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Research paper

End-effectors of the robotic arms for tomato harvesting: A comprehensive review

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Abstract

Integrating robotic technologies into agricultural practices has witnessed significant strides, particularly in tomato harvesting. This review paper offers a comprehensive examination of robot arms' end effectors developed for the intricate task of harvesting tomatoes. Drawing insights from a diverse range of sources spanning Google Scholar, Scopus, IEEE Xplorer, and AnimoSearch, the study analyzes the trends, challenges, and future trajectories of employing robotic end effectors in the agricultural context. The investigation encompasses an in-depth exploration of various end-effector methodologies, including grippers, rotational mechanisms, scissor-type tools, and suction devices, elucidating their merits and prevalence in the current research literature. Focusing on the utilizations of end effectors in agricultural robotic harvesting systems, the review delves into fruit detachment methods, types of end tools designed explicitly for harvesting tomatoes, and the integration of sensors into end effectors for enhanced capabilities. The paper highlights the nuanced criteria involved in end effector design, emphasizing operational characteristics, technical features, and the need for adaptability to diverse fruit shapes. Furthermore, a detailed analysis of the challenges faced by end effectors in tomato harvesting is presented, with proposed solutions and recommendations for future research. The discussion extends to the future trends in this evolving field, envisioning advancements in sensing technology, artificial intelligence integration, adaptability, autonomy, and sustainability. In conclusion, the synthesis of technological innovation and agricultural expertise holds promise for reshaping tomato harvesting, paving the way for more sustainable, efficient, and cost-effective farming practices.

1. Introduction

The agricultural sector globally confronts fresh challenges concerning the balance between supply and demand. Given projections of a world population reaching 9 billion by 2050, there's a pressing need to double agricultural output to satisfy rising food requirements [1].

The labor-intensive process of individually picking ripe produce has posed a persistent concern for farmers and growers. Hence, adopting robotics and mechanized harvesting techniques has emerged as a viable solution to address these challenges effectively [2]. Furthermore, the increasing adoption of advanced intelligent farming methods and precision agriculture is driving a surge in agricultural robot innovation. For example, fruit harvesting traditionally involves arduous manual labor. However, integrating agricultural robots improves efficiency, promoting competitiveness by reducing dependence on manual labor during harvests [3].

Despite these technological advancements, there is a projected 50% decline in the agricultural workforce by 2050, potentially leading to a shortage of 5 million skilled harvesting workers. Consequently, this challenge may impact gathering more than 10% of the world's fruit production [4]. Harvesting is characterized by its seasonal nature, low compensation, repetitive tasks, and dependence on manual labor, providing limited opportunities for professional growth.

The experienced workforce in this sector is gradually retiring, while younger generations show minimal enthusiasm for taking up these positions. Labor shortages contribute to delays in the harvesting process, and even a slight delay of a few days can result in a significant decline in quality, potentially causing an 80% reduction in market value. Consequently, farmers around the globe encounter an approximate annual revenue loss of USD 30 billion due to unharvested fruit sales [5]. Hence, there has been a notable transformation in crop management in recent decades. The assessment of harvesting robots encompassed various aspects, including the crops they harvested, performance metrics, design methodologies, hardware choices, and algorithm features. On average, these robots achieved an 85% success rate in localization, 75% in detachment, and 66% in overall harvest success, with only a 5% rate of fruit damage. However, peduncle damage was higher at 45%, and the average cycle time was 33 seconds. Notably, a kiwi harvesting robot achieved the fastest cycle time, completing a cycle in just 1 second [6].

Robotic arms have become integral to automated agriculture, fulfilling essential crop planting, harvesting, and packaging functions. Utilizing these systems has the potential to reduce dependence on human labor while improving the efficiency of agricultural activities. Precisely programming robotic arms to execute specific tasks swiftly promises to increase crop yields and reduce labor costs [7]. As a result, the evolution of automated systems is geared towards mitigating labor shortages, expediting harvesting processes, and optimizing overall efficiency in crop harvesting. Harvesters rely on their manual dexterity in traditional manual harvesting to prune leaves or branches, grip the fruit, and separate it from the plant, sometimes using cutting tools.

Expertise and familiarity are crucial in manual harvesting, and unseasoned harvesters could unintentionally harm the plants. Despite this, human hands and bodies possess inherent grasping capabilities, supported by the ability to feel, and the strength of muscles allows for quick adjustment to different crop shapes and textures, facilitating the accurate application of the required force for detachment [8]. Nevertheless, human capabilities are constrained by the impact of fatigue. In contrast, a robotic system can sustain continuous harvesting with precision without succumbing to exhaustion, ensuring a consistent output. Hence, scientists aim to mimic human harvesting capabilities by creating kinematic models for robotic arm movements and advanced end-of-arm tools with sensors for handling crops [9].

The end effector acts as an external attachment affixed to the robot's wrist, enabling participation in various tasks in harvesting robots. In this context, the end tool acts as the link between the robot and the particular product, which, in this case, pertains to tomatoes.

Inadequate design of the terminal device poses a potential risk to the tomatoes, compromising the overall efficiency of the harvesting system, as noted in reference [10].
Given the diverse range of tomato varieties, it becomes crucial for each harvesting system to incorporate a tailored end effector that aligns with the distinctive characteristics of the tomatoes undergoing harvest. The extensive literature review conducted for this article spans the years from 2007 to 2023.

2. Literature review

Researchers globally have recently put forth various robot end effectors tailored for harvesting tomatoes in agriculture. Park and team [3] present an innovative end-effector designed for a robot specialized in harvesting fruits and vegetables: its mechanism and field experimentation. Their work demonstrates advancements in end-effector technology targeted explicitly toward efficient tomato harvesting. Takeshi *et al.* [11] suggest and verify tomato recognition for harvesting robots considering overlapping leaves and stems. Their study addresses a crucial aspect of robotic tomato harvesting by focusing on the challenges posed by the plant's natural environment, particularly in scenarios where leaves and stems obscure the fruit. Ziyue *et al.* [12] review the structural advancements and methods for recognizing and localizing the end-effector of robots designed for picking fruits and vegetables. Their comprehensive review provides valuable insights into the state-of-the-art technologies and methodologies for developing end-effectors suitable for various agricultural applications, including tomato harvesting. Shivaji [13] has focused on crafting a tomato harvesting robot that emphasizes the identification of tomato peduncles and approach methods. This research contributes to developing specialized robotic systems capable of accurately identifying and harvesting tomatoes, addressing the intricacies of navigating and harvesting within a dense plant canopy.
Ting *et al.* [14] have implemented a robust cherry tomato detection algorithm in a greenhouse scene based on SSD. Their work showcases the application of computer vision techniques in automating the detection and localization of tomatoes, laying the foundation for precise robotic harvesting systems capable of operating in controlled environments. Takuya *et al.* [15] have evaluated the tomato growth state map for the automation of monitoring and harvesting. By leveraging advanced mapping techniques, their research explores the potential for automation in monitoring tomato growth stages, thereby enabling optimized harvesting strategies tailored to the developmental status of the crop. Jeahwi *et al.* [16] present an innovative end effector designed to harvest fruits and vegetables for a robot, showcasing its mechanical structure and a field trial. Their study contributes to the ongoing efforts to develop versatile end-effectors capable of handling a variety of agricultural produce, including tomatoes, with efficiency and precision.

3. Materials and methods

This review article's data sources and scientific information were gathered from Google Scholar, Scopus, IEEE Xplorer, and AnimoSearch, a search tool at De La Salle University in Manila. Initially, the study employed keyword combinations such as "end-effector" and "robotic tomato harvesting." Fig. 1 illustrates the taxonomy for extracting keywords from the database on the Web of Science.

