaging for strawberry (*fragaris x ananassa duch.*). *Environ. Control in Biol.*, 44(2), 133-142. <http://dx.doi.org/10.2525/ecb.44.133>
- Nagata, M., Tallada, J. G., Kobayashi, T., Cui, Y., & Gejima, Y. (2004). Predicting maturity quality parameters of strawberries using hyperspectral imaging. ASAE Paper No. 043033. St. Joseph, MI: ASAE. <http://dx.doi.org/10.13031/2013.16704>
- National Robotics Engineering Center. (2014). NREC to automate strawberry blossom and weed removal. Pittsburgh, PA: NREC. Retrieved from http://www.nrec.ri.cmu.edu/about/news/13_10_strawberry.php
- Ohta, Y. I., Takeo, K., & Toshiyuki, S. (1980). Color information for region segmentation. *Computer Graphics and Image Process.*, 13(3), 222-241. [http://dx.doi.org/10.1016/0146-664X\(80\)90047-7](http://dx.doi.org/10.1016/0146-664X(80)90047-7)
- Pan, L., Zhang, W., Zhu, N., Mao, S., & Tu, K. (2014). Early detection and classification of pathogenic fungal disease in post-harvest strawberry fruit by electronic nose and gas chromatography-mass spectrometry. *Food Res. Int.*, 62, 162-168. <http://dx.doi.org/10.1016/j.foodres.2014.02.020>
- Pedersen, S. M., Fountas, S., Have, H., & Blackmore, B. S. (2006). Agricultural robots-system analysis and economic feasibility. *Precision Agric.*, 7(4), 295-308. <http://dx.doi.org/10.1007/s11119-006-9014-9>
- Penuelas, J., Save, R., Marfà, O., & Serrano, L. (1991). Remotely measured canopy temperature of greenhouse strawberries as indicator of water status and yield under mild and very mild water stress conditions. *Agric. and Forest Meteorol.*, 58(1-2), 63-77. [http://dx.doi.org/10.1016/0168-1923\(92\)90111-G](http://dx.doi.org/10.1016/0168-1923(92)90111-G)
- Pertot, I., Kuflik, T., Gordon, I., Freeman, S., & Elad, Y. (2012). Identifier: A web-based tool for visual plant disease identification, a proof of concept with a case study on strawberry. *Comput. Electron. Agric.*, 84, 144-154. <http://dx.doi.org/10.1016/j.compag.2012.02.014>
- Rajendra, P., Kondo, N., Ninomiya, K., Kamata, J., Kurita, M., Shiigi, T.,... Kohno, Y. (2009). Machine vision algorithm for robots to harvest strawberries in tabletop culture greenhouses. *Eng. Agric., Environ. and Food*, 2(1), 24-30. [http://dx.doi.org/10.1016/S1881-8366\(09\)80023-2](http://dx.doi.org/10.1016/S1881-8366(09)80023-2)
- Rajendra, P., Mitsutaka, K., Kazunori, N., Gosei, O., & Hayashi, S. (2011). Shading compensation methods for robots to harvest strawberries in tabletop culture. *IEEE/SICE Int. Symp. on Syst. Integration* (pp. 172-177). New York, NY: IEEE. <http://dx.doi.org/10.1109/SII.2011.6147440>
- Razavi, F., Pollet, B., Steppe, K., & Van Labeke, M. C. (2008). Chlorophyll fluorescence as a tool for evaluation of drought stress in strawberry. *Photosynthetica*, 46(4), 631-633. <http://dx.doi.org/10.1007/s11099-008-0108-7>
- Reyns, P., Missotten, B., Ramon, H., & De Baerdemaeker, J. (2002). A review of combine sensors for precision farming. *Precision Agric.*, 3(2), 169-182. <http://dx.doi.org/10.1023/A:1013823603735>

- Rieder, R., Pavan, W., Maciel, J. M. C., Fernandes, J. M. C., & Pinho, M. S. (2014). A virtual reality system to monitor and control diseases in strawberry with drones: A project. In D. P. Ames, N. W. T. Quinn, & A. E. Rizzoli (Ed.), *7th Int. Cong. on Environ. Modeling and Software*. San Diego, CA.
- Rodríguez, F., Moreno, J. C., Sánchez, J. A., & Berenguel, M. (2013). Grasping in agriculture: State-of-the-art and main characteristics. In G. Carbone (Ed.), *Grasping in robotics, mechanisms and machine science* (pp. 385-409). London, U.K.: Springer-Verlag. http://dx.doi.org/10.1007/978-1-4471-4664-3_15
- Rovira-Más, F. (2010). Sensor architecture and task classification for agricultural vehicles and environments. *Sensors*, *10*(12), 11226-11247. <http://dx.doi.org/10.3390/s101211226>
- Saenz, E., Jimenez, M., & Ramirez, A. (2013). Strawberries collecting robot prototype in greenhouse hydroponic systems. *Proc. 18th Symp. Image, Signal Processing and Artificial Vision*, (pp. 146-149). New York, NY: IEEE. <http://dx.doi.org/10.1109/STSIWA.2013.6644933>
- Saitoh, S., Hayashi, S., Yamamoto, S., Yoshida, H., Iwasaki, Y., Takahashi, N.,... Kano, K. (2010). Development of a movable bench system for strawberries. *Proc. 5th Int. Symp. Machinery and Mechatronics Agric. and Biosyst. Eng.* Fukuoka, Japan.
