JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Role of Robotics in Fruit & Crop Harvesting

Rahul Sharma

M.Tech Robotics

School of Mechanical Engineering

Lovely Professional University, Punjab, India

Abstract

Due to the increasing demand for agricultural products and labor shortage, there is a strong need for automation in agriculture. This paper reviews the various techniques and recent developments in the field of fruit & crop harvesting. But due to various challenges like a lot of variation in the work environment and limitation of sensing capabilities, it isn't easy to commercialize the use of such robots. There are various solutions like human-robot collaboration and modifying production methods that need to be implemented to increase such robots' productivity.

Introduction

The world's population is increasing day by day, and so is the demand for agricultural products. We have to increase the productivity of agriculture by 50% to provide sufficient food to the fast-growing population in the next 30 years [1]. Also, there will be a shortage of labour and farmers due to urbanization and modern culture. As we knew, the tasks in agriculture are highly repetitive and very dull, so there is a strong need for automation and robotization in agriculture. Some crops like wheat, corn, etc., can be harvest in one moment with the help of big machines, but there are some crops like apple, orange, etc., which can be selectively harvested because these crops do not ripen uniformly. Also, we need to ensure that no damage happens to trees and fruits, which makes selective harvesting the most challenging task on the farm.

Other than labour shortage and cost, there are various factors to promote robots in agriculture. Robots have better precision, a better quality of operation, accuracy, and speed than humans. Robots can also detect the crop after harvesting, which can improve food production. There are different challenges for robots in fruit harvesting as compared to robots that work in a stable work environment of industries:

1. **Safety**: A harvesting robot should be safe for its environment. Most of the fruits and vegetables are very delicate, so it needs to handle proper care so that there will be no damage to the plant and the robot manipulator itself. Any damage to fruit can lead to rejection of the fruit in the fruit market, and damage to the plant can stop producing different fruits.

2. **Variation**: Compared to industrial robots that work in a stable environment with known artificial objects, the harvesting robot has to work in an unknown environment with natural things. There is lots of variation in its work environment. Every fruit is different in shape, size, colour, etc., which needs to be harvested selectively. There is lots of variation caused by climate change, affecting different conditions like temperature, humidity, illumination, etc. Other than this, there are different production methods, soil types, irrigation methods resulting in different growth patterns.

System Requirement

This section presents the system requirement for the functionality of robotic harvesting. The functionality of this robot needs the following sequence of tasks to be performed:

1. Detecting fruit and its various properties (like ripeness) in the scene and localizing fruit in 3-dimensional spaces.

2. Approach to target Fruit.

3. Detachment of Fruit from the plant.

4. Guiding the detached fruit to the storage container.

Task 1: Detection and localization of fruit:

The machine vision system is used to detect and find its location in 3D space. Recent developments in the field of visual identification and machine vision system increase the application of robots in fruit harvesting. Agriculture robots also use artificial intelligence to identify the target in the scene [2]. Fruit harvesting is a time-consuming task that motivates researchers to research in this field. Most of the fruit fields have rough terrain & there are lots of obstacles in the form of rocks that cause high vibration in the vision system of mobile harvesting robot when it has to travel from one plant to another plant in the field. We have to use dynamic target tracking and de-blurring algorithms to overcome this challenge. Tang et al. (2018) [3] used a binocular vision system to track vibration caused by rough terrain and detect the deformation surface. The machine vision system should see different fruit types and environmental changes (Zhao et al., 2016) [4], collect information, and learn automatically from it. A robot system should have some network transmission function that enables it to send the fruit images to the server (Garcia Sanchez et al., 2011) [5]. The first task of the fruit harvesting robot is to use a vision system to collect information about the fruit environment (Zou et al., 2012;) [6]. It includes camera calibration (Wang et al., 2019) [7], target recognition and positioning, target background recognition, 3D reconstruction, visual positioning-based robot behavior planning, and vision. Vibrations caused by wind or manipulator, inaccurate positioning caused by various tasks, and variation in the illumination of the fruit environment are the significant challenges in the machine vision system of the harvesting robot. The table represents the different performance parameters of the fruit harvesting robots.

References	Harvesting success rate (%)	Harvesting time per fruit(s)	Recognition accuracy (%)	Recognition time (s)
Zou et al. (2016) [8]	84-88	11.3-15.5	85-94	0.8
Liu et al. (2019) [9]	/	/	93.5	/
Onishi et al. (2019) [10]	/	16	90	2
Vitzrabin and Edan (2016) [11]	79	/	/	/
Williams H. A. M. et al. (2019) [12]	86	2.78	/	/
Hemming et al. (2014) [13]	/	/	90	/
Qingchun et al. (2012) [14]	86	/	/	/
Williams H. A. M. et al. (2019) [15]	51.0	5.5	76.1	3
Majeed et al. (2018) [16]	/	/	88-93	/

Stereo Vision System

There are two types of stereo vision systems currently being used. The first is a binocular vision system based on optical geometry. In which we use optical principles and optimal algorithms to obtain the 3D position of the target. The second is the RGB-D camera based on the time of flight method (TOF), which uses an infrared sensor to obtain information about the target fruit. One limitation of the TOF method is that it is very sensitive to any interference and may not work if powerful light is present in the scene. Another limitation is the working distance of the infrared sensor. The optimal geometry-based system does not rely on artificial intelligence. Hence the optical geometry-based system can use in indoor and outdoor environments. To ensure stability vision system based on optimal geometry is used. On the other hand, the principle of the RGB-D camera is very simple, and the system is also very compact, which can be used for many local tasks.

The optical geometry-based stereo vision system consists of two or more two cameras separated by some distance (Zou et al., 2012) [17]. First of all, cameras are calibrated. After that, two or more images of a target are obtained through the vision system. Then, obtained images are classified to identify the target object in the scene. The binocular vision-based stereo system is based on monocular vision. The early monocular-based stereo vision system used a single camera to detect a 2D image of the target. Researchers began to explore 3D images and stereoscopic machine vision (Roberts, 1965) [18].