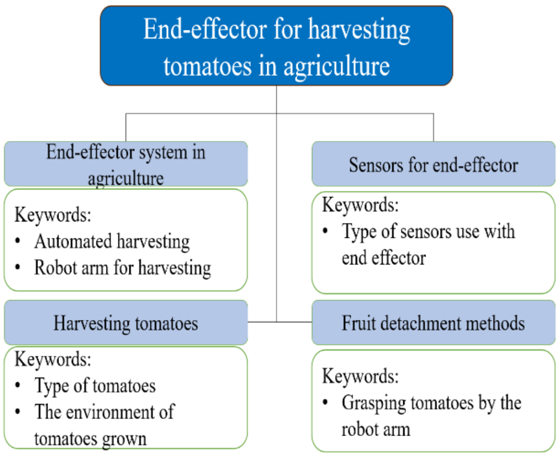

Fig. 1. The classification system according to Web of Science database.

The aim is to determine the trends and volume of research about using robot arm end-effectors in tomato harvesting within the agricultural context.

All identified papers underwent a thorough examination to gauge their relevance to the topic, and those needing more pertinent information regarding end effectors used in field applications were excluded. The assessment of all end effectors employed in tomato harvesting robots typically relied on the following criteria: their capabilities, intended final application, presence of sensors, integration with a robotic arm, and their current developmental stage.

These evaluation criteria shed light on the leading technologies utilized in agricultural practices. By analyzing the number of journal articles published annually from 2007 to 2023, we were able to discern research trends and interests. Graphs were generated to represent these findings visually, and the keywords "end-effector" and "robotic tomato harvesting" are reflected in the results observed in Figs. 2 and 3.

In Fig. 2, the number of publications per year peaked in 2021, with 1,200 papers using the keyword "end effector." The graph indicates a consistent annual increase in publications from 2007 to 2023.

Similarly, in Fig. 3, the number of publications peaked in 2022 and 2023, with eight papers using the keywords "end effector" and "tomato harvesting robot." This graph also shows a steady rise in publications each year from 2007 to 2023.

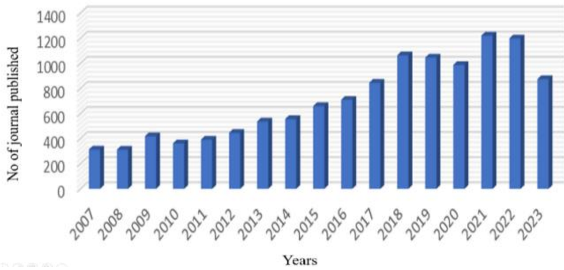

Fig. 2. The number of publications per year according to AnimoSearch in chronological order based on the keyword "end effector".

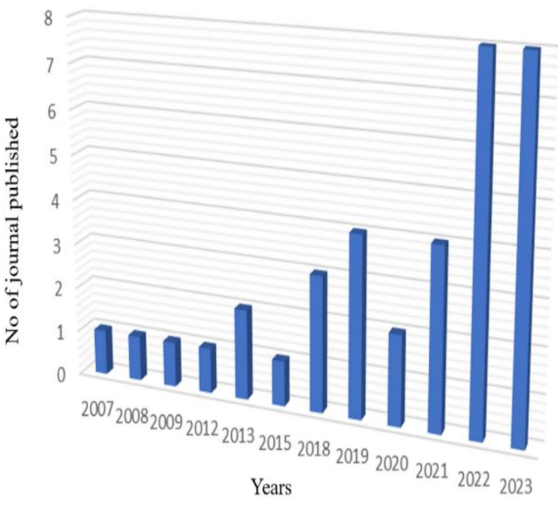

Fig. 3. The number of publications per year according to AnimoSearch in chronological order based on the combination of the keywords "end effector" and "tomato harvesting robot".

4. Utilizations of end-effectors in agricultural robotic harvesting systems

The end effector, a crucial component of the harvest system, has the potential for continuous improvement and refinement to ensure optimal performance in the harvesting process, as detailed in the reference [17]. The actions performed by the robot arm's end effector during harvesting often lead to unintended damage to the fruit, as explained in connection [18].

Automated harvesting robots encounter significant challenges in detecting and accurately locating fruit, as highlighted in [19].

The harvesting of fruits commonly presents challenges due to diverse unorganized obstacles, such as branches and foliage, frequently hindering the efficient operation of the harvesting system. Therefore, creating and implementing a successful harvesting system requires finding a careful equilibrium between speed and effectiveness. The harvesting end effector, responsible for detaching fruits from trees, plays a crucial role in any harvesting mechanism. Its adaptability to specific fruits is standard practice, allowing for the customization of end effectors based on the harvested fruit [20]. Nevertheless, the versatile design enables relatively minor adjustments to accommodate produce of similar dimensions or different fruit types, as discussed in the reference.

The design of the end effector requires adherence to specific criteria, outlined as follows: (1) operational characteristics, including adaptability to diverse shapes, prevention of damage to the harvested product, consistent and highly precise operations, and (2) technical features, encompassing swift activation, minimal maintenance requirements, lightweight construction, and low energy consumption, as detailed in reference [21]. Consequently, the ensuing sections of this discussion will thoroughly examine fruit detachment methodologies, emphasizing the necessity of an effective end effector. Following that, a comprehensive overview will be presented, conducting a detailed analysis of the main types of end effectors that meet the criteria for harvesting tomatoes.

Finally, a thorough discussion will follow, encompassing supplementary sensors and vision systems tailored for agricultural end effectors and considerations of operational conditions. Furthermore, fundamental principles regarding developing agricultural end effectors will be introduced.

4.1. Fruit detachment methods

Various methods are available for separating fruits from their attachment points, including techniques such as gripping and pulling, gripping and spinning, gripping and slicing, and several others. However, it is essential to note that the simplest and most commonly used method for fruit detachment involves the straightforward process of grasping and pulling, as emphasized in reference [10].

This method entails gripping and pulling, separating the fruit from the plant by detaching it, cutting the stem, and cleanly separating it from the crop. However, this pulling motion exerts a significant force on the fruit, potentially causing damage and unintended disturbance to the plant. The shaking induced by pulling may lead to a chain reaction, causing all the fruits on the tree to sway, and an undesirable outcome may be the accidental detachment of not only the fruit but also the stem from the plant itself. An alternative approach to mitigate the risk of fruit damage involves delicately grasping the fruit from the branch and executing a precise cutting action, as discussed in reference [22].

Stem cutting offers a viable alternative that minimizes the risk of damaging the harvested produce. However, it presents a more significant challenge. Identifying and cutting a small branch can be more difficult in real-world field settings due to dense foliage and obstructions than capturing the entire fruit. A potential solution to address this challenge while reducing the force exerted on the stem involves rotating the fruit before extracting it from the tree, as proposed in reference [23].

This rotation before pulling is a well-established method in manual harvesting, making it easier to break the branch at its junction with the fruit. Suction-based approaches for detachment are commonly employed as well. Although suction, as a standalone method, shares similarities with grasping, it is essential to recognize that the force applied through suction can potentially harm the fruit, leading to injury at the point of contact and the risk of piercing or damaging the fragile skin of the fruit. As a result, integrating a vacuum is often considered necessary as an additional element working in tandem with another detachment approach, usually in combination with gripping, as described in reference [12].

This review explores end-of-arm tools designed for automating fruit harvesting in agricultural settings. It has been observed that using a vacuum-based gripper can complement the grasping approach. In this study, 'grasping' refers to directly handling the fruit customizing the end tool to match the fruit's shape. An alternative technique involves gripping the fruit by its stem. Vacuum-based grasping, on the contrary, utilizes pressure force for seizing. Rotation entails applying rotational motion to the end tool to separate the peduncles. As depicted in Fig. 4, cutting involves dividing the stem using scissors, a blade, or another cutting device.

4.2. Different types of end tools for harvesting tomatoes

The end tools designed for tomato harvesting integrate various specialized elements, with the primary choices generally being a gripper or a specialized tool.

