

Article

Design and Field Evaluation of an End Effector for Robotic Strawberry Harvesting

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Abstract: As the world's population continues to rise while the agricultural workforce declines, farmers are increasingly challenged to meet the growing food demand. Strawberries grown in the U.S. are especially threatened by such stipulations, as the cost of labor for such a delicate crop remains the bulk of the total production costs. Autonomous systems within the agricultural sector have enormous potential to catalyze the labor and land expansions required to meet the demands of feeding an increasing population, as well as heavily reducing the amount of food waste experienced in open fields. Our team is working to enhance robotic solutions for strawberry production, aiming to improve field processes and better replicate the efficiency of human workers. We propose a modular configuration that includes a Delta X parallel robot and a pneumatically powered end effector designed for precise strawberry harvesting. Our primary focus is on optimizing the design of the end effector and validating its high-speed actuation capabilities. The prototype of the presented end effector achieved high success rates of 94.74% in simulated environments and 100% in strawberry fields at Farias Farms, even when tasked to harvest in the densely covered conditions of the late growing season. Using an off-the-shelf robotic configuration, the system's workspace has been validated as adequate for harvesting in a typical two-plant-per-row strawberry field, with the hardware itself being evaluated to harvest each strawberry in 2.8–3.8 s. This capability sets the stage for future enhancements, including the integration of the machine vision processes such that the system will identify and pick each strawberry within 5 s.



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Keywords: robotic strawberry harvesting; delta robot; pneumatic end effector design; 3D printing; workspace analysis; field evaluation

1. Introduction

As the world's population continues to rise, demand for food will increase in the future, which will put more pressure on farmers to cater to the food demand [1,2]. With growers continuing to encounter increased coercion to meet such stipulations, they will further find it necessary to expand both in terms of farmable land and manual labor, as current crops are known to have limited yield fertility. However, due to shifts in societal and occupational trends, finding manual laborers to meet such a demand for expansion will become increasingly difficult. In the United States, agriculture is one of the sectors most impacted by severe labor shortages. Over the years, the agricultural workforce in the country has declined rapidly. Increasing urbanization and changing demographics in the country are negatively impacting the employment rates in the agricultural sector. Youths are not attracted toward following agricultural practices and are migrating to cities for career

opportunities [2]. Although these factors are imposing an immoderate demand on the agricultural sector, robotic and autonomous solutions have become increasingly prominent in mitigating such economic stresses. Factors such as a shortage of agricultural workers, an aging farmer population, and rising wages have driven farmers and researchers to explore the development of automation systems in agriculture [3]. The adoption of agricultural robots can also contribute to the sustainability of farming practices. These robots are adaptable and can be used in both small-scale and large-scale farming operations, which allows farmers to expand their production capabilities to keep up with the demands of a larger population [4]. Such emerging technologies have the potential to not only heavily reduce the amount of food waste caused by a diminishing agricultural workforce but further allow for crops to expand and thrive amongst an increasing population.

This work focuses its attention on the multi-billion-dollar strawberry farming industry in the United States, as labor shortages and political policies toward migrant workers threaten its sustainability. In 2023, the United States harvested 27.5 million hundredweight strawberries, valued at approximately 3.40 billion USD, with California yielding roughly 90% of the country's output, measuring 24.6 million hundredweight [5]. In this context, the efficient management and execution of harvest operations have clear implications for farm profitability but also relate to issues of food waste, effective integrated pest management strategies, and the relative attractiveness of advances in robotic harvest technology [6]. Although harvesting robots were originally flagged as picking less efficiently than human workers, evidence throughout the literature suggests that these technologies are not as far behind harvest crews as previously believed. The utilization of automated systems to supplement time periods of peak production can help dramatically reduce food waste, especially in regions like California, where the harvest is in abundance compared to the available labor.

With the struggles of labor shortages in agriculture being prominent not only in the U.S. but all around the world, the search for robotic support in the harvesting sector has become much more imminent. Allowing for a more straightforward picking process, European and Asian countries have been planting strawberry crops to be grown on tabletops since the 1970s, which makes maintenance and harvest much easier and more efficient [7,8]. Without having to “crouch” below a bush for the collection of ripe berries, this development has further catalyzed the emergence of autonomous strawberry harvesting overseas [9–12]. Yamamoto et al. [11] and Hayashi et al. [12] presented the results of their stationary robotic strawberry picker that harvested from below tabletop-grown berries planted on movable benches. Reporting a success rate of 67.1% and a cycle time of 31.5 s per strawberry, the moving tabletops were found to cause unavoidable swinging of the fruit, which further increased the robot's harvesting time and intensified the damage imposed by the robot on the berries [11]. Developing two different robotic configurations, the harvester proposed in [13–15] expanded on a previous design that utilized a commercial 5 degrees of freedom (DOF) serial arm and prototyped gripper to “swallow” the berries into a trapdoor. The initial design achieved a success rate of 53.6–96.8%, depending on the growing conditions, and a harvest time of 10.6 s. The new design, however, adopted a much cheaper Cartesian-type arm with the same gripper swallowing the fruits directly into market punnets, to be more cost-affordable for farmers. The new configuration achieved a similar success rate of 50.0–97.1% on the first harvesting attempt and 75.0–100% on its second attempt, while showing a much faster harvest time of 6.1 s with a single arm attached and 4.6 s with two operating. Although research opportunities continue to progress in robotic tabletop cultivation, a commercially available product has yet to be established amongst the masses. In recent years, however, a few solutions have emerged that are edging themselves toward economic viability as they are under constant development. The

German company Organifarms produced a strawberry-picking robot known as “BERRY”, which was linked to the work presented in [16] by the comprehensive review discussed in [17]. Utilizing a very flexible 7 DOF serial arm and a 2.5 DOF gripping mechanism, the robot initially reached a success rate of 83% at an average harvest time of 28.2 s per berry [16]. Recent developments by the company, shown in [18], have resulted in faster harvesting speeds, with the autonomous configurations only requiring human interaction when all available punnets have been filled with strawberries. In the UK, Dogtooth Technologies has commissioned a fleet of strawberry-picking robots containing two 6 DOF serial arms operating in tandem with one another. The arms are completely custom-designed by the company and utilize a dual-inspection system, examining the quality of the fruit both before and after picking the stalk [19]. As of 2023, these robots can harvest at about 25% the speed of a human worker but are growing faster with each iteration, even being shipped to Australia for use in tabletop-grown fields [20]. Perhaps showing the most promising of harvesting speeds is the solution constructed by the Belgian company Octinion. Their autonomous robot known as “Rubion” employs a 3D-printed soft gripper to only harvest strawberries when damage to the fruit can be avoided, twisting and plucking the fruit from its peduncle. Initial testing showed the robot’s performance at a success rate of 70% but with a much faster harvest time compared to other robots, taking 4 s per strawberry [21].