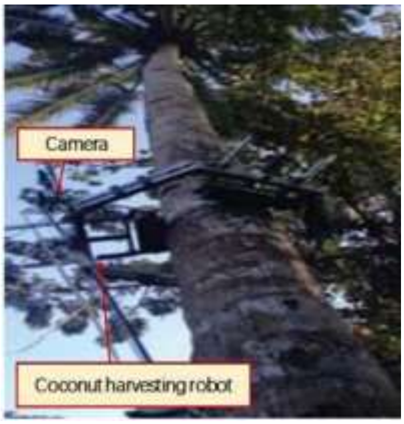

Fig.1.Autonomous coconut-harvesting-robot (Wibowo et al., 2016) [19]

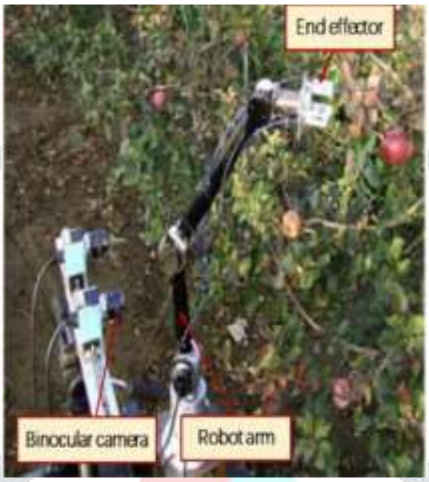

Fig.2. apple harvesting robot (Si et al., 2015). [20]

Laser Active Vision Technology

The laser-based vision system to identify fruits was proposed by Jimenez et al. (1999) [21]. This method uses an infrared sensor to detect the three-dimensional position of the fruit in space along with its radius and surface reflectivity. Slaughter et al. (1986)[22] proposed an active triangulation-based system that consists of several independent lasers. The light produced from each laser is projected on the object. s. Kondo et al. (2009)[23] used a laser finger on a grape, cucumber, and tomato harvesting robot. The problem with the structured light is that it needs complex equipment installation and unpredictable occlusions are also there. Due to this, in some cases, the laser is blocked by some obstacles in the work environment, and sometimes the laser may be out of focus due to long distance, which results in inaccurate measurements. Fig.3 represents an apple harvesting robot.

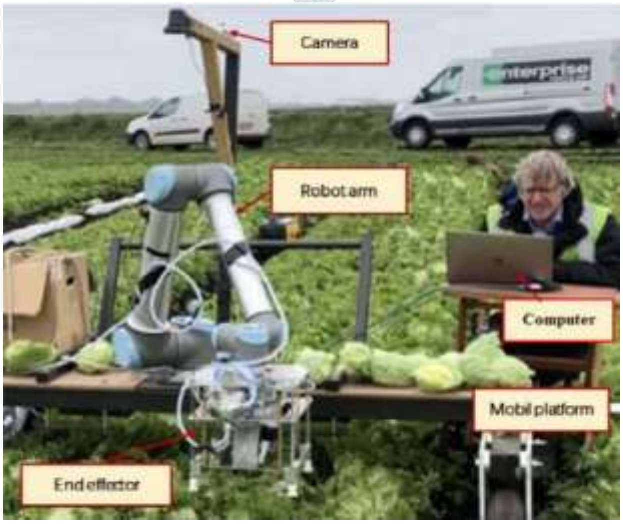

Fig.3. Iceberg lettuce picking robot (Birrell et al., 2019) [24]

Task 2 & 4: Approach to Target fruit and Guiding Harvested fruit to Storage Container.

To harvest the fruit from the plant, a robotic manipulator need to guide the end effector to the desired target so that after harvesting the fruit, it can be stored in some storage container. So the first design consideration for the manipulator is that it should adapt itself according to the crop environment because there are many variations in the work environment of a robotic harvester like the shape and size of each fruit is different, and stem length varies from fruit to fruit. The second design consideration for the manipulator is that it should be strong enough to handle the payload of fruit and handle various forces acting on it during the harvesting operation.

Another design consideration is that system can work in a harsh agricultural environment where dirt, wind, and rain are very common. So robot motors, actuators, wires, and sensors should be protected from rainwater and dirt. Power source for compressor, actuators is readily available in the indoor environment, but robotic harvester works in agriculture fields, requiring an external power source. Another design consideration for the manipulator is that it should damage the plants and end effector as the collision between them is widespread during the operation. After the successful detachment of fruit from the plant, it is needed that detached fruit is being guided to the storage tank. For this operation, a dedicated robot was used to pick the detached fruit from the ground and place it in the storage container, but dropping the fruits on the ground lead to damage to the fruits, and such fruits are not accepted in the fruit market. The crop environment plays a vital role in the design of the manipulator. For this, we can consider three various methods to set up the crop environment.

Greenhouse

A greenhouse is a controlled environment for crop production in which we can control environmental factors such as humidity, temperature, illumination, etc. Plants grow in an artificial environment where only an optimal amount of water and nutrients are provided to the plants. Henten [25] and van Henten et al. [26] describe the greenhouse production cycle and various activities. Robots developed in the past three decades have been discussed in [27].

Robots had a cycle time of 33s and a harvesting success rate of 66%. The success rate for fruit detachment and localization were 75% and 85%, respectively. A robotic system, SWEEPER (www.sweeper-robot.eu), was developed for sweet pepper harvesting in the EU projects. This system consists of six degrees of freedom manipulator, RGB-D camera with GPU controller for localization of the target, a specially designed end effector, and a storage container to store harvested fruits.