Fig. 4. The end-effector employed in agricultural robotics for fruit harvesting detaches fruits by gripping them from the stem and cutting [24].

As a crucial element of tomato harvesting systems, grippers establish temporary, direct contact with the tomatoes, enabling their retrieval either by holding onto the tomato's body or firmly clamping onto the stem. Vacuums, constructed precisely as advanced suction devices, are considered a subset of grippers. This classification of end effectors used in this study for tomato harvesting is thus divided into four distinct categories based on their respective methods of detachment:

1. Grippers with contact-grasping capability
2. Rotational mechanism
3. Scissor-based tool
4. Suction device

These four recognized categories of end-effectors employed in tomato harvesting and their visual representations are illustrated in Fig. 5 of this study. End tools from these specified categories can be combined. Hence, a terminal tool connected to a harvesting system can employ various methods for separating tomatoes, including grasping and rotating, holding and vacuuming, gripping and cutting, suction and cutting, and alternative techniques.
Contact-grasping grippers securely retrieve tomatoes but can be obstructed by branches, leaves, or neighboring tomatoes and may damage delicate fruits. Vision systems can struggle with dynamic environmental factors, complicating precise stem identification. Conversely, suction end effectors require only partial fruit exposure for effective gripping, as reference [12] noted.

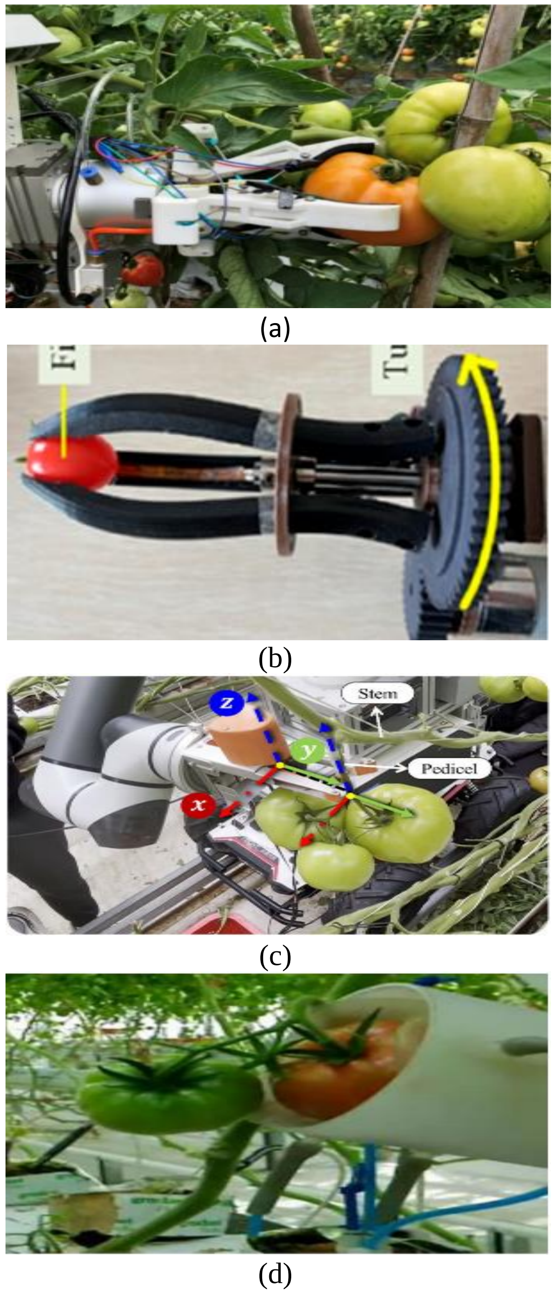

Fig. 5. Various options for end effectors in tomato harvesting include: (a) the end effector with grippers with contact-grasping capability [25], (b) the end effector with scissor-based tool [3], (c) the end effector with rotational mechanism [23], and (d) the end effector with suction device [12].

For grasping grippers, incorporating rotation mechanisms is effective for breaking peduncles and suitable for tomato harvesting, as outlined in reference [24]. However, relying solely on rotation can damage tomatoes, necessitating an additional tool for harvesting.

Scissor tools, preferred for this purpose, require precise stem detection to avoid damaging the tomatoes. In contrast, grasping, pulling, or rotating can be performed more efficiently, as emphasized in reference [10].

These delicate robotic components prevent collisions and minimize damage to tomatoes and hardware through gentle interactions. Recent research in soft robotics has developed promising grippers for robotic tomato harvesting, as shown in studies [26]. However, their intricate implementation poses challenges that need refinement before practical application, as noted in the same reference. Selecting the appropriate end effector depends on understanding the specific application requirements and environmental conditions [27].

4.3. The force of end effectors for tomato harvesting

Tomatoes are delicate fruits that require careful handling during harvesting to prevent damage and maintain their quality. The force applied by end effectors plays a crucial role in ensuring efficient harvesting without compromising the integrity of the produce [28]. Tomatoes have tender skin and are susceptible to bruising or crushing if excessive force is applied. Therefore, the force exerted by end effectors must be gentle enough to avoid damaging the fruit. The force required to detach tomatoes from the vine varies depending on factors like ripeness and variety.

End effectors should be capable of applying sufficient force to detach ripe tomatoes effectively while minimizing stress on the plant. While gentleness is essential, efficiency is also crucial in tomato harvesting. The force exerted by end effectors should be optimized to ensure timely and productive harvesting operations. End effectors should incorporate a soft gripping mechanism that provides a gentle yet secure hold on the tomato without causing damage. Smooth materials such as silicone or rubber can cushion the contact between the end effector and the fruit [29] (See Fig 6).

Implementing variable force control mechanisms allows operators to adjust the force exerted by the end effectors according to the specific requirements of the harvesting conditions. This flexibility ensures optimal performance across different tomato varieties and ripeness stages [30].

Integrating feedback sensors into the end effectors enables real-time monitoring of the force applied during harvesting. This feedback mechanism allows for precise control and adjustment, ensuring consistent performance and minimizing the risk of overexertion [31].

The force of end effectors for tomato harvesting must strike a delicate balance between gentleness and efficiency. By considering factors such as tomato delicacy, detachment force, and design considerations, end effectors can be optimized to achieve optimal harvesting performance while preserving the quality of the produce.

4.4. Sensors integrated into end effectors

Robotic end effectors aim to replicate the skill and precision of human hands, striving to achieve this by incorporating a sophisticated array of tactile and visual sensors meticulously integrated into their design.

This integration empowers them to sense and respond to touch and visual stimuli, as referenced [32]. When strategically positioned between an end effector and the harvested item, these sensors act as intermediaries and serve as invaluable sources of data and feedback.

They provide insights that can be utilized to enhance and optimize the effectiveness and adaptability of the terminal device, tailored to the distinctive features and needs of the harvested item, as explained in reference [33].

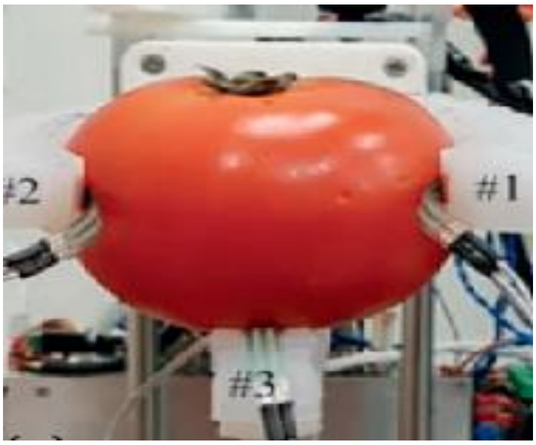

Fig. 6. A soft robotic three-fingered gripper [29].

The sensors associated with end-effectors in the intricate domain of grasping operations exhibit a comprehensive taxonomy, effectively categorized into four overarching types, as systematically outlined in reference [34].