Since most strawberries grown in the U.S. are cultivated on beds raised by less than a foot from the ground in open fields, a different form of these autonomous technologies must be explored to mitigate food waste and labor shortages. As opposed to tabletop cultivation, which is typically carried out inside of specialized greenhouses, strawberries in an open field grow with very little predictability. Berries sprouting from tabletops are strategically planted to hang from either side of their troughs in an organized manner, while those grown on raised beds extrude outward in all directions from the plant’s base. Outdoor environments additionally create inconsistent lighting conditions and fruit height, requiring more complex forms of machine vision processes for identification. The establishment of open-field configurations is not something that can be feasibly altered and requires increased effort for harvest; identifying an economically viable solution has been particularly challenging for researchers.. Recently developed by the multidisciplinary team in [22], an autonomous strawberry harvester utilizing a parallel robot equipped with a five-finger gripper was evaluated for use in an open-field strawberry patch. The system experienced a success rate of 71.7% and a picking speed of 7.5 s, with its performance being limited by variable lighting conditions and fruit height estimation as well as a lack of flexibility in the gripper design. Although there has been far less research development in autonomous open-field harvesting, quite a few advancements have been made in efforts to establish a solution with commercial viability. Advanced Farm Technologies has integrated large autonomous vehicles that employ four custom-designed gantry arms (two per row of strawberries) and soft grippers to harvest berries in Oxnard, CA, at a rate of 100 lbs/h while covered by large tarps to avoid large variations in lighting conditions [23]. The company known as Agrobot developed their E-Series, which contains configurations containing up to 24 independent robotic arms. They are capable of harvesting both tabletop-grown strawberries and those in an open field, currently offering pre-commercial trials in the United States [24]. Harvest CROO Robotics offers a bus-like machine mounted with LIDAR to autonomously navigate through strawberry fields while its fleet of 16 independently working grippers harvest the strawberries. The system is conditioned to work with a separate clamping device that temporarily moves the surrounding foliage from the view of the cameras, which can potentially cause damage to the plants [25]. A more feasible solution is that presented by Traptic, which employs only two off-the-shelf parallel robots with customized grippers made of food-safe silicone belts to harvest strawberries onto a

large conveyor belt. This solution is configured to be attached to commercial-type tractors to avoid the need for the manufacturing of customized vehicular navigation and is operated by a human driver [26].

The work presented throughout this paper aims to provide an automated strawberry harvesting solution for growers that is both efficient and affordable. As opposed to its counterparts, the system presented herein utilizes an off-the-shelf robot that is open-source and much more feasible for farming applications, being priced in the hundreds of dollars rather than the thousand-dollar configurations proposed by other researchers. This work primarily focuses on the hardware required for such a delicate task. Still under development for use in outdoor conditions, the fruit localization and path-finding routines for the system will not be discussed thoroughly in this paper. Rather, the work presented considers the design of a much more agile end effector for use in open-field strawberry environments than those previously developed, implementing powerful pneumatics for potential reductions in harvesting times.

2. Materials and Methods

2.1. Design of the End Effector and Optimizing Path-Finding Solution

In parallel with the development of camera calibration and path-finding solutions, it is crucial to ensure that we meet the design requirements established to optimize these procedures.

2.1.1. Hardware Design

The design of such a configuration in the agricultural sector must not only be robust in application, but also desirable to farmers both in terms of affordability and environmental impact. Despite several challenges in different agricultural operations, farmers are also concerned about the cost required to invest in agricultural robotics and automation. Some farmers are afraid to invest their money in technologies that may not benefit them in the future. One of the suggestions that may be used in designing agricultural robots is the use of modular robotic designs with great robustness [4]. Providing an adaptable design that is modularized and scalable allows for the developed system to meet the needs of farmers growing strawberries in variable open-field conditions. With differences in fruit bed dimensions and number of plants per row of strawberries being established at the discretion of each grower, it was essential for our solution to be easily adoptable across a wide range of fields. Keeping this in mind, the chosen robotic configuration and the end effector developed were of an interchangeable nature, to be conveniently detachable and/or built upon as required by each unique environment.

Such agricultural technologies, furthermore, must not cause damage to the environment, especially when harvesting fruit as delicate and prone to bruising as strawberries. Configurations that are excessively rigid or bulky have been shown to impose impurities upon not only the target fruit but also those surrounding it, leaving the berries unmarketable for sale. Aside from reasons related to profitability, leaving a damaged strawberry on its stalk has lasting effects on the plants' ability to produce healthy fruit [6].

2.1.2. Design Requirements of the End Effector

1. The end effector must not exceed the maximum 0.500 kg payload of the utilized Delta X robot.
2. The combined configuration must have a mass that is minimized and contains a reduced number of parts, to diminish positioning errors.
3. Pneumatics should be introduced to the system and responsible for the actuation of the harvesting mechanism without causing interference.

4. The picking configuration must be capable of simultaneously cutting, pinching, and holding the stems containing strawberries at nearly instantaneous speeds.
5. Harvesting procedures must be accomplished without causing damage to the strawberry plants, nor interfering with the surrounding foliage.
6. A servo motor should be employed as a fourth rotational axis on the moving base of the robot to maximize the number of possible harvesting locations.
7. The end effector must be offset such that the grabbing point for targeting strawberry stems is aligned with the center of the robot's moving platform.

2.2. Delta X Robot

The delta robot, also referred to as a parallel robot, has become an increasingly popular configuration amongst pick-and-place applications. Since its invention in 1985 by Robert Clavel, this variety of robots has made a significant impact within industrial settings due to their good precision, coupled with high speed and acceleration [27]. Containing a moving platform that has the potential to be equipped with a myriad of different attachments, the delta robot is known for being extremely versatile amongst automated applications. As a result, its impact on various industries with objectives ranging from food packaging to flight simulations is enormous [28].

Delta Robot Architecture

Delta robots can be arranged in a variety of topologies depending on implementation, containing up to six DOF. Typically, a parallel robot is designed such that all actuators remain fixed to the support structure of the robot, thereby minimizing the mass of the moving parts of the robot and enabling very fast accelerations. Indeed, this goal of achieving a high speed/fast acceleration has been the primary driving force in the development of parallel robots for industry, and, today, architectures such as the delta robot are widespread in many high-precision, high-throughput manufacturing applications [27]. The chosen Delta X, however, is composed of three rotation-based DOF, each of which is underactuated by servo stepper motors attached at 120 degrees from one another. This type of configuration is known to be better suited for high-speed and high-stiffness manipulation [28]. With the objective to eventually harvest at efficiencies equivalent to the output of a human picker, the Delta X is equipped for such aspirations at a low cost to the average farmer.

Equally spaced from one another, the actuators employed by Delta X operate with identical closed-loop kinematics. Each stepper servo motor, attached to a gearbox, rotates its respective arm, which, in turn, rotates the corresponding forearm via universal ball joints. The forearms are composed of lightweight rods moving in parallel with one another, each connected to a single platform by additional universal ball joints. Each arm of Delta X can operate independently from the others but is constrained to a single moving platform that translates the rotational inputs into Cartesian-type movements. Even while in motion, the moving stage characteristically always remains parallel to the stationary base. See Figure 1 for the complete architecture.