This system was evaluated on 262 fruits [28], resulting in a 66% success rate in optimal crop environment 18% in commercial crop environment shows the need for a specially designed crop environment for robotic harvesting

Fig.4. Prototype of sweet pepper harvesting robot SWEEPER (www.sweeper-robot.eu)

Orchard

The environmental parameters are uncontrollable in an orchard, which makes the variation in the natural conditions difficult. The layout of the orchard also has fewer structures compared to the greenhouse, especially robot navigation in the mountainous environment is a more challenging task. Robotic operations are more accessible in modern orchards in which trees are trimmed and trained extensively compared to traditional orchards having tress in 3d structures [29]. We can use mechanical harvesters when fruits are allowed to be damaged and when all fruits can be harvested in one moment, especially for the juice market and for nuts [30]. However, selective harvesting for the fresh fruit market is a more complex and challenging task. Sa et al. [31] show a deep neural network application to detect different types of fruits, including apples, oranges, and mango. Silwal et al. [32] proposed a design of a robotic system for fresh market apples. The system was an open-loop control system with seven degrees of the manipulator, a global camera setup, and a grasping end-effector resulting in an average picking time of 6s. The success rate was 84%.

Fig.5.Apple harvesting robot (Silwal et al., 2017) [33]

Open Field

Open field is another type of crop production method in which crops are produced on the flat strips of the land. For this type of crop, the mechanical harvester is the most efficient way of harvesting because these crops can be harvested in one moment. Selective harvesting for these crops is more challenging due to environmental variations compared to controlled crop production methods. Chatzimichali et al. [34] proposed a robotic design to harvest white asparagus selectively. The procedure consists of two cameras to identify the asparagus and caterpillar platform. Leu et al. [35] presented a harvesting robot design for the harvesting of green asparagus, consisting of one RGB-D camera, a four-wheeled platform, and two harvesting tools (fig.6).

Fig.6. Green asparagus harvesting end effector [35].

Task 3: Fruit Detachment

After reaching the target location with the help of a manipulator, fruit needs to be detached from the plant by using an end effector. The end effector is the tool that is attached at the end of the robotic manipulator. An end effector should be capable of handling a high degree of variability that exists in the work environment of the crops. Karkee and Zhang (2012) [36] have discussed the various sources of variation in the crop environment. Due to multiple factors, there is natural variation in fruit shape, size, color, weight, etc. these variations largely depend on the production methods. Fig.7 shows the two pictures of apples growing on the same plant.

Fig.7. variation in apple position and orientation [36]

The apples shown on the left side are isolated and are more accessible to the end effector. However, apples on the right are more clustered and are oriented in an unpredictable direction, and are less accessible. The parameters related to fruit growth patterns play an essential role in the design criteria of the end effector and its method of fruit detachment. The second design consideration of the end effector is that it should not damage fruits and trees. The detached fruit should be free from any surface damage to be accepted in the fresh fruit market. The physical properties of the fruit also play an essential role in selecting the detachment process and overall end effector. There are various methods to detach the fruits from the stem. Gripping is a single DOF method that uses vacuum or open/ close type of devices.

On the other hand, grasping is a multi-DOF method that is adaptive to fruit shape. The various method used for fruit detachment, including gripping and cutting in which fruit is gripped, its stem is being cut by use of some blade or thermal device. All technologies use gripping only during fruit picking and use forces produced by the end effector for the detachment process. This section reviewed 39 different robotic harvesting technology developed between 1985 and 2018 ((Bac et al. (2014)) [37]. All technologies developed for fruit and vegetable harvesting.

Study	Fruit	Fruit Detachment Method	Manipulator DOF	Manipulator Actuators	Number of End Effector Actuators	Types of End Effector Actuators
Grand d'Esnon et al., 1987[38]	Apple	Grip	4	Hydraulic	1	Vacuum
Setiawan, Furukawa, & Preston, 2004 [39]	Apple	Grip	6	Electric (industrial)	1	Vacuum generator
Baeten et al., 2008 [40]	Apple	Grip	6	Electric (industrial)	1	Vacuum pump
Bulanon & Kataoka, 2010[41]	Apple	Grip	3	Electric (custom)	2	DC motor & stepper motor
Zhao et al., 2011[42]	Apple	Grip & Cut	5	Electric & Hydraulic? (custom)	2	DC Motor & pneumatic pump
Silwal et al., 2017[43].	Apple	Grasp	7	Electric (custom)	3	Electric
Hohimer et al., 2018[44].	Apple	Grasp	5	Electric (custom)	3	Pneumatic
Irie et al, 2009[45]	Asparagus	Grip & Cut	4	Electric (custom)	2	Electric motor
Chatzimichali et al., 2009[46].	Asparagus	Grip & Cut	3	Electric (custom)	2	Pneumatic pump & DC motor
Edan et al., 2000[47].	Cantaloup	Grip & Cut	3	Electric? (custom)	2	Pneumatic (?)
Tanigaki et al., 2008[48].	Cherry	Grip	4	Electric (custom)	3	Servomotors & vacuum pump
Van		Grip & Cut		Electric	2	Pneumatic pump

Henten et al., 2002[49].	Cucumber		7	(industrial)		& electric motor
Tang et al., 2009[50].	Cucumber	Cut	6	Electric (custom)	1	Electric motor
Aljanobi et al., 2010[51].	Date Palm	Grip	5	Electric (custom)	1 (?)	Motor (?)
Wan Ishak, Kit, & Awal, 2010[52].	Eggplant	Cut	3	Electric (custom)	1	DC Motor
Monta, Kondo, & Shibano,1995[53].	Grape	Grip & Cut	5	Electric? (custom)	?	?
Scarfe et al., 2009[54].	Kiwi	Grip	3	Electric (custom)	1 (?)	Electric motor
Cho et al., 2002 [55].	Lettuce	Grip & Cut	3	Electric & Pneumatic (custom)	1 (?)	Pneumatic
Liu et al., 2011[56].	Lychee	Grip & Cut	-	-	1	Pneumatic
Reed et al., 2001[57].	Mushrooms	Grip	3	Pneumatic (custom)	3	Stepper motor & rotary pneumatic
Pool and Harrell, 1991[58].	Orange	Grip	3	Hydraulic (custom)	1	Hydraulic
Muscato et al., 2005[59]	Orange	Cut	3	Electric & Pneumatic (custom)	3	Pneumatic
Lee and Rosa, 2006[60]	Orange	Cut	3	Hydraulic & pneumatic (custom)	1	Pneumatic cylinder
Haifeng et al, 2002[61]	Pineapple	Grip	-	-	2	Stepper motors
Foglia and Reina, 2006[62]	Radicchio	Grip & Cut	2	Pneumatic (custom)	2	Pneumatic muscles
Kondo et al., 1996[63]	Cherry Tomato	Grip & Cut	7	Electric? (custom)	2	Pneumatic & solenoid
Monta et al., 1998[64]	Tomato	Grip	7	Electric (custom)	2	DC motor & vacuum pump
		Grip &Grasp		Electric		Vacuum pump & stepper