- Sanders, K. F. (2005). Orange harvesting systems review. *Biosyst. Eng.*, *90*(2), 115-125. <http://dx.doi.org/10.1016/j.biosystemseng.2004.10.006>
- Sankaran, S., Mishra, A., Ehsani, R., & Davis, C. (2010). A review of advanced techniques for detecting plant diseases. *Comput. Electron. Agric.*, *72*(1), 1-13. <http://dx.doi.org/10.1016/j.compag.2010.02.007>
- Scheiner, E. (2013). Gov't pays \$1,123,463 to develop strawberry harvest-aiding robots. Retrieved from <http://cnsnews.com/news/article/eric-scheiner/govt-pays-1123463-develop-strawberry-harvest-aiding-robots>
- Schmoldt, D. (2012). *AUVSI's Unmanned Systems Mission Critical*, *2*(1), 26-27. Retrieved from http://issuu.com/auvsi/docs/mission_critical_spring2012
- Scottford, I. M., & Miller, P. C. H. (2005). Applications of spectral reflectance techniques in Northern European cereal production: A review. *Biosyst. Eng.*, *90*(3), 235-250. <http://dx.doi.org/10.1016/j.biosystemseng.2004.11.010>
- Shalal, N., Low, T., McCarthy, C., & Hancock, N. (2013). A review of autonomous navigation systems in agricultural environments. *Soc. Agric. Eng. (SEAg): Innovative Agric. Tech. for a Sustainable Future*. Barton, Australia.
- Slaughter, D. C., Giles, D. K., & Downey, D. (2008). Autonomous robotic weed control systems: A review. *Comput. Electron. Agric.*, *61*(1), 63-78. <http://dx.doi.org/10.1016/j.compag.2007.05.008>
- National Institute of Food and Agriculture. (2011). Specialty crop research initiative, external review-self-study document. Washington, DC: NIFA. Retrieved from <http://nifa.usda.gov/sites/default/files/resources/SCRI%20Self-Study%20document.pdf>
- UC Davis College of Engineering. (2014). Stavros Vougioukas strawberry harvesting aid. Davis, CA: Univ. of California. Retrieved from <https://www.flickr.com/photos/ucdaviscoe/sets/72157640115402516/>
- Suprem, A., Mahalik, N., & Kim, K. (2013). A review on application of technology systems, standards and interfaces for agriculture and food sector. *Comput. Standards & Interfaces*, *35*(4), 355-364. <http://dx.doi.org/10.1016/j.csi.2012.09.002>
- Takeda, F. (1999). Out-of-season greenhouse strawberry production in soilless substrate. *Adv. Strawberry Res.*, *18*, 4-15.
- Takeshita, D., Yamamoto, S., Hayashi, S., Saitoh, S., & Imou, K. (2010). Visual feedback control for picking strawberries by robotic harvester. *Proc. 5th Int. Symp. Machinery and Mechatronics for Agric. Biosyst. Eng.* Fukuoka, Japan.
- Tallada, J. G., Nagata, M., & Kobayashi, T. (2006). Detection of bruises in strawberries by hyperspectral imaging. ASABE Paper No. 063014. St. Joseph, MI: ASABE. <http://dx.doi.org/10.13031/2013.20854>
- Tarrio, P., Bernardos, A. M., Casar, J. R., & Besada, J. A. (2006). A harvesting robot for small fruit in bunches based on 3-d stereoscopic vision. ASABE Paper No. 701P0606. St. Joseph, MI: ASABE. <http://dx.doi.org/10.13031/2013.21885>
- Tektu T100 strawberry harvester-Horticultureweek. (2010). Technical product of the year 2010: Tektu T100 strawberry harvester, Tech2reality. Retrieved from <http://www.hortweek.com/technical-product-year-2010-tektu-t100-strawberry-harvester-tech2reality/article/984362>
- Thorp, K. R., & Tian, L. F. (2004). A review on remote sensing of weeds in agriculture. *Precision Agric.*, *5*(5), 477-508. <http://dx.doi.org/10.1007/s11119-004-5321-1>
- Tillett, N. D. (1991). Automatic guidance sensors for agricultural field machines: A review. *J. Agric. Eng. Res.*, *50*, 167-187. [http://dx.doi.org/10.1016/S0021-8634\(05\)80012-5](http://dx.doi.org/10.1016/S0021-8634(05)80012-5)
- Tillett, N. D. (1993). Robotic manipulators in horticulture: A review. *J. Agric. Eng. Res.*, *55*(2), 89-105. <http://dx.doi.org/10.1006/jaer.1993.1035>
- USDA-REEIS. (2014). Frail-Bots: Fragile crop harvest-aiding mobile robots. Washington, DC: USDA-REEIS. Retrieved from <http://www.reeis.usda.gov/web/crisprojectpages/1000459-nri-small-frail-bots-fragile-crop-harvest-aiding-mobile-robots.html>
- Vargas, A. M., Kim, M. S., Tao, Y., Lefcourt, A., & Chen, Y. R. (2004). Safety inspection of cantaloupes and strawberries using multispectral fluorescence imaging techniques. ASAE Paper No. 043056. St. Joseph, MI: ASABE. <http://dx.doi.org/10.13031/2013.16715>
- Wang, C., Chung, W., Liao, J., Chung, C., Kuo, Y., & Lin, T. (2012). Strawberry anthracnose disease assessment using hyperspectral imaging. *Proc. 6th Int. Symp. Machinery and Mechatronics Agric. and Biosyst. Eng.* Jeonju, Korea.