All these categories are meticulously depicted in Fig. 7: (1) switching sensors, serving as binary indicators of contact; (2) tactile sensors, providing nuanced haptic feedback and assessing grasp quality; (3) visual sensors, enabling the end effector to perceive and respond to its surroundings; and (4) measuring sensors, facilitating precise quantification and measurement of forces and distances.

The gripper engaged and clamped the fruit when both pairs of photocells were blocked. At this stage, pressure and collision sensors utilized force-sensitive resistance. Once the gripper's pressure sensor detected a specific pressure level, the electric cutter activated to sever the pedicel. The cutter ceased operation when the switch position sensor was triggered. The collision sensor helped prevent obstacles during the harvesting process [35].

Twenty-four piezoresistive tactile sensors (RX-M0404S) were employed. These sensors were embedded within a layer of silicone skin as tactile arrays.

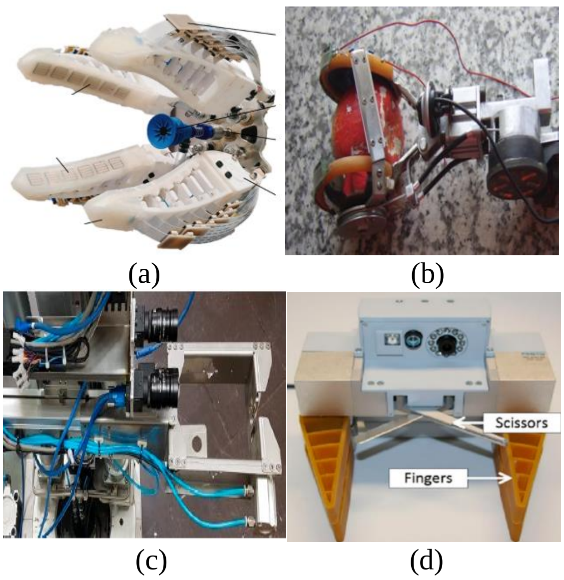

Fig. 7. End-effectors equipped with sensors include (a) the end effector with switching sensors [35], (b) the end effector with tactile sensors [36], (c) the end effector with visual sensors [37], and (d) the end effector with measuring sensors [38].

Each array measures 14 mm × 14 mm and comprises a 4 × 4 grid of taxel elements. When an external force ranging from 0.2 N to 20 N is applied, the resistance of the taxel units changes, and this variation is recorded by a data processing circuit [36].

The sensing module featured a sensor rig moved horizontally along a slide by a motor. This rig had two color cameras for stereovision and a ToF camera (SR4000, Mesa Imaging AG, Switzerland). The color cameras (Prossilica GC2450C; Allied Vision Technologies GmbH, Germany) had a resolution of 5 megapixels and were fitted with low-distortion lenses with a 5 mm focal length (LM5JC10M; Kowa GmbH, Germany) [37].

Three cameras were employed to capture image data in the greenhouse. The BFLY-U3-13S2C-CS camera model (FLIR, Portland, USA) was utilized. Cam1 and Cam2 functioned as a stereo-vision system to determine the distance to objects, while Cam3 was mounted on the end-effector to adjust its pose. An I5-4690 processor and 8GB of RAM were used to manage the vision servo system [38].

Tactile sensors [39] discern object characteristics through direct contact, assessing mechanical attributes like pressure, force, slip, vibration, humidity, and temperature. For harvesting devices, tactile sensors at gripper fingertips measure contact forces and torques, enabling the tracking of structural deformations during grasping, as explained in reference [40].

When an object is in contact, it provides a digital signature with data about the fruit's shape, dimensions, position, and orientation. Visual sensors are crucial in contactless robotic manipulation, identifying obstructions, structures, and gripping locations. Monocular and stereoscopic cameras, as noted in [41], offer visual feedback to the manipulation system.

Stereoscopic cameras provide 3D information, making them ideal for accurately identifying and localizing harvesting points. Measurement sensors determine distances, object dimensions, and tool settings, including velocity, acceleration, force, and torque. Distance measurement uses sensors like ultrasonic, microwave, and laser triangulation, as described in [42].

Sensors like Hall effect sensors, accelerometers, and force-torque sensors assess operational characteristics, as outlined in [43]. Integrating these sensors into hardware and software can yield significant outcomes. Since grasping is time-dependent, sensory data acquisition and integration must be dynamically synchronized [44]. Integrating multiple sensors enhances object manipulation by analyzing data between the end effector and the object, enabling real-time decision-making, as outlined in reference [45]. Sensors enhance an end tool's cognitive capabilities when combined with control strategies, managing functions such as grasping force, object movement, velocity, position, orientation, and contact points, as detailed in reference [46].

4.5. End effectors for harvesting tomatoes

Various configurations of end effectors have been devised and integrated into autonomous harvesting robotics systems. The physical properties of the harvested tomatoes significantly influence choosing a suitable terminal device.

In the subsequent sections, we will examine the end tools used in modern agricultural settings for tomato harvesting, covering the period from 2007 to 2023. The summarized results from the review are briefly outlined in Table 1.

Another work, discussed in reference [48], implemented cherry tomato harvesting practically. The end-of-arm tool included a dual-purpose cutter for severing the stem and a gripper attached to the blades for grasping and releasing the branch. The actuating cylinder could initiate the cutting device's pulling or pushing motion, starting its rotation.

Technical challenges related to the end effector were documented, including difficulties in securely gripping the stem influenced by interactions with the primary branch near the cluster of tomatoes and challenges in providing consistent support and grip after detachment.

In reference [51], an end effector designed for cherry tomatoes was introduced, featuring a gripper with a semi-spherical form capable of securely holding spherical items like tomatoes.

Table 1. The end tools utilized in a tomato harvesting robot are evaluated based on criteria that consider the time needed for the harvesting cycle and the precision of detachment.

End effector harvesting tomatoes		Detachment method				Evaluation	
Types	Year	Grasp	Rotate	Vacuum	Cut	Time (s)	Accuracy (%)
3 Finger gripper [23]	2023	Y	Y	X	X	4.86	95.8
Sleeve/cutter [47]	2023	X	X	X	Y	9.4	96.25
2 Finger gripper/cutter [48]	2018	Y	X	X	Y	8	83
2 Finger gripper/cutter [49]	2018	Y	X	X	Y	X	X
Gripper/suction [12]	2022	Y	X	Y	X	X	83.9
Suction/cutter [3]	2023	X	X	Y	Y	15.5	80.6
3 Finger gripper [25]	2022	Y	X	X	X	X	X
3 Finger gripper [50]	2023	Y	X	X	X	20	88
2 Finger gripper [26]	2020	Y	X	X	X	20.06	92.45
Semispherical/ cutter [51]	2022	X	X	X	Y	56	96

Blades were incorporated to trim the tomato stem at the rims of both cups.

The researchers enhanced harvesting efficiency by introducing a simplified mechanism for the passive cutting of the stem, eliminating the need for a separate stem recognition process.

In reference [52], an end-of-arm tool created explicitly for tomato harvesting was developed. The end-of-arm tool utilized a shear-type gripper to grip, cut, and separate tomatoes. This gripper consisted of several elements, including a telescopic cylinder, an air compressor, a magnetic switch, a relay, and a cutting tool. Due to the sensitivity of tomatoes and the risk of damage, particular emphasis was placed on improving the control system for greater accuracy in detecting and handling tomatoes. The end-effector system encountered challenges related to the presence of fruits, leaves, and stems. Nevertheless, the apparatus demonstrated sufficient adaptability to its surroundings and achieved impressive success rates.

In a study outlined in reference [53], Zhao and his team introduced a tomato harvesting system featuring dual-arm manipulators, each equipped with a unique end effector. One was designed as a cutting tool, while the other was a vacuum cup for collaborative harvesting tasks. Initially, the suction-based terminal device would move toward the center of the tomato to firmly grip it. Afterward, the cutting mechanism would detach the tomato from the stem.