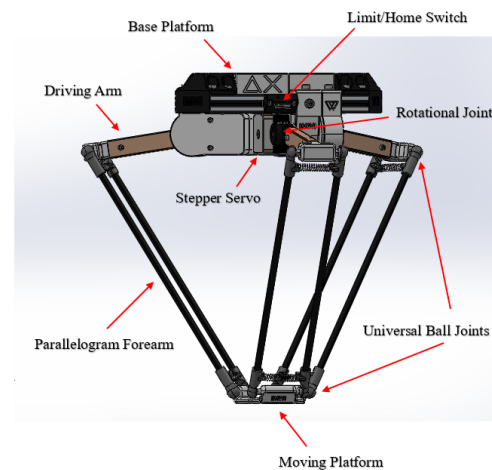


Figure 1. Robot architecture of Delta X1 used for strawberry harvesting.

2.3. End Effector Design

Upon following the design requirements of the end effector previously described, the first two demands presented were met with the use of fused deposition modeling (FDM). Primarily modeled in the computer-aided design (CAD) software known as SolidWorks (Version: 2021 SP04.1), aside from the utilized motor and blade cutter, the end effector was entirely fabricated via 3D printing. Known to keep costs and poundage low in manufacturing, the use of polylactic acid (PLA) filament additionally provides a more environmentally friendly and convenient solution for growers. In recent decades, demand for sustainable materials in place of low-cost and high-strength materials has been triggered globally, which has directed researchers toward biocomposites/green composites. PLA has been the most promising matrix material for sustainable biocomposites owing to its biodegradability, good availability, eco-friendliness, antibacterial property, and good mechanical and thermal properties [29]. Allowing for an increasingly modular and environmentally safe design to be constructed adds significant appeal for farmers to adopt such technologies, all while preserving the payload of the configuration at 0.271 kg. Maintaining a collective mass that is adequately below the suggested maximum of 0.500 kg, the use of 3D printing further permitted the assembly of the custom parts designed into a single, rigid structure. As damping effects are naturally considered with an increased number of bolted connections, the fabrication of a singular modeled part allowed for a large reduction in the quantity of positional inconsistencies experienced by the robot. Diminishing the use of connecting hardware applied to the end effector additionally minimized the mass of the configuration, thus decreasing any wobble imposed by the structure even further. The optimal 3D-printed assembly is depicted in Figure 2.

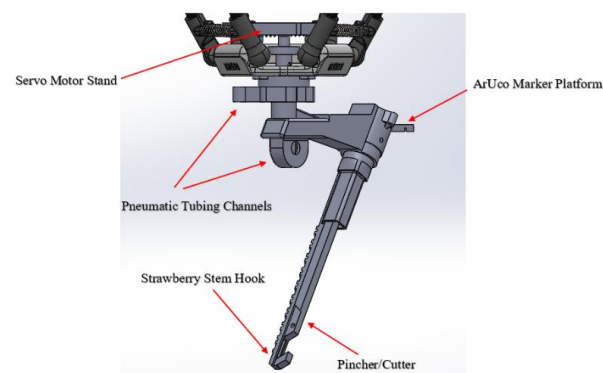


Figure 2. Optimized 3D-printed end effector design for strawberry harvesting.

As shown in Figure 3, the end effector was fabricated to be easily attached to the Tailonz MAL16-25 pneumatic cylinder (Tailonz Pneumatic, Wenzhou, China) with 16 mm bore and 25 mm stroke. The actuator was a double-acting piston, utilizing one of the inlet ports to push the cutting mechanism closed and the other to pull it open for releasing the strawberries into the appropriate location. All 3D-printed parts were modularized to be conveniently detached and replaced as necessary by the user. Utilizing an industrial compressor to maintain the pneumatic configuration at a default of 206.8 kPa (30 psi), the end effector can operate with an immediate response to a change in airflow. Further shown in Figure 3, the use of a single mini utility blade, placed above a 4.75 mm contact point, upon pushing the mechanism closed is responsible for the simultaneous cutting and pinching action. The lightweight blade splits the strawberry stems with ease, while the implemented pneumatic robustly pinches and holds the fruit by the remaining stem length via activation of the Tailonz 4R210-08 air valve (Tailonz Pneumatic, Wenzhou, China).

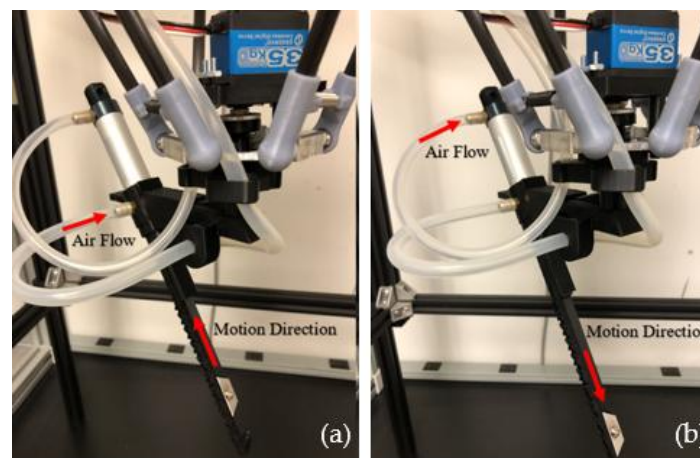


Figure 3. Actuation method of the end effector for the simultaneous cutting, pinching, and holding of strawberry stems: (a) retraction and (b) extension.

Limited by the utilized pneumatic cylinder in the assembly, the 3D-printed cutter was optimized to securely fit the actuation shaft without compromising the structural integrity of the PLA-based hook. The minimization of the hook diameter allowed for an increase in the quantity of strawberries that could be targeted by the end effector without disturbing any surrounding plant foliage. Adhering to such compact tolerances preserved the general workflow, wherein the implemented path-finding routine avoided all collisions within the generated point cloud scene. The outline for such procedures can be seen in Figure 4.

Due to the parallel nature of the robotic configuration selected for the harvesting processes, it was necessary to incorporate a fourth axis for changing the end effector's orientation relative to a target stem. With the designed assembly being optimized to extrude at a constant angle of 60 degrees from the moving platform, a closed-loop control servo motor was applied to adjust the hook's angle of attack. Reference Figure 5 for the dual-bearing configuration.