- Wang, F. (2010). Guidance line detection for strawberry field in greenhouse. *Symp. Photonics and Optoelectronic*, (pp. 1-4). New York, NY: IEEE. <http://dx.doi.org/10.1109/SOPO.2010.5504480>
- Wu, F., Guan, Z., & Whidden, A. (2012). Strawberry industry overview and outlook. Gainesville, FL: Univ. of Florida. Retrieved from <http://www.fred.ifas.ufl.edu/pdf/webinar/Strawberry.pdf>
- Wulf, J. S., Rühmann, S., Rego, I., Puhl, I., Treutter, D., & Zude, M. (2008). Nondestructive application of laser-induced fluorescence spectroscopy for quantitative analyses of phenolic compounds in strawberry fruits (*fragaria x ananassa*). *J. Agric. and Food Chem.*, *56*(9), 2875-2882. <http://dx.doi.org/10.1021/jf072495i>
- Xie, Z., & Zhang, T. (2006). A new method of segmentation of strawberry image [in Chinese with English abstract]. *J. China Agric. University*, *11*(1), 84-86.
- Xu, L., & Zhao, Y. (2010). Automated strawberry grading system based on image processing. *Comput. Electron. Agric.*, *71*(supp.1), S32- S39. <http://dx.doi.org/10.1016/j.compag.2009.09.013>
- Xu, Y., Ehsani, R., Kaplan, J., Ahmed, I., Kuzma, W., Orlandi, J., ... Defterli, S. G. (2014). An octo-rotor ground network for autonomous strawberry disease detection - Year 1 status update. *2nd Int. Conf. on Robotics and Associated High-Tech. and Equipment for Agric. and Forestry*, (pp. 457-466).

- Xu, Y., Imou, K., Kaizu, Y., Saga, K., Takeshita, D., Hayashi, S., ... Saito, S. (2013). A binocular stereovision system for the strawberry harvesting robot. *Int. Information Inst.*, 16(11), 8069-8092.
- Yaghoubi, S., Akbarzadeh, N. A., Bazargani, S. S., Bazargani, S. S., Bamizan, M., & Asl, M. I. (2013). Autonomous robots for agricultural tasks and farm assignment and future trends in agro robots. *Int. J. Mechanical & Mechatronics Eng.*, 13(3), 1-6.
- Yamamoto, S., Hayashi, S., Yoshida, H., & Kobayashi, K. (2014). Development of a stationary robotic strawberry harvester with a picking mechanism that approaches the target fruit from below. *Japan Agric. Res. Quarterly*, 48(3), 261-269. <http://dx.doi.org/10.6090/jarq.48.261>
- Yamamoto, S., Hayashi, S., Yoshida, H., Kobayashi, K., & Shigematsu, K. (2009). Operational performance of a stationary robotic strawberry harvester with a picking mechanism that approaches target from below. *Proc. Int. Symp. on High Tech. for Greenhouse Syst.*, (pp. 325-332). Quebec/Canada.
- Yamamoto, S., Hayashi, S., Yoshida, H., Kobayashi, K., & Shigematsu, K. (2008). Development of an end-effector for a strawberry-harvesting robot. *Proc. Int. Symp. on High Tech. for Greenhouse Syst.*, (pp. 565-572). <http://dx.doi.org/10.17660/actahort.2008.801.63>
- Yamamoto, Y., Ochiai, Y., Saito, S., & Hayashi, S. (2012). Study on automatic packing system for strawberries. *Appl. Eng. Agric.*, 28(4), 593-601. <http://dx.doi.org/10.13031/2013.42074>
- Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture: A worldwide overview. *Comput. Electron. Agric.*, 36(2-3), 113-132. [http://dx.doi.org/10.1016/S0168-1699\(02\)00096-0](http://dx.doi.org/10.1016/S0168-1699(02)00096-0)
- Zhang, T., Chen, L., & Song, J. (2005). Study on strawberry harvesting robot: Images based identifications of strawberry barycenter and plucking position [in Chinese with English abstract]. *J. China Agric. University*, 10(1), 48-51.
- Zwiggelaar, R. (1998). A review of spectral properties of plants and their potential use for crop/weed discrimination in row crops. *Crop Protection*, 17(3), 189-206. <http://dx.10.1016/S0261-2194>