Multiple cutting actions were applied to the branch until the suction end tool successfully grasped and retained the tomato. The collaboration between the two distinct end tools significantly enhanced the efficiency of the harvesting process.

Zhang *et al.* [23] engineered pliable end effectors resembling a human hand's capabilities for picking tomatoes. The structural dimensions of the gripper were established to match the required range for grasping.

The sensor system employed statistical principles for accurate sensor readings and data analysis, ensuring a secure grip and reliable slip detection. The control strategy and algorithm were formulated using a two-tier, two-level approach to ensure efficient and gentle fruit harvesting. In their research outlined in [50], Wang *et al.* devised a technique for managing the positioning of a flexible end tool in robots designed for tomato harvesting. Maintaining the loose-end tool's positioning utilizes a genetic algorithm to determine a viable pose. A quintic interpolation polynomial defines the path of the terminal device, reducing the chances of tomato damage caused by excessive approach speeds. Fig. 8 provides examples of representative end-effectors designed for tomato harvesting purposes and do not destroy the tomato.

The literature review suggests that the most effective method for tomato harvesting involves gripping and cutting. Due to their size, a two- or three-finger gripper is suitable, as shallow gripping and pulling are ineffective.

Separating the tomato stem, possibly through cutting or rotating, is crucial. While vacuum application is an option, tomatoes' thin skin can be pierced; thus, a pliable suction pad is recommended.

(a) (b)

Fig. 8. The end-effector is designed for harvesting tomatoes and does not destroy the tomatoes: (a) the end effector with flexible gripper [50] and (b) the end effector with dual cutting tool [51].

Obtaining 3D data on plant stems and fruit stalk posture for cherry tomato clusters is vital for developing obstruction-free end effectors. Improving gripper gripping status could enhance efficiency and prevent damage during storage and transit by avoiding tomato-sepal detachment.

5. Results and discussion

5.1. Results

The review paper analyzes the various end effectors developed for tomato harvesting using robotic technologies. Drawing from a wide range of scholarly sources, including Google Scholar, Scopus, IEEE Xplorer, and AnimoSearch, the study identifies and examines different methodologies employed in end-effector design. Grippers, rotational mechanisms, scissor-type tools, and suction devices are the leading end effectors discussed.

The investigation reveals that each end effector methodology has its merits and prevalence in the current research literature. Grippers offer versatility in grasping tomatoes of different shapes and sizes, while rotational mechanisms efficiently handle fruits in clustered environments. Scissor-type tools provide precision cutting, and suction devices enable gentle detachment of ripe tomatoes from the vine. Furthermore, the study explores the integration of sensors into end effectors, highlighting their role in enhancing capabilities such as fruit detection, ripeness assessment, and quality control.

It also emphasizes the importance of operational characteristics and technical features in end effector design, particularly regarding adaptability to diverse fruit shapes and sizes.

5.2. Discussion

Referring to the cited sources in the preceding sections, end effectors designed for tomato harvesting have been successfully developed, implemented, and field-tested. These end effectors fall into four categories: (1) grippers designed for grasping (both fruit and stems), (2) rotational mechanisms, (3) scissor-type tools, and (4) suction devices. Each mechanism is individually evaluated, and there is also a combination of various types.

Multi-finger grippers are the most frequently employed terminal devices designed explicitly for grasping tasks, also called grippers for physical contact. In most of the reviewed literature (70%), grippers were used independently or in conjunction with other mechanisms. Among these frequently utilized end effectors, scissor tools were the most prevalent (50%), followed by suction devices (20%). Lastly, rotational mechanisms (10%), as depicted in Fig. 9.

The literature analysis indicates that the most effective approach for fruit harvesting involves either gripping the fruit itself or its stem, which is detached from the plant through pulling or cutting. Maintaining a straightforward design for the terminal device yields more uncomplicated control strategies, resulting in improved performance and faster harvesting.

The methods for detachment include gripping, vacuum suction, rotation, and cutting, with various combinations of these techniques employed. In Fig. 10, a comprehensive overview of the different types mentioned in the referenced literature is presented, categorizing them into six groups: (1) combined grasp and cut, (2) grasp alone, (3) grasp followed by rotation, (4) cutting, (5) cutting with vacuum assistance, and (6) vacuum-grasping.

The predominant approach for detachment is grasping. However, the next step involves a combination of grasping and cutting.

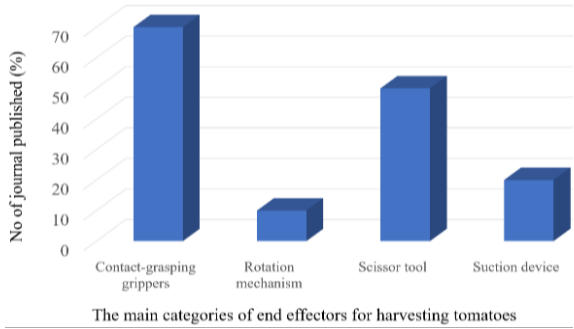

Fig. 9. The publication results describe four main categories of end effectors: grippers for contact-grasping, rotational mechanisms, scissor tools, and suction devices.

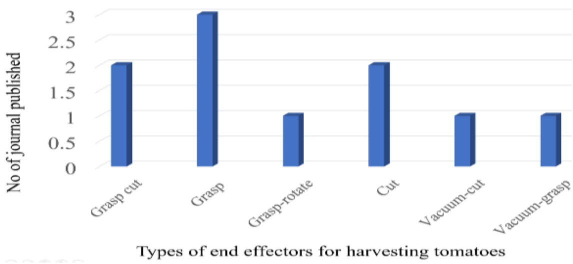

Fig. 10. The publication results describe the types of end effectors based on detachment techniques for harvesting tomatoes.

This combined method ensures secure and damage-free tomato harvesting, avoiding potential harm from excessive pulling. As illustrated in Table 1, comparing the grasp method and grasp-cut techniques, we will see that grasp-cut techniques consistently have shorter harvesting cycles than the grasp method. However, despite its advantages in minimizing direct contact with the fruit's outer surface and reducing the risk of damage, this method faces primary challenges related to the vision systems' difficulty in accurately identifying and locating gripping or points of cutting at the base of the stem. As previously stated, terminal tool systems incorporating rotation rely less on detecting stems, making them more robust against estimation errors. Nonetheless, opting for the more straightforward approach of grasping and pulling the fruit results in a faster and less complex harvesting system. Therefore, grasping emerges as the preferred detachment method for tomatoes.

6.1. Challenge of robot arms' end effectors for harvesting tomatoes

The intriguing challenge of creating end effectors for robotic arms in tomato harvesting is a captivating problem within agricultural robotics. This endeavor focuses on crafting automated systems that can adeptly and gently harvest mature tomatoes from plants, ensuring no damage to the fruit or the plant. Successfully addressing this challenge promises to transform the agricultural sector, decrease labor expenses, and heighten operational efficiency [54].

One of the foremost challenges in tomato harvesting robotics is the need for highly advanced sensing and computer vision systems. These technologies play a pivotal role in identifying ripe tomatoes amidst the foliage, distinguishing between colors, shapes, and sizes, and determining the ripeness of the fruit. Ensuring the robot can discern ripe from unripe tomatoes is crucial for efficient harvesting [55].

Tomatoes are known for their delicacy and susceptibility to damage. To address this issue, end effectors must be meticulously designed to pick them with enough force. The aim is to avoid any form of bruising or puncturing that could render the tomato unsuitable for the market [56].

Agricultural environments are highly variable; tomato plants come in various shapes and sizes. Additionally, tomatoes can be situated at different heights and orientations. Hence, the terminal device needs to adjust to tomato plants' diverse structures and positions [57].

Efficiency and speed are essential in tomato harvesting. A robot should be capable of picking tomatoes at a rate that makes the operation economically viable. This involves optimizing the robot's movements and decision-making processes [58]. Minimizing waste is another crucial aspect of tomato harvesting. The robot must be designed to avoid picking unripe or damaged tomatoes, reducing unnecessary waste and ensuring that only high-quality fruit is harvested [59].