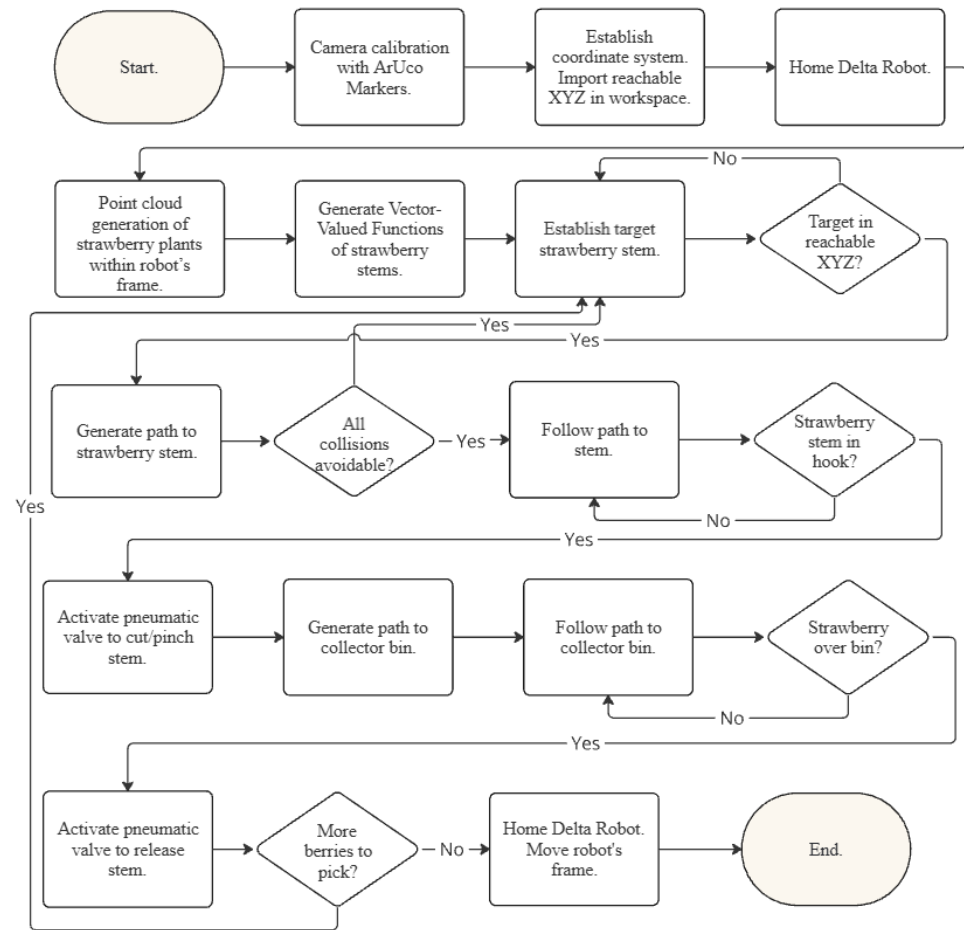


Figure 4. General outline for robotic harvesting procedures.



Figure 5. Servo motor-driven fourth axis for the end effector.

2.4. Workspace Analysis

Upon utilization of an off-the-shelf parallel robot mechanism, it was crucial to ensure that the system's workspace could sufficiently cover the dimensions of a typical two-plant-per-row strawberry field. The robot workspace represents the set of all spatial positions that can be reached by the end effector without collision and singularity. It is an important index to measure the performance of a robot [6]. With field testing operations being targeted for validation in this type of field configuration, the analysis of a single Delta X1 robot was evaluated and found to be more than adequate for use. It was vital to perform this assessment to ensure that all reachable points being fed into the path-planning routines were accurate, as to maximize the system's harvest efficiency and production output. The analysis of a robot's workspace is of great significance to the design of the mechanical body, trajectory planning, and the control system [6].

Utilizing MATLAB (Version R2023a) to visualize the workspace of Delta X1, a plugging method similar to the approach presented in [6] was adopted to pass a series of desired joint angle positions into the robot's forward kinematic equations. The kinematic scheme of the delta robot used for this analysis is depicted in Figure 6 [30]. Since the goal was to examine all possible XYZ coordinates of the robot based upon constraints placed on the actuated arms, the inverse kinematic solution was not needed and will not be discussed in this section.

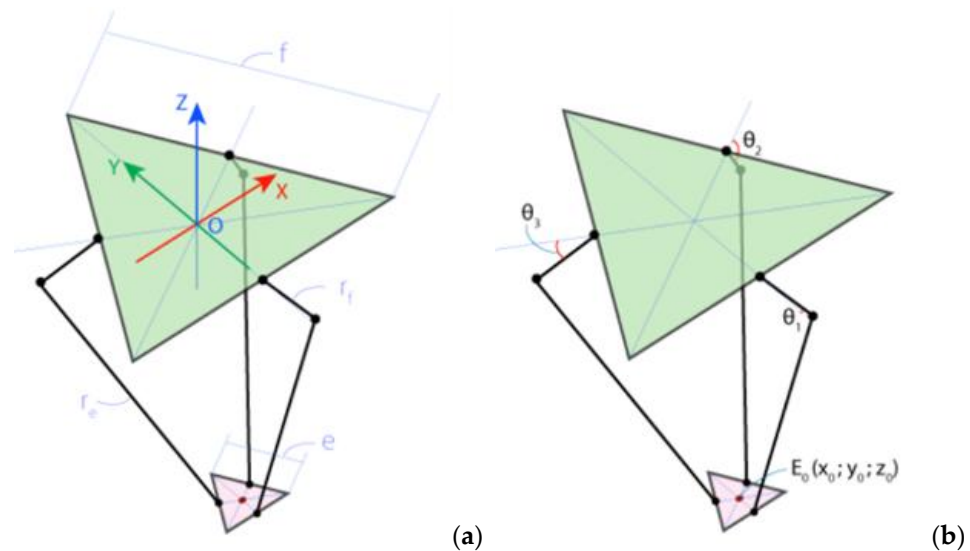


Figure 6. The kinematic scheme of a delta robot used for analysis: (a) the coordinates (X, Y, and Z) and the dimensions; and (b) the joint angles (θ_1 , θ_2 , and θ_3) and the end effector position E_0 with coordinates x_0 , y_0 , and z_0 [30].

Following the geometric approach described in [30] to examine the forward kinematics of a delta robot, all measurements and equations used in the analysis were confirmed to have been incorporated in the robot's open-source firmware by Delta X. This method is adopted by Delta X, as it is documented and approved in numerous source, and is based on the proceedings developed by Prof. Paul Zsombor-Murray in his analysis of the original Clavel's delta robot [31]. As shown in Figure 6, the delta robot can be generalized with the two platforms as parallel equilateral triangles, wherein the dimension f (259.04 mm) represents the side length of the stationary platform and e (120 mm) is the side length of the moving platform. The respective lengths of the arms are labeled r_f (130 mm) and the forearms are identified as r_e (315 mm).

Although the forearms of Delta X1 consist of parallel rods that rotate freely around universal ball joints, they can be geometrically modeled as a single link between the driving arms and the end effector due to their nature of maintaining identical angles with their connecting joints. The primary goal of the forward kinematic solution is to translate the desired angular inputs (θ_1 , θ_2 , and θ_3) of the robot's arms into a set of Cartesian coordinates (x_0 , y_0 , and z_0) for the moving platform at E_0 by examining the behavioral constraints of the system.