Ling et al., 2004[65]	Tomato		6	(industrial)	2	motor linear actuator
Zhao et al., 2016[66]	Tomato	Grasp & Cut	3	-	2	Pneumatic (?)
Antonelli et al., 2011[67]	Saffron	Grip	3	Electric (custom)	3	EM solenoids & vacuum pump
Liu et al., 2007[68]	Spherical Fruit	Grip & Cut	6	Electric (industrial)	3	DC servomotors & vacuum pump
Hayashi et al. 2010[69]	Strawberry	Grip & Cut	3	Electric? (custom)	2	Pneumatic
Feng et al., 2012[70]	Strawberry	Grip & Cut	6	Electric (industrial)	1	Pneumatic
Han et al., 2012[71]	Strawberry	Grip & Cut	4	Electric (custom)	4	Electric motors

Manipulator Actuation

The selection of the degree of freedom of the manipulator plays an important role in the harvesting operation. The work environment of different fruits is different. Seven of the 39 technologies used robotic manipulators with electric actuators. Electrical servomotor and stepper motors are used where the weight of manipulation & the payload is low. Hydraulic and pneumatic actuators are used for heavy payloads because of their high power-to-weight ratio. The breakdown of manipulator actuators used in the remaining technologies is shown as:

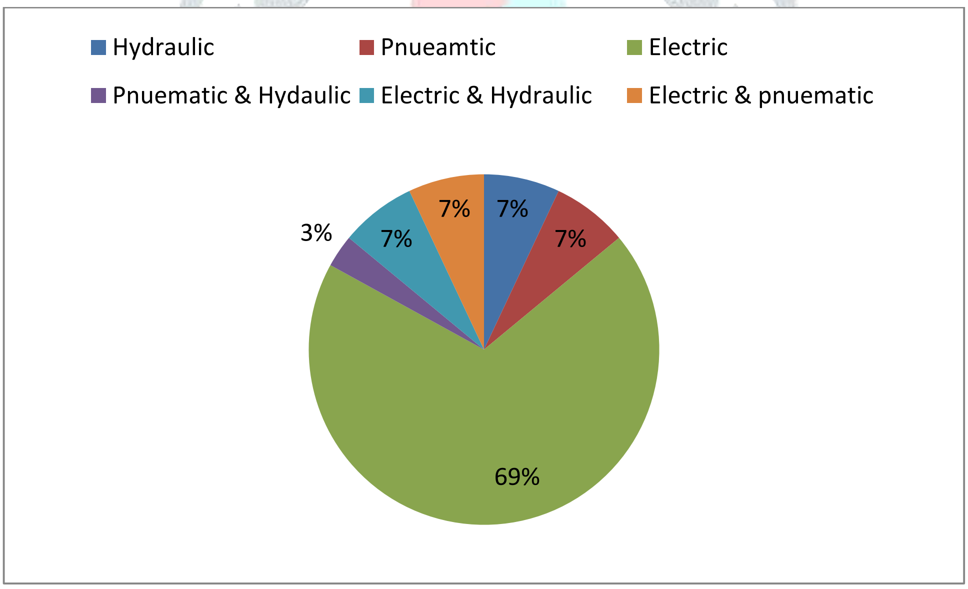

Fig.8. Breakdown of manipulator actuators

End Effector Actuation

Most of the technologies used one or two actuators, and the number of actuators used by all harvesting technologies varies from one to four. Most of the actuators used were either pneumatic or electric. Breakdown of all the end effector actuators used in different technologies is shown n fig.9. Most of the technologies used electrical or pneumatic type end effectors for the fruit detachment process. The breakdown of different types of actuation used for the end effector is shown in fig.10. These findings show that a system might benefit from using electrical & pneumatic actuation for end effector & electrical actuation for the manipulator for fruit picking.