The robot should be prepared to operate effectively in various environmental conditions, including rain or extreme heat. Additionally, safety is paramount, primarily if these robots work near human workers. Safety measures must be implemented to avoid accidents and ensure the well-being of all involved [60]. Data processing plays a central role in tomato harvesting robots. The system needs to process vast amounts of data from its sensors and make real-time decisions about which tomatoes to pick. Moreover, energy efficiency is critical to the robot's overall operation, allowing it to work for extended periods without frequent recharging [61].

In agriculture, cost-effectiveness is a crucial consideration. The cost of developing and maintaining these robots should be economically viable for farmers, ensuring that the adoption of this technology is financially feasible [62].

7. Future trends

The future of robot arms' end effectors for tomato harvesting will likely see substantial advancements in sensing technology and the integration of artificial intelligence. In the future, robots will feature enhanced sensors and AI algorithms to enhance their capacity for recognizing ripe tomatoes, evaluating fruit quality, and making instant decisions regarding harvesting. This advancement is poised to result in heightened precision and efficiency in the harvesting process [63].

Future end effectors will be designed to offer even gentler and more precise manipulation of tomatoes. Materials and mechanical design innovations will allow robots to handle tomatoes carefully, minimizing damage and bruising. This will be critical for maintaining the quality of harvested tomatoes and reducing waste [64]. As tomato plants come in various shapes and sizes, future end effectors must be adaptable. These end effectors will be designed to handle different plant architectures and adapt to varying positions and orientations of tomatoes. This adaptability will be crucial for widespread adoption in diverse agricultural settings [65].

Automation and autonomy will be key trends. Future tomato harvesting robots will become more self-sufficient and capable of operating autonomously in the field. They will integrate with other robotic systems, offering seamless collaboration and coordination in large-scale farming operations [66]. Improved data processing capabilities and machine learning will empower robots to make more informed decisions. They will acquire knowledge from their experiences, constantly refining their harvesting techniques. This development is anticipated to enhance harvesting efficiency and adaptability to dynamic conditions [67].

In the future, there will be a strong emphasis on energy efficiency and sustainability in robot arms' end effectors. These robots will be designed to operate on a single charge for extended periods, reducing the need for frequent recharging. Additionally, efforts will be made to make the entire tomato harvesting process more environmentally friendly [68]. As the technology matures, there will be a drive towards cost-effective solutions. Manufacturers will work to make these robots more affordable for farmers, thereby increasing their accessibility. This affordability will be critical in the widespread adoption of tomato harvesting robots [69].

Safety will remain a paramount concern, mainly as these robots work alongside human labor. Future trends will include the development of safety protocols, standards, and regulations specific to agricultural robotics to ensure the well-being of workers [70].

8. Conclusions

The review paper provides valuable insights into integrating robotic technologies for tomato harvesting. It focuses on the development and utilization of end effectors, the components of the robotic system that directly interact with the tomatoes. The paper thoroughly explores different approaches to designing and implementing these critical components by extensively examining various methodologies and technologies. As a result, several key conclusions can be drawn regarding the most effective strategies and innovations in this field:

(1) The study highlights the diversity of end effector methodologies, including grippers, rotational mechanisms, scissor-type tools, and suction devices. Each methodology offers unique advantages regarding fruit detachment, handling, and adaptability to different tomato varieties.

(2) The review identifies several challenges inherent in tomato harvesting, such as tomatoes' delicate nature, variability in fruit shapes and sizes, and efficient handling in clustered environments. These challenges underscore the importance of developing robust and versatile end effectors capable of addressing these complexities.

(3) Integrating sensors into end effectors emerges as a key trend, enabling enhanced capabilities such as fruit detection, ripeness assessment, and quality control. Sensor technology advancements promise to improve further the efficiency and accuracy of robotic tomato harvesting systems.

(4) The discussion on future trends in robotic tomato harvesting highlights the potential for advancements in sensing technology, artificial intelligence integration, adaptability, autonomy, and sustainability. Continued research and innovation in these areas are crucial for driving the evolution of robotic harvesting systems and realizing their full potential in agricultural applications.

(5) The synthesis of technological innovation and agricultural expertise holds promise for reshaping tomato harvesting practices. By leveraging robotic technologies and advancements in end-effector design, the farm industry can achieve more sustainable, efficient, and cost-effective farming practices, ultimately benefiting both farmers and consumers.

In conclusion, the review paper underscores the importance of ongoing research and collaboration between researchers, engineers, and farmers to overcome challenges and unlock the full potential of robotic tomato harvesting systems. By addressing these challenges and seizing emerging opportunities, the agricultural industry can usher in a new era of innovation and efficiency in tomato harvesting practices.

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References

[1] B. Marcel, E. V. Henten, J. Billingsley, J. Reid and D. Mingcong, "IEEE robotics and automation society technical committee on agricultural robotics and automation", *IEEE Rob. Autom. Mag.*, Vol. 20, No. 2, pp. 20-24, (2013).

[2] A. Zahedi, A. M. Shafei and M. Shamsi, "Application of hybrid robotic systems in crop harvesting: kinematic and dynamic analysis", *Comput. Electron. Agric.*, Vol. 209, pp. 1-19, (2023).

[3] P. Yonghyun, S. Jaehwi, P. Jeonghyeon, J. Yuseung, J. Jongpyo and H. I. Son, "A novel end-effector for a fruit and vegetable harvesting robot: mechanism and field experiment'', *Precis. Agric.*, Vol. 24, No. 3, pp. 948-970, (2023).

[4] M. B. Lee, C. Kennelly, R. Watson and C. N. Hewitt, "Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation", *Elem. Sci. Anth.*, Vol. 6, No. 1, pp. 1-14, (2018).

[5] B. Aurélie, S. Apurba, B. M. Mvumi, N. Patrick, D. Hawi, M. G. Ferruzzi, L. K. Nyanga, M. Sarah and K. I. Tomlins, "Estimation of nutritional postharvest losses along food value chains: A case study of three key food security commodities in sub-Saharan Africa", *Food Secur.*, Vol. 14, No. 3, pp. 571-590, (2022).

[6] B. C. Wouter, E. J. V. Henten, J. Hemming and Y. Edan, "Harvesting robots for high-value crops: State-of-the-art review and challenges ahead", *J. Field Rob.*, Vol. 31, No. 6, pp. 888-911, (2014).

[7] M. H. M. Saad, H. N. Maisarah and M. R. Sarker, "State of the art of urban smart vertical farming automation system: Advanced topologies, issues and recommendations", *Electron.*, Vol. 10, No. 12, pp. 1-40, (2021).

[8] C. A. Morar, I. A. Doroftei, I. Doroftei, and M. G. Hagan, "Robotic applications on agricultural industry. A review", *IOP Conf. Ser.: Mater. Sci. Eng.*, Vol. 997, No. 1, pp. 1-15, (2020).

[9] K. Abdul, H. Saddam, A. Muhammad, C. Muhammad, J. Masud, S. R. Saleem and F. Umar, "Development Challenges of Fruit-Harvesting Robotic Arms: A Critical Review", *Agric. Eng.*, Vol. 5, No. 4, pp. 2216-2237, (2023).

[10] V. Eleni, V. N. Tsakalidou, K. Ioannis, G. Theodoros, P. Theodore and V. G. Kaburlasos, "An overview of end effectors in agricultural robotic harvesting systems", *Agric.*, Vol. 12, No. 8, pp. 1-35, (2022).

[11] I. Takeshi, F. Ryo, S. Masanori, F. Seiji and N. Fusaomi, "Tomato recognition for harvesting robots considering overlapping leaves and stems", *J. Rob. Mechatron.*, Vol. 33, No, 6, pp. 1274-1283, (2021).