2.4.1. Simulated Workspace Analysis

Upon inserting the robot's geometry and developed equations into a MATLAB function, the workspace of the system could then be visualized with only a few lines of code. Plotting the robot workspace is an essential part of realizing a robot model. The workspace represents all the possible points in space that a robot's end effector can reach; however, it is crucial to attain the conditions of singularity to define the limits of the workspace [32].

As discussed thoroughly in [28] through an analysis of kinematic Jacobians, the two main singularities to consider occur at the boundaries of the workspace, wherein the robot is either retracted to its home position or its driving arms are completely extended. When in the home position, delta robot configurations are limited to motion in the negative Z direction and could impose damage unto the arms if moved in the XY directions. Additionally, should any of the arms become fully stretched out at the elbow, a singularity would occur such that further motion of the end effector would cause the link to become locked at the elbow or, even worse, inversion of the joint.

Similarly to [33], the range of joint angles presented in Table 1 is used in the forward kinematic function, which is executed through a MATLAB script during the simulation.

Table 1. Angular range of inputs used for simulated workspace visualization via forward kinematics.

Rotation Angle of Stepper Servo θ_i	Angular Range (Degrees)
θ_1	−40–80
θ_2	−40–80
θ_3	−40–80

2.4.2. Manual Workspace Analysis

Utilizing the open-source Delta X software (Version 0.9.5) to manually analyze the workspace of Delta X1, G-Code inputs could efficiently be uploaded to the robot for the establishment of acceptable harvesting locations in comparison to the simulated results. By splitting the robot's allowable Z positions into variable heights across the volumetric region, acceptable XY locations were identified relative to the performance of the links and their proximity to the limit/home switches. A workspace area was verified at each Z height on the condition that the inputs did not cause singularity, wherein only a maximum of two limit switches could be met at a time without exceeding their end position during motion. As the moving platform began to attain lower positions, the boundaries of the workspace were determined by the maximum reach of the arms without locking or inversion of the elbow. The robot's software was utilized to first establish an XY square perimeter every 5 mm in Z height, as this allowed for the evaluation of the limits for two of the arm links. A diamond-type perimeter was then examined at the same Z heights to examine the limitations of the final link, due to the triangular nature of the design.

2.4.3. Workspace Results

As shown by the collection of green discrete points in Figure 7, the theoretical working space of the delta robot is ellipsoidal, and, when it is near the $z = 0$ plane, there is an unreachable interval (void). The size of this area is determined by the length of the active arm, the length of the driven arm, and the size of the dynamic and static platform [33].

Regarding the manual workspace analysis, accepting the smaller radius of the eight collected datapoints as the workspace boundary for each Z height to further reduce chances of singularity being achieved, a characteristically cylindrical shape could be identified as the working region of Delta X1. The collection of G-Code inputs combined with MATLAB programming further allowed the acquisition of a more accurate visualization of the robot's workspace, also shown in Figure 7.

In comparison to the simulated (green) workspace of Delta X1, the actual (blue) working volume of the robot was proven to have a smaller radius than expected, as seen in Figure 7. However, due to its cylindrical shape, the actual workspace remained amply consistent as the lower regions of the allowable Z heights were reached rather than converging inward, which is appreciably preferable for harvesting applications. The difference in radius depicted in the XY plane between the volumes and contrasting Z

height limits were predominantly due to constraints set forth in the robot's firmware, being restricted to operate within a radius of 170 mm and a maximum reach of -401.81 mm in the Z direction.

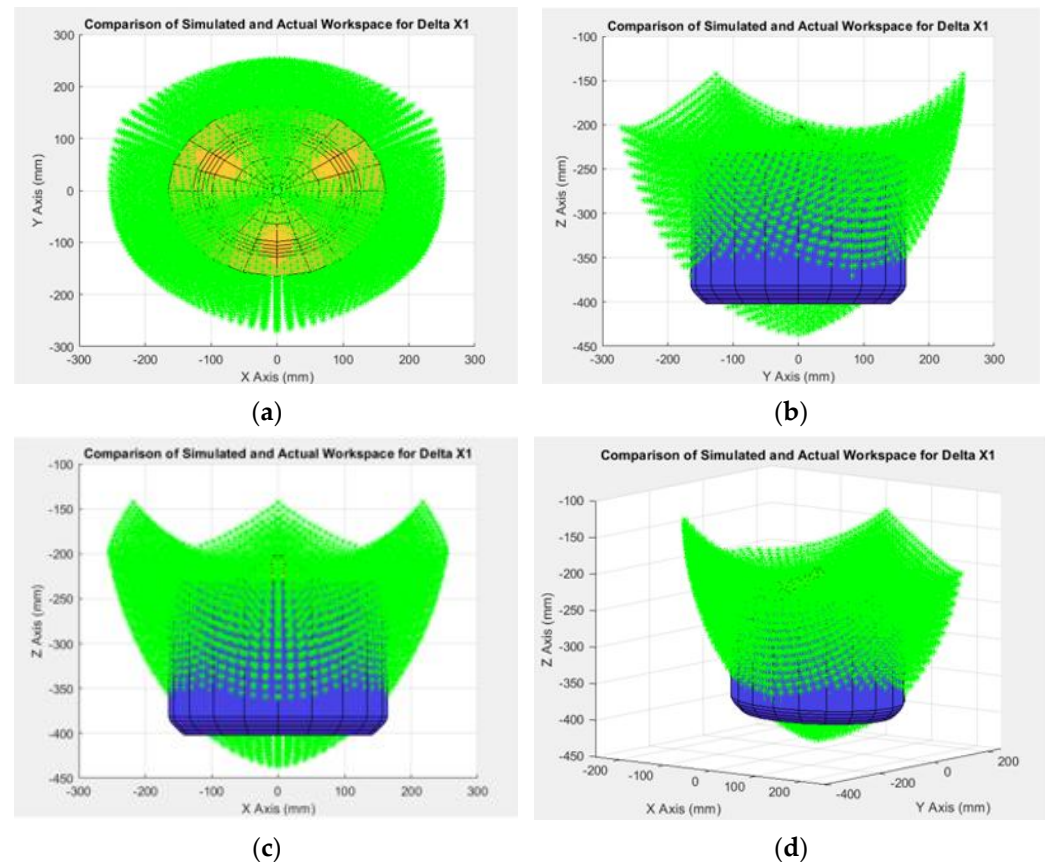


Figure 7. Comparison of simulated (green) and actual (blue) workspace for Delta X1 in MATLAB: (a) XY planar view; (b) YZ planar view; (c) XZ planar view; and (d) 3D view.

2.4.4. Workspace Validation

Although proven to be smaller than calculated by the kinematics, the volume determined through manual characterization of the robot's workspace was found to be more than sufficient for the intended harvesting applications. Utilizing the resulting Cartesian coordinates plotted in MATLAB as volumetric dimensions to be modeled in SolidWorks, an identically cylindrical shape could be generated efficiently for use within Blender. As shown by Figure 8, the bulk of the workspace simultaneously covers the height of width of a typical two-bush-per-row strawberry plant structure effectively, without requiring the use of the diminishing upper region.