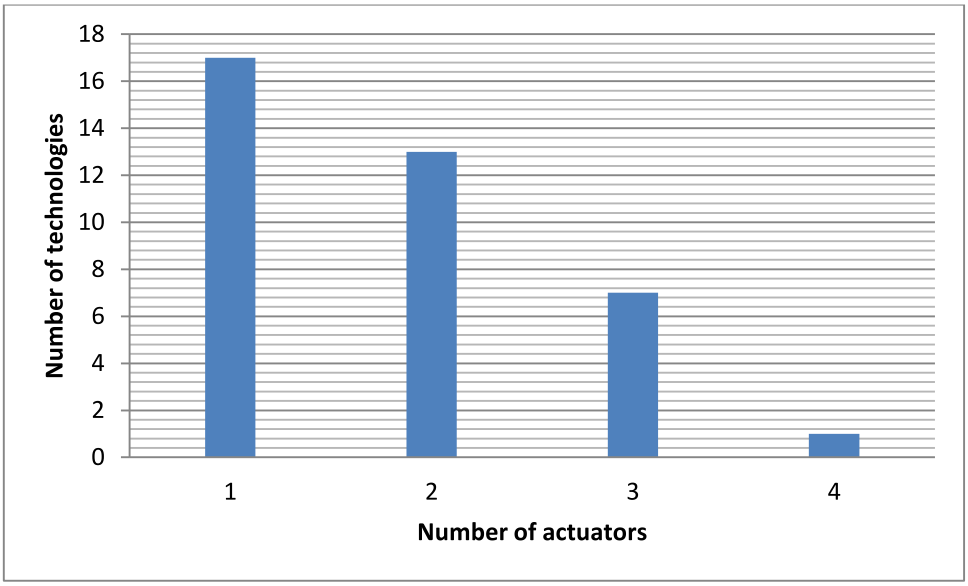

Fig.9. Breakdown of all end effector actuators

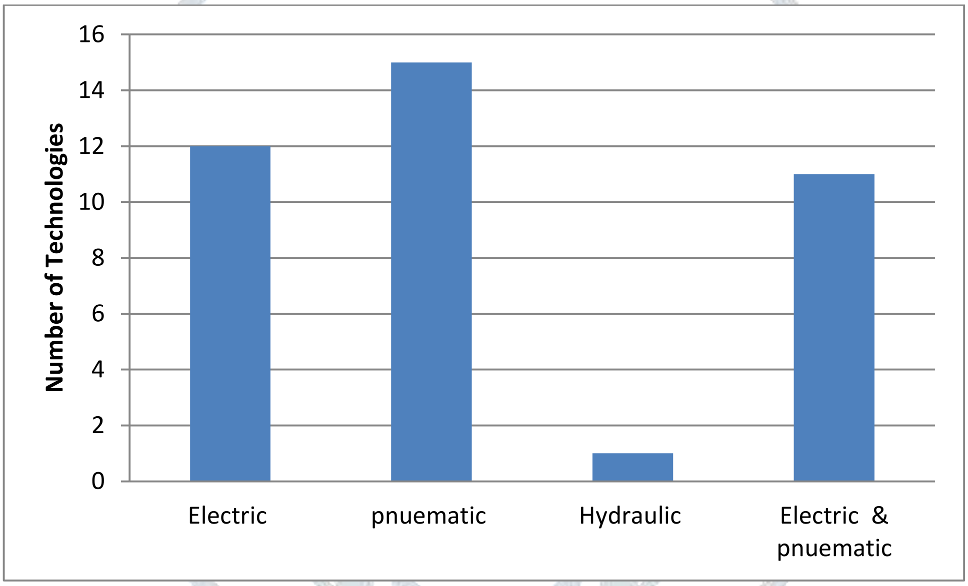

Fig.10. Breakdown of all End Effector Actuators used

Fruit Detachment Methods

There are various methods used for the fruit detachment, including grip, grasp, grip & cut the stem, etc. Combination of gripping & cutting is the most commonly used method for the fruit detachment process. Only one end effector used the grasp method to grasp the fruit according to its shape. The breakdown of all fruit detachment methods used by all technologies is shown in fig.10.

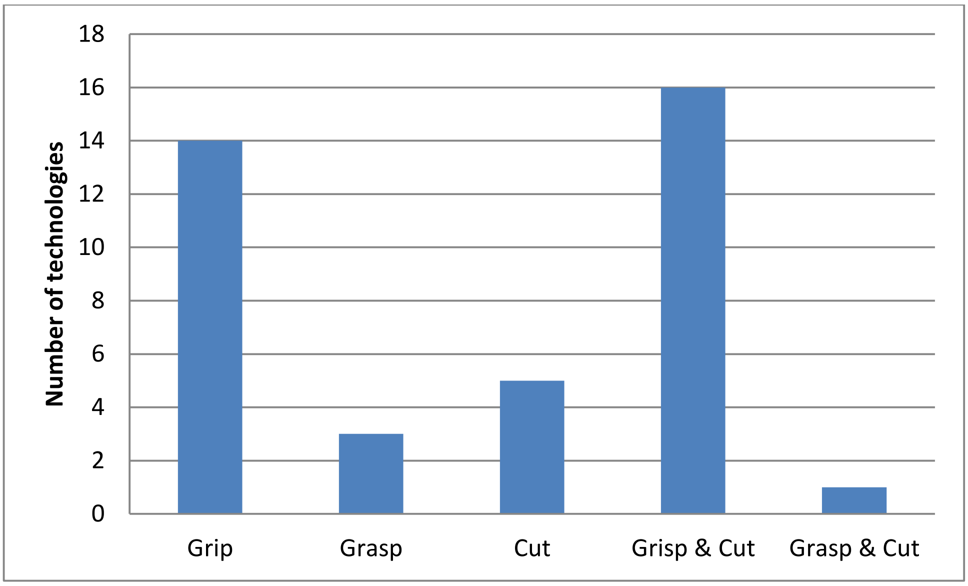

Fig.10. Breakdown of all fruit detachment methods

Future Scope & Solution to Technical Problems

There is bright scope of robotics in fruit or crop harvesting. There are a lot of challenges in the operation of the harvesting robot. Here are some solutions and improvements we can make in harvesting robots.

1. **Reducing variation in the work environment:** The performance of the machine vision system depends on the variation in the work environment of the harvesting robot. We can enhance the productivity of the machine vision system by reducing the plant population and reducing the variation of plants by arranging in some particular sequence. We can use different plant production methods like greenhouse and orchards. To reduce the complexity of the scene, breeding for the robot is another way. Modification and standardization of the cultivation systems offer opportunities to reduce variation.

2. **Enhancing robotic technology:** Including more domain knowledge in the design and operation of robots to reduce the variation. For this, we have to model the world in which the robot has to operate, which will provide clues about the work environment and the presence or absence of objects. Another way is to extend the capabilities of sensors so that we can better feedback from the sensors.

3. **Human-robot collaboration:** The kind of variation in the agriculture field can be tackled by human-robot collaboration. They will help each other enhance the productivity of the overall operation of the harvesting robot. A human operator can guide the robot to target fruits, and the robot can harvest with its end effector.