[12] L. Ziyue, Y. Xianju and W. Chuyan, "A review on structural development and recognition–localization methods for end-effector of fruit–vegetable picking robots", *Int. J. Adv. Rob. Syst.*, Vol. 19, No. 3, pp. 1-29, (2022).

[13] B. Shivaji, "Deliberation on design strategies of automatic harvesting systems: A survey", *Rob.*, Vol. 4, No. 2, pp. 194-222, (2015).

[14] Y. Ting, L. Lin, Z. Fan, F. Jun, G. Jin, Z. Junxiong, L. Wei, Z. Chunlong and Z. Wenqiang, "Robust cherry tomatoes detection algorithm in greenhouse scene based on SSD", *Agric.*, Vol. 10, No. 5, pp. 1-14, (2020).

[15] F. Takuya, Y. Shinsuke and I. Kazuo "Tomato Growth State Map for the Automation of Monitoring and Harvesting", *J. Rob. Mechatron.*, Vol. 32, No. 6, pp. 1279-1291, (2020).

[16] S. Jeahwi, L. Sechang, S and H. I. Son, "A Review of End-effector for Fruit and Vegetable Harvesting Robot", *J. Korean. Rob. Soc.*, Vol. 15, No. 2, pp. 91-99, (2020).

[17] X. Xu, H. Jingjing, L. Ming, X. Yongwei and Z. Hongduo, "Parameter analysis and experiment of citrus stalk cutting for robot picking", *Eng. Agric.*, Vol. 41, No. 5, pp. 551-558, (2021).

[18] G. Rafael, J. Dennis and K. B. Walsh, "Evaluation of End Effectors for Robotic

Harvesting of Mango Fruit", *Sustainability.*, Vol. 15, No. 8, pp. 1-18, (2023).

[19] Y. Takeshi, K. Takuya and F. Takanori, "Fruit recognition method for a harvesting robot with RGB-D cameras", *ROBOMECH J.*, Vol. 9, No. 1, pp. 1-10, (2022).

[20] R. Jiacheng, F. Jun, Z. Zhiqin, Y. Jinliang, T. Yuzhi, Y. Ting and W. Pengbo, "Development and Evaluation of a Watermelon-Harvesting Robot Prototype: Vision System and End-Effector", *Agron.*, Vol. 12, No. 11, pp. 1-17, (2022).

[21] F. Gualtiero, S. Marco, D. Gino, T. Kirsten, S. R. Bernd, F. Juergen, K. L. Terje, S. Guenther, R. Gunther, F. Joerg, N. H. Hans and V. Alexander, "Grasping devices and methods in automated production processes", *CIRP Ann.*, Vol. 63, No. 2, pp. 679-701, (2014).

[22] V. F. Tejada, M. F. Stoelen, K. Kusnierek, N. Heiberg and A. Korsaeth, "Proof-of-concept robot platform for exploring automated harvesting of sugar snap peas", *Precis. Agric.*, Vol. 18, No. 6, pp. 952-972, (2017).

[23] Z. Fu, C. Zijun, W. Yafei, B. Ruofei, C. Xingguang, F. Sanling, T. Mimi and Z. Yakun, "Research on flexible end-effectors with humanoid grasp function for small spherical fruit picking", *Agric.*, Vol. 13, No. 1, pp. 1-18, (2023).

[24] V. Eleni, T. Konstantinos, N. Alexandros, K. Theofanis, G.A. Papakostas, T. P Pachidis, M. Spyridon, K. Stefanos and V. G. Kaburlasos, "An autonomous grape-harvester robot: integrated system architecture", *Electron.*, Vol. 10, No. 9, pp. 1-22, (2021).

[25] X. Dongbo. C. Liang, L. Lichao, C. Liqing and W. Hai, "Actuators and sensors for application in agricultural robots: A review", *Mach.*, Vol. 10, No. 10, pp. 1-31, (2022).

[26] S. Yinggang, Z. Wei, L. Zhiwen, W. Yong, L. Li and C. Yongjie, "A "Global–Local" Visual Servo System for Picking Manipulators", *Sens.*, Vol. 20, No. 12, pp. 1-21, (2020).

[27] V. Eleni, V. N. Tsakalidou, K. Loannis, G. Theodoros, P. Theodore and V. G. Kaburlasos, "An overview of end effectors in agricultural robotic harvesting systems", *Agric.*, Vol. 12, No. 8, pp. 1-35, (2022).

[28] J. Wanteng, X. Huang, S. Wang and H. Xiongkui, "A Comprehensive Review of the Research of the "Eye–Brain–Hand" Harvesting System in Smart Agriculture", *Agron.*, Vol. 13, No. 9, pp. 1-49, (2023).

[29] Y. Weikang, L. Zhao, X. Luo, G. Junxian and L. Xiangjiang, "Perceptual soft end-effectors for future unmanned agriculture", *Sens.*, Vol. 23, No. 18, pp. 1-28, (2023).

[30] N. Eduardo, R. Fernández, D. Sepúlveda, M. Armada and G. D. S. Pablo, "Soft grippers for automatic crop harvesting: A review", *Sens.*, Vol. 21, No. 8, pp. 1-27, (2021).

[31] M. Longtao, C. Gongpei, L. Yadong, C. Yongjie, F. Longsheng and Y. Gejima, "Design and simulation of an integrated end-effector for picking kiwifruit by robot", *Inf. Process. Agric.*, Vol. 7, No. 1, pp. 58-71, (2020).

[32] C. Shoue, P. Yaokun, Y. Hongyan, T. Xiaobo and C. Changyong, "Smart soft actuators and grippers enabled by self-powered tribo-skins", *Adv. Mater. Technol.*, Vol. 5, No. 4, pp. 1-10, (2020).

[33] D. Zhen, J. Yannick, Z. Liwei and Z. Jianwei, "Grasping force control of multi-fingered robotic hands through tactile sensing for object stabilization", *Sens.*, Vol. 20, No. 4, pp. 1-21, (2020).

[34] Z. Baohua, X. Yuanxin, Z. Jun, W. Kai and Z. Zhen, "Actuators and sensors for application in agricultural robots: A review", *Mach.*, Vol. 10, No. 10, pp. 1-31, (2022).

[35] D. A. Zhao, L. Jidong, L. Wei, Y, Zhang and Y. Chen, "Design and control of an apple harvesting robot" *Biosyst. Eng.*, Vol. 110, No. 2, pp. 112-122, (2011).

[36] Z. Hongyu, K. Hanwen, W. Xing, A. Wesley, M. Y. Wang and C. Chao, "Branch interference sensing and handling by tactile enabled robotic apple

harvesting", *Agron.*, Vol. 13, No. 2, pp. 1-16, (2023).

[37] B. C. Wouter, H. Jochen, B.A.J Tuijl, B. Ruud, W. Ehud and E. J. Henten, "Performance evaluation of a harvesting robot for sweet pepper", *J. Field Rob.*, Vol. 34, No. 6, pp. 1123-1139, (2017).

[38] L. Bongki, K. DongHwan, M. ByeongRo, H. JiHo and O. SeBu, "A vision servo system for automated harvest of sweet pepper in Korean greenhouse environment", *Appl. Sci.*, Vol. 9, No. 12, pp. 1-23, (2019).

[39] P. S. Girão, P. M. P. Ramos, P. Octavian and M. D. P. José, "Tactile sensors for robotic applications", *Meas.*, Vol. 46, No. 3, pp. 1257-1271, (2013).

[40] L. Wang, B. Zhao, J. Fan, X. Hu, S. Wei, Y. Li, Q. Zhou and C. Wei, "Development of a tomato harvesting robot used in greenhouse", *Int. J. Agric. Biol. Eng.*, Vol. 10, No. 4, pp. 140-149, (2017).