Since the end effector was designed such that its grabbing point would be aligned with the center of the robot's moving platform, all stems identified within the radius of the workspace were considered acceptable harvesting locations. Shown by Figure 8, as the robot's frame is moved along the rows for harvest, all strawberry stems extruding from a typical two-plant-per-row setup lie within the workspace at a particular point in time. This was evaluated to be more than sufficient in meeting the requirements of this project's scope, as the two-plant-per-row configuration is the most commonly used among growers. To accommodate strawberry beds raised at variable heights and account for the negative Z offset caused by the end effector design, the robot's frame was fitted with additional 20/20 extrusions such that its height could be made changeable via sliding nuts.



Figure 8. Simulated validation of the manually determined Delta X1 workspace compared to a typical two-plant-per-row strawberry field: (a) XZ planar view; (b) XY planar view; and (c) 3D view.

Validation of the workspace was completed by utilizing the point cloud scenes generated in Abberit's Hawaii location and further confirmed by the dimensions of strawberry rows at Farias Farms. However, as each individual grower is permitted to cultivate this fruit in whichever row shape and size they deem fit, it is important to consider the modular nature of Delta X1. If the row width exceeds the workspace, as when harvesting fields with four plants per row, it is suggested that an additional Delta X1 unit be incorporated to work in tandem with the other, similar to the system presented by Traptic [26].

2.5. Harvesting Time Analysis

2.5.1. Simulink Simulated Analysis

Prior to implementing path-planning solutions in the robot's firmware for use in two-plant-per-row strawberry fields, a simulated model of the harvesting procedures needed to be adopted for the evaluation of the hardware's capabilities. With the expectation of harvesting each strawberry in 5 s, it was essential for the off-the-shelf robotic configuration to meet such stipulations itself. Open-source simulations from MathWorks operate under the same fundamentals as the solution proposed in this paper, wherein a delta robot performs a pick-and-place task based on camera feedback. Generating a path via forward and inverse kinematics such that the end effector reaches its target relative to the camera and robot frame, a more in-depth description of the simulation's function blocks can be found in [34].

Although the above simulation shared a similar framework with the developed strawberry harvesting application, it lacked the ability to imitate the performance of our custom end effector design and, thus, required a few assumptions to be made in Simulink's analysis.

1. The implemented fourth axis was expected to rotate in the time duration elapsed for the XYZ motion of the moving platform to its target. Its rotation would not contribute to the total harvesting time.
2. Being pneumatically operated, the gripper's actuation method did not contribute to the total harvesting time as its motion was instantaneous.
3. The moving platform could not exceed a feed rate of 0.7 m/s as per specifications of Delta X1.

2.5.2. Hardware Validation Analysis

Upon simulating harvesting procedures with the actual Delta X hardware and end effector, the worst-case scenario was repeated to again evaluate the expected maximum harvest time. However, with all components of the end effector being present, the assumptions placed upon the Simulink model were not required for the hardware analysis. Tasked to harvest artificial strawberries attached to the stems of an actual strawberry plant, the fourth axis rotation and pneumatic actuation of the end effector gripper were implemented accordingly, such that the robot would maneuver to the target strawberry hanging at a pre-described orientation.

3. Results

3.1. Validation of the End Effector

3.1.1. Simulated Validation

With most of the end effector's development being completed before Washington's growing season, it was crucial for the proposed design to be optimized to interact within a strawberry field environment before attempting field trials. Having limited access to strawberry plants in regions local to our team, point cloud-generated scenes were constructed in fields from Abberit's Hawaii location for utilization. Upon manually navigating a 3D model of the hook through the presented scenes, as shown in Figure 9, the original configuration was found to perform with a success rate of 63.16%. The end effector was required to effectively hook each respective stem for harvest, avoiding collisions with both the surrounding foliage and other berries.

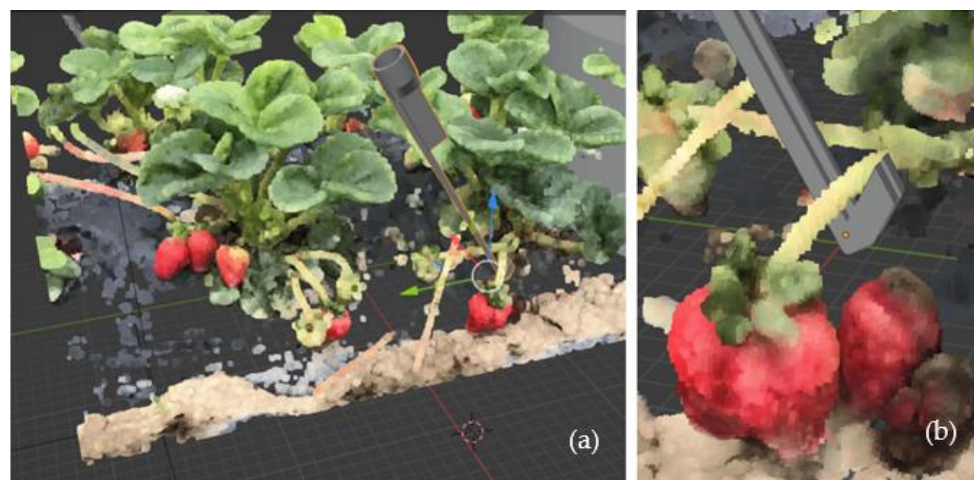


Figure 9. (a) Simulated validation of end effector hook in Blender, with the original configuration, and (b) magnified view of the stem and the end effector hook.

However, the rotation of the cutting mechanism by 90 degrees around the pneumatic cylinder allowed for the stems to be targeted at a much higher multitude of angular arrangements. Instead of being limited to an approach which aligned the hook to be ± 5 degrees parallel to the stem, the rotated hook could harvest at any angle between 0° and 135° from the plane perpendicular to the stem extrusion. As shown in Figure 10, the modified configuration was no longer bound to target strawberry stems from above, on either side of the extruded stem, but could hook stems from outside of the foliage, reaching inward from underneath the plant's canopy. The rotation of the cutting mechanism further allowed for the establishment of only a singular pinching point, eliminating the need for the robot to "pluck" a berry from its respective stem, as a clean cut could be made above

the fruit at each harvest. Following the same criterion as the original design, the altered end effector performed with an increased success rate of 94.74%.