Conclusion

This paper reviews the role of robotics in fruit & crop harvesting and various techniques and methods used in harvesting robots from machine vision to fruit detachment. Various technical challenges and limitations of the system also have been discussed. And for all problems, various possible solutions also have been discussed. To increase the productivity of the harvesting robot, we have to implement such solutions in the robotic system

References

[1]. UN: World population prospects: the 2017 revision, key findings and ad-vance tables. ESA/P/WP/248.https://esa.un.org/unpd/wpp/ Publications/Files/WPP2017_KeyFindings.pdf (2017).

[2]. Edan, Y., Han, S., and Kondo, N. (2009). Automation in Agriculture, Springer Handbook of Automation. Berlin: Springer Berlin Heidelberg, 1095–1128.

[3]. Tang, Y., Li, L., Feng, W., Liu, F., Zou, X., and Chen, M. (2018). Binocular vision measurement and its application in full-field convex deformation of concrete-filled steel tubular columns. Measurement 130, 372–383

[4]. Zhao, D., Lv, J., Ji, W., and Zhang, Y. (2011). Design and control of an apple harvesting robot. Biosyst. Eng. 110, 112–122.

[5]. Garcia-Sanchez, A., Garcia-Sanchez, F., and Garcia-Haro, J. (2011). Wireless sensor network deployment for integrating video-surveillance and data-monitoring in precision agriculture over distributed crops. Comput. Electr. Agricult. 75, 288–303.

[6]. Zou, X., Zou, H., and Lu, J. (2012). Virtual manipulator-based binocular stereo vision positioning system and errors modelling. Mach. Vis. Appl. 23, 43–63.

[7]. Wang, Y., Yang, Y., Yang, C., Zhao, H., Chen, G., Zhang, Z., et al. (2019). Endeffector with a bite mode for harvesting citrus fruit in random stalk orientation environment. Comput. Electr. Agricult. 157, 454–470

[8]. Zou, X., Ye, M., Luo, C., Xiong, J., Luo, L., Wang, H., et al. (2016). Faulttolerant design of a limited universal fruit-picking end-effector based on vision-positioning error. Appl. Eng. Agricult. 32, 5–18.

[9]. Liu, T., Ehsani, R., Toudeshki, A., Zou, X., and Wang, H. (2019). Identifying immature and mature pomelo fruits in trees by elliptical model fitting in the Cr-Cb color space. Precis. Agricult. 20, 138–156.

[10]. Onishi, Y., Yoshida, T., Kurita, H., Fukao, T., Arihara, H., and Iwai, A. (2019). An automated fruit harvesting robot by using deep learning. ROBOMECH J. 6:13. doi: 10.3390/s19204599

[11]. Vitzrabin, E., and Edan, Y. (2016). Changing task objectives for improved sweet pepper detection for robotic harvesting. IEEE Robot. Automat. Lett. 1, 578–584. Wang, C., Lee, W. S., Zou, X., Choi, D., Gan, H., and Diamond, J. (2018).

[12]. Williams, H., Ting, C., Nejati, M., Jones, M. H., Penhall, N., Lim, J., et al. (2019). Improvements to and large-scale evaluation of a robotic kiwifruit harvester. J. Field Robot. 37, 1–15.

[13]. Hemming, J., Ruizendaal, J., Hofstee, J. W., and van Henten, E. J. (2014). Fruit detectability analysis for different camera positions in sweet-pepper. Sensors 14, 6032–6044. doi: 10.3390/s140406032

[14]. Qingchun, F., Xiu, W., Wengang, Z., Quan, Q., and Kai, J. (2012). New strawberry harvesting robot for elevated-trough culture. Int. J. Agricult. Biol. Eng. 5, 1–8.

[15]. Williams, H. A. M., Jones, M. H., Nejati, M., Seabright, M. J., Bell, J., Penhall, N. D., et al. (2019). Robotic kiwifruit harvesting using machine vision, convolutional neural networks, and robotic arms. Biosyst. Eng. 181, 140–156.

[16]. Majeed, Y., Zhang, J., Zhang, X., Fu, L., Karkee, M., Zhang, Q., et al. (2018). Apple tree trunk and branch segmentation for automatic trellis training using convolutional neural network based semantic segmentation. IFAC PapersOnLine 51, 75–80.

[17]. Zou, X., Zou, H., and Lu, J. (2012). Virtual manipulator-based binocular stereo vision positioning system and errors modelling. Mach. Vis. Appl. 23, 43–63.

[18]. Roberts, L. (1965). Machine perception of three-dimension solids, in optical and electro-optimal. Form. Process. 10, 190–193

[19]. Wibowo, T. S., Sulistijono, I. A., and Risnumawan, A. (2016). "End-to-end coconut harvesting robot," in Proceedings of the in 18th IEEE International Electronics Symposium (IES), Warwick, 444–449

[20]. Si, Y., Liu, G., and Feng, J. (2015). Location of apples in trees using stereoscopic vision. Comput. Electr. Agricult. 112, 68–74.

[21]. Jimenez, A. R., Ceres, R., and Pons, J. L. (1999). "A machine vision system using a laser radar applied to robotic fruit harvesting," in Proceedings of the IEEE Workshop on Computer Vision Beyond the Visible Spectrum: Methods and Applications (CVBVS'99), Hilton Head, SC, 110–119.

[22]. Slaughter, D., Harrell, R., and Adsit, P. (1986). Image enhancement in robotic fruit harvesting. Am. Soc. Agricult. Eng. Microfiche Collect.

[23]. Kondo, N., Yamamoto, K., Shimizu, H., Yata, K., Kurita, M., Shiigi, T., et al. (2009). A machine vision system for tomato cluster harvesting robot. Eng. Agricult. Environ. Food 2, 60–65.