[41] F. Gualtiero, S. Marco, D. Gino, T. Kirsten, S. R. Bernd, F. Juergen, K. L. Terje, S. Guenther, R. Gunther, F. Joerg, N. H. Hans and V. Alexander, "Grasping devices and methods in automated production processes", *CIRP Ann.*, Vol. 63, No. 2, pp. 679-701, (2021).

[42] L. Wang. R. Gao, J. Váncza, J. Krüger, X. V. Wang, S. Makris and G. Chryssolouris, "Symbiotic human-robot collaborative assembly", *CIRP Ann.*, Vol. 68, No. 2, pp. 701-726, (2019).

[43] A. M. Dollar and R. D. Howe, "A robust compliant grasper via shape deposition manufacturing", *IEEE/ASME Trans. Mechatron.*, Vol. 11, No. 2, pp. 154-161, (2006).

[44] Z. JunJie, Y. ZiYang and L. KaiFeng, "Multi-sensor information fusion detection system for fire robot through back propagation neural network", *PLoS One.*, Vol. 15, No. 7, pp. 1-13, (2020).

[45] L. Deng, Y. Shen, G. Fan, X. He, Z. Li and Y. Yuan, "Design of a soft gripper with improved microfluidic tactile sensors for classification of deformable objects", *IEEE Rob. Autom. Lett.*, Vol. 7, No. 2, pp. 5607-5614, (2022).

[46] A. S. M. Rodriguez, H. Mohssen and P. Jamie, "Hybrid control strategy for force and precise end effector positioning of a twisted string actuator", *IEEE/ASME Trans. Mechatron.*, Vol. 26, No. 5, pp. 2791-2802, (2020).

[47] Y. R. Li, W. Y. Lien, Z. H. Huang and C. T. Chen, "Hybrid Visual Servo Control of a Robotic Manipulator for Cherry Tomato Harvesting", *Actuators.*, Vol. 12, No. 6, pp. 1-17, (2023).

[48] F. Qingchun, Z. Wei, F. Pengfei, Z. Chunfeng and W. Xiu, "Design and test of robotic harvesting system for cherry tomato", *Int. J. Agric. Biol. Eng.*, Vol. 11, No. 1, pp. 96-100, (2018).

[49] Y. Takeshi, F. Takanori and H. Takaomi, "Fast detection of tomato peduncle using point cloud with a harvesting robot", *J. Rob. Mechatron.*, Vol. 30, No. 2, pp. 180-186, (2018).

[50] W. Dong, D. Yongxiang, L. Jie and G. Dongbing, "Adaptive end-effector pose control for tomato harvesting robots", *J. Field Rob.*, Vol. 40, No. 3, pp. 535-551, (2022).

[51] Y. Azamat, K. Koichi, Y. Yoshio, B. Zholdas, M. Zhassuzak and A. Yedilkhan, "Development of Continuum Robot Arm and Gripper for Harvesting Cherry Tomatoes", *Appl. Sci.*, Vol. 12, No. 14, pp. 1-22, (2022).

[52] L. Wang, B. Zhao, J. Fan, X. Hu, S. Wei, Y. Li, Q. Zhuo and C. Wei, "Development of a tomato harvesting robot used in greenhouse", *Int. J. Agric. Biol. Eng.*, Vol. 10, No. 4, pp. 140-149, (2017).

[53] Y. Zhao, L. Gong, C. Liu and Y. Huang, "Dual-arm robot design and testing for harvesting tomato in greenhouse", *IFAC-Pap. Online.*, Vol. 49, No. 16, pp. 161-165, (2016).

[54] O. Yurni, D. Tresna, R. Pola and N. Muhammad, "Tomato harvesting arm robot manipulator; a pilot project", *J. Phys. Conf. Ser.*, Vol. 1500, No. 1, pp. 1-10, (2020).

[55] Y. Takeshi, O. Yuki, K. Takuya and F. Takanori, "Automated harvesting by a dual-arm fruit harvesting robot",

ROBOMECH J., Vol. 9, No. 1, pp. 1-14, (2022).

[56] F. Spyros, M. Nikos, M. Loannis, R. Efthymios, H. Santos and P. E. Christoph, "Agricultural robotics for field operations", *Sens.*, Vol. 20, No. 9, pp. 1-27, (2020).

[57] C. F. L. Matheus, K. Anne, V. Constantino, B. Antonio, D. C. Jaime and R. G. JuanJesús, "Monitoring plant status and fertilization strategy through multispectral images", *Sens.*, Vol. 20, No. 2, pp. 1-21, (2020).

[58] K. Farzad, R. Giovanni, Y. Ilkay, S. Amir, N. Sajjad, F. A. Anka, E. Fahri, Z. Metin, L. Stefania and M. Anselme, "A smart and mechanized agricultural application: From cultivation to harvest", *Appl. Sci.*, Vol. 12, No. 12, pp. 1-22, (2022).

[59] Z. Linlu, H. Mingzheng, L. Jiuqin, L. Pingzeng, L. Tianhua and S. Fei, "Design and Experiment of Nondestructive Post-Harvest Device for Tomatoes." *Agric.*, Vol. 12, No. 8, pp. 1-19, (2022).

[60] Y. Ke, Z. Liyun, Z. Yanling, Y. Qian, L. Xiaohong and K. Sujatha, "Design of a workstation based on a human-interfacing robot for occupational health and safety", *Work 68.*, Vol. 68, No.3, pp. 863-870, (2021).

[61] Z. Hongyu, W. Xing, A. Wesley, K. Hanwen and C. Chao, "Intelligent robots for fruit harvesting: Recent developments and future challenges", *Precis. Agric.*, Vol. 23, No. 5, pp. 1856-1907, (2022).

[62] S. Robert and H. Mark "Robots in agriculture: prospects, impacts, ethics, and policy", *Precis. Agric.*, Vol. 22, No 3, pp. 818-833, (2021).

[63] Z. Hongyu, W. Xing, A. Wesley, K. Hanwen and C. Chao, "Intelligent robots for fruit harvesting: Recent developments and future challenges", Precis. Agric., Vol. 23, No. 5, pp. 1856-1907, (2022).

[64] Y. Weikang, Z. Lin, L. Xuan, G. Junxian and L. Xiangjiang, "Perceptual Soft End-Effectors for Future Unmanned Agriculture", *Sens.*, Vol. 23, No. 18, pp. 1-28, (2023).

[65] Z. Shuhe, H. Minglei, J. Xuexin, Z. Zebin, W. Xinhui and W. Wuxiong, "Study on Mechanical Properties of Tomatoes for the End-Effector Design of the Harvesting Robot", *Agric.*, Vol. 13, No. 12, pp. 1-18, (2023).

[66] K. Maria, L. Dimitrios, M. Chrysanthos, D. Christos and K. G. Arvanitis, "Bio-inspired robots and structures toward fostering the modernization of agriculture", *Biomimetics.*, Vol. 7, No. 2, pp. 1-31, (2022).

[67] J. Jing and T. Dacheng, "Empowering things with intelligence: a survey of the progress, challenges, and opportunities in artificial intelligence of things", *IEEE Internet Things J.*, Vol. 8, No. 10, pp. 7789-7817, (2021).

[68] D. Lexing, L. Tianyu, J. Ping, Q. Aolin, H. Yuchen, L. Yujie, Y. Mingqin and D. Xin, "Design and Testing of Bionic-Feature-Based 3D-Printed Flexible End-Effectors for Picking Horn Peppers", *Agron.*, Vol. 13, No. 9, pp. 1-20, (2023).

[69] Y. Weikang, Z. Lin, L. Xuan. G. Junxian and L. Xiangjiang, "Perceptual soft end-effectors for future unmanned agriculture", *Sens.*, Vol. 23, No. 18, pp. 1-28, (2023).

[70] B. Vasiliki, A. Zoe, V. Zisis and G. Antonios, "Sustainable crop protection via robotics and artificial intelligence solutions", *Mach.*, Vol. 11, No. 8, pp. 1-15, (2023).

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