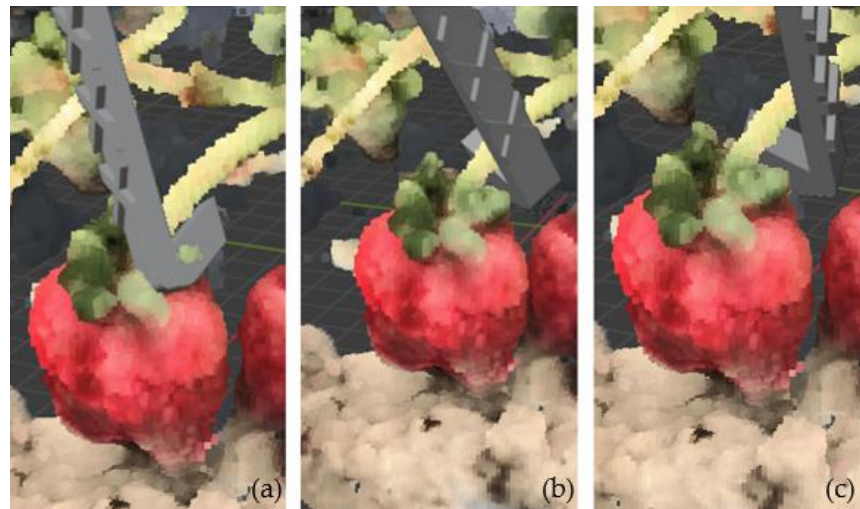


Figure 10. Simulated validation of end effector in Blender with the optimized configuration: (a) hook perpendicular to stem extrusion at 0 degrees; (b) hook parallel to stem extrusion at +90 degrees; and (c) hook positioned parallel to the stem at +45 degree angle.

Due to the discrete set of datapoints used to construct the given environments having a limited resolution in the visualization toolbox, only strawberries with distinguishable stems were considered for validation. As other berries were considered reachable by the hook, they contained stems that were far too distorted to be harvested, since the end effector targeted the stems themselves rather than the fruits. Furthermore, on account of the point cloud environments having a reduced number of strawberries within each generated scene, fruits that were premature for picking were additionally used for the hook's evaluation.

3.1.2. Field Test Validation

Upon commencement of the field evaluation of the robot, it was evident that the end effector and path-finding subsystems needed to be initially validated separately. Similar to the evaluation conducted in the simulated environment, our team was responsible for manually navigating the cutting mechanism through the strawberry fields at Farias Farms for harvest. Berries were required to be chosen at random throughout the field to avoid bias. Following the same criterion of picking the fruit without colliding with surrounding foliage and other strawberries, the end effector operated flawlessly, with a success rate of 100%. Reference Figure 11 for field testing implementation.



Figure 11. Field testing validation of the end effector in its optimal configuration.

With both the simulation and field testing being conducted using similar configurations in terms of approach and criterion, a summary of their results is compiled into a single arrangement in Table 2.

Table 2. Results for end effector validation via manual manipulation in strawberry field environments.

	Configuration	No. Harvested	Total Berries	Success Rate
Simulated	Rotated 0°	12	19	63.16%
Simulated	Rotated 90°	18	19	94.74%
Field	Rotated 90°	32	32	100%

The field test assessments within Farias Farms were carried out in the month of July, known to be the conclusion of strawberry season in Washington State. As strawberry plants mature throughout the growing season, their leaf canopies become increasingly dense in foliage. Aside from the leaves which are borne along the plant's crown in its early stages, strawberries have compound leaves in which the blade (flattened part of the leaf) is divided into three separate leaflets, called a "trifoliate". The strawberry leaf captures light, the source of energy used by plants for food manufacture in photosynthesis. Thus, the number of leaves and total plant leaf area can be correlated with fruit production directly [35].

This means that the end effector's validation was accomplished under the growing season's most burdensome conditions in terms of foliage. A larger plant size and a heavy leaf canopy can hinder picking, as it becomes increasingly difficult to navigate strawberries with large "bushes" [35]. Although the configured design was capable of harvesting while avoiding collisions with an excess of surrounding foliage, the chosen timeframe for field testing resulted in a lower number of berries being available for harvest. This factor of interference could possibly introduce additional challenges to successful picking. However, the proposed design allows for multiple berries to be picked at once due to the implementation of pneumatics for actuation of the pincher/cutter, providing a high pinching force. Further validation would be required to evaluate the feasibility of picking clusters of the fruit.

3.2. Harvesting Time Results

3.2.1. Simulated Results

Having modified the simulated motion such that it mimicked the expected movement of Delta X1 during harvest, a worst-case scenario was incorporated to identify the maximum harvesting time that could be experienced by the hardware. Such conditions included the delta robot starting at its home position and having to lower the moving platform before approaching its target, wherein the system would be prompted to harvest a "strawberry" at the maximum radius and reach of the workspace. The robot would then be instructed to maneuver the target to the other maximum end of the workspace to release the berry, once again at its maximal reach. As seen in Figure 12, the simulated result gave a baseline harvesting time of 3.9 s, wherein the moving platform did not exceed the maximum 0.7 m/s feed rate.

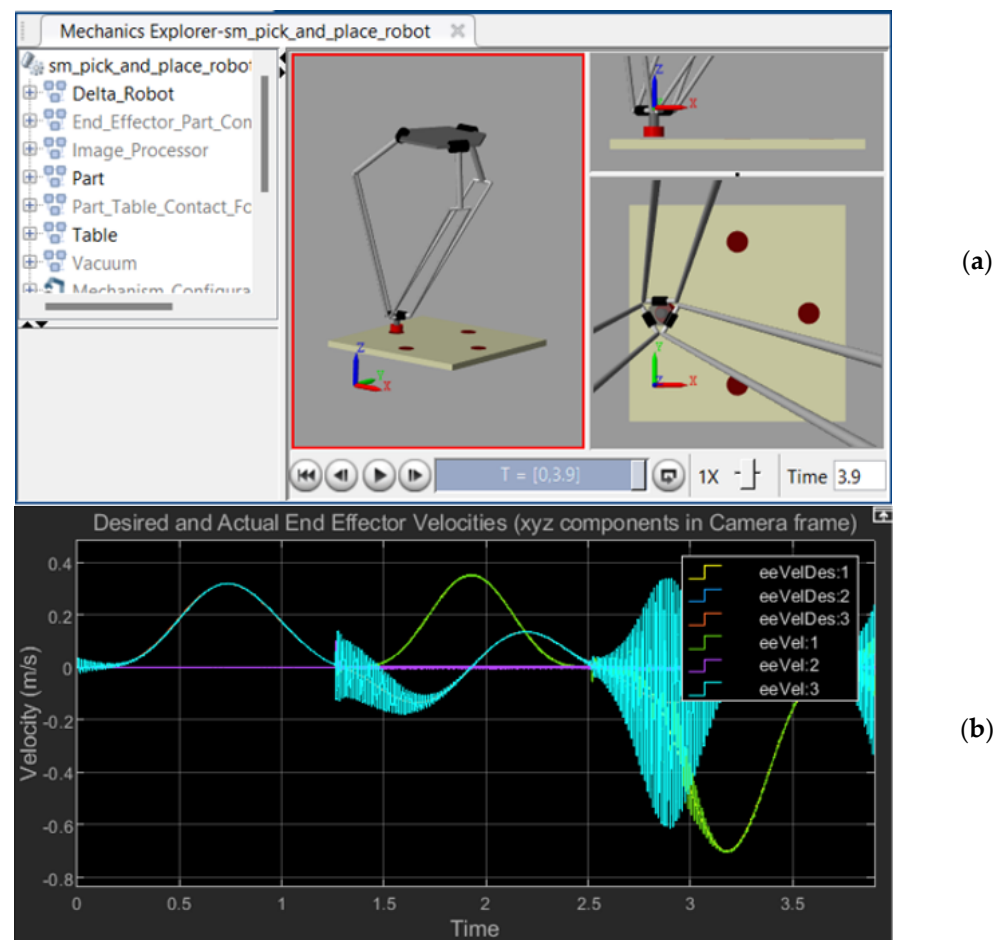


Figure 12. (a) Simulated visualization of worst-case scenario harvesting using a delta robot in MATLAB and (b) Simulink plot of moving platform velocities during motion.