[24]. Birrell, S., Hughes, J., Cai, J. Y., and Iida, F. (2019). A field-tested robotic harvesting system for iceberg lettuce. J. Field Robot. 37, 1–21. doi: 10.1002/rob.21888

[25]. van Henten EJ. Greenhouse mechanization: state of the art and future perspective. Acta Hortic. 2006;710:55–69

[26]. van Henten EJ, Bac CW, Hemming J, Edan Y: Robotics in protected cultivation. Paper presented at the Proceedings ofthe 4th IFAC conference on modelling and control inagriculture, Espoo, 27–30 Aug 2013.

[27]. Bac CW, van Henten EJ, Hemming J, Edan Y. Harvesting robots for high-value crops: state-of-the-art review and challenges ahead. J Field Robot. 2014;31(6):888–911.

[28]. Arad B, Balendonck J, Barth R, Ben-Shahar O, Edan Y, Hellstrom T, et al. Development of a sweet pepper harvesting robot. J Field Robot. 2020;37(6):1027–39. https://doi.org/10.1002/rob.21937.

[29]. Zhang Q: Automation in tree fruit production: principles and practice. CABI, (2018)

[30]. Zhang Q: Automation in tree fruit production: principles and practice. CABI, (2018).

[31]. Sa I, Ge Z, Dayoub F, Upcroft B, Perez T, McCool C. DeepFruits: a fruit detection system using deepneural networks. Sensors. 2016;16(8):1222.

[32]. Silwal A, Davidson JR, Karkee M, Mo CK, Zhang Q, Lewis K. Design, integration, and field evaluation of a robotic apple harvester. J Field Robot. 2017;34(6):1140–59. https://doi.org/10.1002/rob. 21715 This paper provides a complete robotic system for selective apple harvesting.

[33]. Silwal, A., Davidson, J. R., Karkee, M., Mo, C., Zhang, Q., and Lewis, K. (2017). Design, integration, and field evaluation of a robotic apple harvester. J. Field Robot. 34, 1140–1159.

[34]. Chatzimichali AP, Georgilas IP, Tourassis VD: Design of an advanced prototype robot for white asparagus harvesting. In: 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 14–17 July 2009 2009, pp. 887–892.

[35]. Leu A, Razavi M, Langstädtler L, Ristić-Durrant D, Raffel H, Schenck C, et al. Robotic green asparagus selective harvesting. IEEE/ASME Trans Mechatronics. 2017;22(6):2401–10. https:// doi.org/10.1109/TMECH.2017.2735861.

[36]. Karkee, M., & Zhang, Q. (2012, September/October). Mechanization and Automation Technologies in Specialty Crop Production. ASABE Resource Magazine, pp. 16-17.

[37]. Jaiswal, A., Kumar, B., 2017. Material Compositions Affects Vacuum System In Gripping Technology. Int. J. Sci. Technol. 15–23. Jamali, N., Kormushev, P., Vinas, A.C., Carreras, M., Caldwell, D.G., 2015.

[38]. Grand D'Esnon, A., Rabatel, G., Pellenc, R., Journeau, A., & Aldon, M. J. (1987). MAGALI: A Self-Propelled Robot to Pick Apples. ASAE Paper 87-1037. St. Joseph, MI

[39]. Setiawan, A. I., Furukawa, T., & Preston, A. (2004). A Low-Cost Gripper for an Apple Picking Robot. IEEE International Conference on Robotics and Automation. New Orleans, Louisiana

[40]. Baeten, J., Donne, K., Boedrij, S., Beckers, W., & Claesen, E. (2008). Autonomous Fruit Picking Machine: A Robotic Apple Harvester. Field and Service Robotics, 42, 531-539.

[41].Bulanon, D. M., & Kataoka, T. (2010). Fruit Detection System and an End Effector for Robotic Harvesting of Fuji Apples. Agricultural Engineering International: CIGR Journal, 12(1), 203-210.

[42].Zhao, Y., Gong, L., Liu, C., & Huang, Y. (2016). Dual-arm Robot Design and Testing for Harvesting Tomato in Greenhouse. IFAC-PapersOnLine.

[43].Silwal, A., Davidson, J., Karkee, M., Mo, C., Zhang, Q., & Lewis, K. (2017).

.Design, integration, and field evaluation of a robotic apple harvester. Journal of Field Robotics 34(6), 1140-1159.

[44].Hohimer, C., Wang, H., Bhusal, S., Miller, J., Mo, C., & Karkee, M. (2018). Design and Field Evaluation of a Robotic Apple Harvesting System with a 3D-Printed Soft-Robotic End-Effector. Transactions of the ASABE.

[45].Irie, N., Taguchi, N., Horie, T., & Ishimatsu, T. (2009). Asparagus Harvesting Robot Coordinated with 3-D Vision Sensor. IEEE International Conference on Industrial Technology, (pp. 1-6). Gippsland, Australia.

[46].Chatzimichali, A. P., Georgilas, I. P., & Tourassis, V. D. (2009). Design of an Advanced Prototype Robot for White Asparagus Harvesting. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, (pp. 887- 892). Singapore.

[47].Edan, Y., Haghighi, K., Stroshine, R., & Cardenas-Weber, M. (1992, July). Robot Gripper Analysis: Finite Element Modeling and Optimization. Applied Engineering in Agriculture, 8(4), 563-570.

[48].Tanigaki, K., Fujiura, T., Akase, A., & Imagawa, J. (2008). Cherry-Harvesting Robot. Computers and Electronics in Agriculture, 63, 65-72.

[49].Van Henten, E. J., Van Tuijl, B. J., Hemming, J., Kornet, J. G., Bontsema, J., & Van Os, E. A. (2003). Field Test of an Autonomous Cucumber Picking Robot. Biosystems Engineering, 86(3), 305-313.

[50].Tang, X., Zhang, T., Liu, L., Xiao, D., & Chen, Y. (2009). A New Robot System for Harvesting Cucumber. ASABE International Meeting, (pp. 3873-3885). Reno, Nevada.

[51].Aljanobi, A., Al-hamed, S., & Al-Suhaibani, S. (2010). A Setup of Mobile Robotic Unit for Fruit Harvesting. 19th International Workshop on Robotics in Alpe-Adria-Danube Region, (pp. 105-108). Budapest, Hungary.

[52].Wan Ishak, W., Kit, W., & Awal, M. (2010). Design and Development of Eggplant Harvester for Gantry System. Pertanika J. Sci. & Technol., 18(2), 231-242.

[53].Monta, M., Kondo, N., & Ting, K. C. (1998). End-Effectors for Tomato Harvesting Robot. Artificial Intelligence Review, 12, 11-25.

[54].Scarfe, A. J., Flemmer, R. C., Bakker, H. H., & Flemmer, C. L. (2009)Development of an Autonomous Kiwifruit Picking Robot. 4th International Conference on Autonomous Robots and Agents. Wellington, New Zealand.

[55].Cho, S., Chang, S., Kim, Y., & An, K. (2002). Development of a Three- degrees-of-freedom Robot for Harvesting Lettuce using Machine Vision and Fuzzy Logic Control. Biosystems Engineering, 82(2), 143-149.

[56].Liu, J., Li, P., & Li, Z. (2007). A Multi-Sensory End-Effector for Spherical Fruit Harvesting Robot. IEEE International Conference on Automation and Logistics. Jinan, China.

[57].Reed, J. N., Miles, S. J., Butler, J., Baldwin, M., & Noble, R. (2001). Automatic Mushroom Harvester Development. Journal of Agricultural Engineering Research, 78(1), 15-23.

[58].Pool, T. A., & Harrell, R. C. (1991, March-April). An End-Effector for Robotic Removal of Citrus from the Tree. Transactions of the ASAE, 34(2), 373- 378

[59].Muscato, G., Prestifilippo, M., Abbate, N., & Rizzuto, I. (2005). A Prototype of an Orange Picking Robot: Past History, the New Robot and Experimental Results. Industrial Robot: An International Journal, 32(2), 128-138.

[60]Lee, B. S., & Rosa, U. A. (2006). Development of a Canopy Volume Reduction Technique for Easy Assessment and Harvesting of Valencia Citrus Fruits. Transactions of the ASABE, 49(6), 1695-1703

[61].Haifeng, W., Bin, L., Guangyu, L., & Liming, X. (2012, October). Design and Test of Pineapple Harvesting Manipulator. Transactions of the Chinese Society of Agricultural Engineering, 28(2), 42-46.

[62].Foglia, M. M., & Reina, G. (2006). Agricultural Robot for Radicchio Harvesting. Journal of Field Robotics, 23(6/7), 363-377.

[63].Kondo, N., Nishitsuji, Y., Ling, P., & Ting, K. (1996). Visual Feedback Guided Robotic Cherry Tomato Harvesting. Transactions of the ASAE, 39(6), 2331-2338.

[64]Monta, M., Kondo, N., & Shibano, Y. (1995). Agricultural Robot in Grape Production System. International Conference on Robotics and Automation, (pp. 2504-2509). Nagoya, Japan

[65]Ling, P. P., Ehsani, R., Ting, K. C., Chi, Y., Ramalingam, N., Klingman, M. H., & Draper, C. (2004). Sensing and End-Effector for a Robotic Tomato Harvester. ASAE/CSAE International Meeting, Paper 043088, (p. 12 pp). Ottawa, Canada.

[66].Zhao, D., Lu, J., Ji, W., Zhang, Y., & Chen, Y. (2011). Design and Control of an Apple Harvesting Robot. Biosystems Engineering, 110, 112-122.

[67].Antonelli, M., Auriti, L., Beomonte Zobel, P., & Raparelli, T. (2011).Development of New Harvesting Module for Saffron Flower Detachment. The Romanian Review Precision Mechanics, Optics & Mechatronics, 39, 163-168

[68].Liu, J., Li, P., & Li, Z. (2007). A Multi-Sensory End-Effector for Spherical Fruit Harvesting Robot. IEEE International Conference on Automation and Logistics. Jinan, China

[69].Hayashi, A. (1994). Geometric motion planning for highly redundant manipulators using a continuous model. University of Texas at Austin

[70].Feng, Q., Zheng, W., Qiu, Q., Jiang, K., & Guo, R. (2012). Study on Strawberry Robotic Harvesting System. IEEE International Conference on Computer Science and Automation Engineering (CSAE), (pp. 320-324). Zhangjiajie, China

[71].Han, K., Kim, S., Lee, Y., Kim, S., Im, D., Choi, H., & Hwang, H. (2012). Strawberry Harvesting Robot for Bench-type Cultivation. Journal of Biosystems Engineering, 37(1), 65-74

[72].Kitamura, S., & Oka, K. (2005). Recognition and Cutting System of Sweet Pepper for Picking Robot in Greenhouse Horticulture. IEEE International Conference on Mechatronics and Automation. Niagara Falls, Canada.

[73].Jia, B., Zhu, A., Yang, S., & Mittal, G. (2009). Integrated Gripper and Cutter in a Mobile Robotic System for Harvesting Greenhouse Products. IEEE International Conference on Robotics and Biomimetics. Guilin, China.

[74].Umeda, M., Kubota, S., & Iida, M. (1999). Development of "STORK", a Watermelon-Harvesting Robot. Artificial Life Robotics, 3, 143-147

75].Hwang, H., & Kim, S.-C. (2003). Development of Multi-functional Tele- operative Modular Robotic System for Greenhouse Watermelon. IEEE/ASME International Conference on Advanced Intelligent

[76].Sakai, S., Iida, M., Osuka, K., & Umeda, M. (2008). Design and Control of a Heavy Material Handling Manipulator for Agricultural Robots. Autonomous Robots, 25(3), 189-204.