3.2.2. Hardware Validation

Establishing a maximum feed rate of 0.7 m/s within the Delta X software, four different accelerations were varied throughout the analysis as the robot followed the repeated G-Code commands. Completing a series of ten trials at each acceleration, the results with the standard deviations are summarized in Table 3, wherein the operation of the robot at half of its maximum acceleration (4 m/s^2) produced harvesting times very similar to the simulated output. However, pushing toward the configuration's maximum acceleration rate of 8 m/s^2 , as per Delta X's specifications, allowed for further reduction in the robot's time to harvest, such that Abberit may be permitted a whole extra second to implement their path-finding procedures.

Table 3. Harvesting time results for hardware validation at varied acceleration rates and a constant feed rate of 0.7 m/s.

Acceleration (m/s^2)	2	4	6	8
AVG Harvest Time (s)	4.84 ± 0.12	3.78 ± 0.08	3.16 ± 0.05	2.80 ± 0.08

With the tested and calculated harvesting times of our end effector, a comparison of the harvesting times for benchmark competition strawberry harvesters using configurations with a single robotic arm is presented in Table 4.

Table 4. Comparison of harvesting times utilizing configurations with a single robotic arm.

Strawberry Harvester	Harvesting Time per Berry (s)
Yamamoto et al. [11]	31.5
Xiong et al. [15]	6.1
Organifarms “BERRY” [18]	28.2
Octinion “Rubion” [21]	4
Tituaña et al. [22]	7.5
This work	2.8, 5 *

* Calculated.

4. Discussion

4.1. End Effectors

Having examined the application of a myriad of different gripper types, such as more traditional servo-actuated fingers [22,25,36], various forms of soft grippers [30,33], combinations of suction devices with pneumatically operated soft fingers [11,23], and grippers containing both active and passive fingers to “swallow” strawberries [13–15], it is evident that this form of solution comes with limitations. Gripping mechanisms that are designed to target the berries themselves often lack the flexibility needed to harvest within such tight tolerances. The fingers must have a large-enough surface area to reduce the stress imposed upon the strawberries at the required force for proper fruit detachment [26]. The stroke of the fingers must also be able to open wide enough for fully grasping berries of all sizes, without being too bulky and causing interference with other strawberries and other obstructions from the plant. Being limited to only picking strawberries ranging from 30 to 40 mm in size, the gripper designed in [22] was still not slender enough to harvest within patches containing multiple adjacent berries and, instead, imposed damage on surrounding fruits. Similarly, the configuration presented in [13–15] faced a common source of error amongst growing conditions of not being able to harvest berries larger than 45 mm in diameter. However, an increase in the size of the gripper design was not an option, as the prototype already had issues with maneuvering through obstacles delicately. The system designed in [11] implemented air nozzles to blow air at adjoining strawberries during the gripper’s approach of a target berry to push them aside; however, this method was found to increase the harvesting time, and damage was still experienced by fruits with proximity to the fingers. When soft materials are not used, it can be difficult to supply enough force to the strawberry for successful detachment without bruising the fruit, as experienced by [13–15,22]. Both designs required that multiple attempts be performed on berries for a successful harvest, with [22] experiencing 72.9% of its failure due to mechanical reasons, as the gripper could not securely hold the fruit well enough to break the stem.

Inspired by the concept presented in [16,18,19,24,37], wherein the end effector targets the fruit’s stem rather than the berries themselves, the solution proposed in this work aims to mitigate such limitations with an approach that is much more slender and causes less fruit damage. Since the identification of a strawberry stem is more computationally heavy, as seen in [16,18,19,38,39], the presented configuration was fitted with powerful pneumatics for actuation of the end effector to help alleviate the increases in harvesting times caused by a more complex approach. The pressurized system provides a force that is more than sufficient for stem detachment at instantaneous speeds without damaging the fruit, avoiding the need for multiple attempts at harvest. It was also outfitted with only a single “finger” to cut and pinch strawberry peduncles rather than the typical two-finger designs presented in [16,18,19,24,37], to maneuver much more freely in the tight tolerances of open-field environments.

4.2. Future Work

Future work in this field should focus on further automating hardware systems, so that robots may be capable of navigating through strawberry fields without human intervention. Additionally, a solenoid valve should be introduced for programmed control of the end effector's gripping mechanism, rather than continuing to use a manual valve. It is also suggested that small pumps be utilized in place of the industrial compressor originally used to establish the proof of concept for the end effector's actuation, to reduce the bulk of the system as it maneuvers through a strawberry field's rows. The pumps should be programmed to operate with an optimized duty cycle to reduce power consumption, as the robot will be working in outdoor conditions. Most importantly, it is critical that the developed hardware be evaluated using machine vision and that it be capable of harvesting strawberries throughout all stages of the growing season. Strawberries should then be categorized and validated for harvest based on five different growing conditions, as defined in [22].

5. Conclusions

While there has been significant progress in robotic solutions for strawberry production, research on autonomous open-field strawberry harvesting remains relatively limited. This work seeks to enhance these processes, aiming to replicate the efficiency of human workers with ease. It proposes a modular configuration as a practical solution for growers. The system comprises a Delta X parallel robot and a pneumatically powered end effector designed to delicately harvest strawberries by their stems. However, this work focuses on optimizing the end effector design and validating its harvesting capabilities using high-speed actuation methods. The utilization of a completely open-source parallel robot mechanism from Delta X was further evaluated to be exceedingly sufficient for strawberry harvesting applications. Its modular nature and openly available firmware enabled the creation of an adaptable system design, suitable for fields of varying dimensions and requirements. Delta X1 was evaluated to have a workspace that is more than adequate for harvesting strawberries in typical two-plant-per-row strawberry fields, meeting the scope of this project amply.

The end effector prototype with optimized rotation of the cutting mechanism demonstrated high success rates of 94.74% in simulated environments and 100% at Farias Farms, even in densely covered late-season conditions. Utilizing an off-the-shelf robotic configuration, the system's workspace was validated as adequate for harvesting in a typical two-plant-per-row strawberry field, with each strawberry picked in 2.8–3.8 s. This capability sets the stage for future enhancements, including the integration of machine vision processes to enable the system to identify and pick each strawberry within 5 s.

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