Design and Testing of a Self-Propelled Multi-Station Orchard Harvesting Equipment (Post-Print)

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Abstract

To address the problems of high manual labor intensity, low operational efficiency, and insufficient supporting machinery in modern orchard fruit harvesting, and in consideration of the dwarfing rootstock wide-row dense planting mode and agronomic cultivation requirements, this study designed a self-propelled multi-station orchard harvesting equipment. The overall structure and working principle of the equipment were first introduced, followed by parameter analysis, calculation, and structural design of key components—including the crawler-type self-propelled chassis, extended operation platform, and automatic fruit conveying, boxing, and transfer system—based on the "two sides, two heights, six stations" picking operation mode. Field test results demonstrated that the designed self-propelled multi-station orchard harvesting equipment can match the harvesting speed of six manual stations, achieving an apple harvesting damage rate of 4.67%, a boxing uniformity coefficient of 1.475, and a boxing speed of 72.9 fruits/min, thereby satisfying the operational requirements for orchard harvesting.

Full Text

Design and Test of Self-Propelled Orchard Multi-Station Harvesting Equipment

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Abstract: To address the challenges of high labor intensity, low operational efficiency, and insufficient supporting machinery in modern orchard fruit harvesting, this study designed a self-propelled orchard multi-station harvesting equipment integrated with the dwarfing rootstock wide-row dense planting mode and agronomic requirements. The overall structure and working principle of the equipment were first introduced. Subsequently, based on the "two sides, two heights, six stations" harvesting operation mode, parameter analysis, calculation, and structural design were conducted for key components including the crawler self-propelled chassis, extended operation platform, automatic fruit conveying and boxing system, and transfer system. Field test results demonstrated that the designed self-propelled orchard multi-station harvesting equipment could synchronize with the manual harvesting speed of six stations, with an apple harvesting damage rate of %, a boxing uniformity coefficient of , and a boxing speed of , meeting the operational requirements for orchard harvesting.

Keywords: crawler chassis; extended operation platform; automatic conveyor boxing; boxing uniformity coefficient; harvesting damage rate; transfer system

In 2020, China' s orchard area reached 12.6463 million hectares, with fruit production reaching 287 million tons, ranking first in the world in both area and output. Apple and citrus cultivation accounted for over 30% of the total national fruit planting area [1]. Apple and citrus trees are primarily planted in hilly and mountainous regions, relying entirely on manual harvesting operations that suffer from low efficiency and high labor intensity. In the 1960s, European and American countries developed wheeled self-propelled harvesting platforms that utilized vision systems to estimate fruit distribution and instrumented picking bags to measure each worker' s picking speed, thereby controlling hydraulic lift heights to improve harvesting efficiency by 9.5% [2, 3]. Although these systems significantly improved harvesting efficiency and reduced labor intensity, their high cost made them unsuitable for widespread application in China due to terrain and planting pattern differences [4-6].

Researchers worldwide have conducted extensive studies on orchard harvesting equipment. Silwal et al. [7] developed a machine vision-based system combined with a gripping end-effector, achieving an 84% average apple picking success rate and demonstrating the significant potential of robotic apple harvesting, though large-scale application remains distant. Fei et al. [8, 9] transformed traditional harvesting platforms into collaborative robot (co-robot) work platforms that could assist multi-station workers in picking fruits at different heights while completing automatic collection and boxing. Zhang et al. [10] developed a low-cost apple picking assist device that effectively reduced fruit damage during boxing but did not address the uniformity of apple distribution within boxes.

In recent years, numerous researchers have designed and studied small lifting-type auxiliary operation platforms that solved the problem of requiring ladders for fruit harvesting but could only assist manual layered picking at different heights without providing fruit conveying and boxing functions [11-13]. Gao et al. [14] developed a picking robot based on a small crawler operation platform that completed picking and storage of different fruits through an actuator, though recognition difficulty under complex canopy conditions resulted in low overall work efficiency. Yang et al. [15] designed a "two sides, three heights, six stations" tractive picking platform that achieved apple conveying from picking stations to fruit boxes, but the tractive structure resulted in large turning radii and required additional power traction. Fan et al. [16] designed a wheeled multi-station picking platform that achieved fruit collection and boxing, but the rear-mounted fruit box structure prevented continuous row-to-row replacement in orchards.

To address the poor passability of traditional wheeled chassis and the low efficiency and high damage rate of automatic fruit boxing during harvesting operations, this study developed a self-propelled orchard multi-station harvesting equipment based on a crawler chassis structure. The equipment features an extended operation platform, a front-and-rear unobstructed fruit box continuous operation loading/unloading system, and an automatic fruit conveying and boxing device, meeting the requirements for auxiliary manual harvesting operations in modern wide-row dense planting modes while achieving efficient harvesting and low-damage uniform boxing.

2.1 Overall Structural Design

Considering that platform operators have lower flexibility than ground operators during machine movement, resulting in slower harvesting speeds, one additional workstation was added to each side of the upper platform to ensure consistent picking speeds between upper and lower layers, establishing a "two sides, two heights, six stations" picking operation mode. The overall machine structure and fruit conveying path are shown in [Figure 3: see original paper] and [Figure 4: see original paper], consisting primarily of the crawler chassis, manned operation platform, automatic fruit conveying system, fruit box loading/unloading mechanism, and fruit boxing system. The automatic fruit conveying system comprises inclined conveying devices, horizontal conveying devices, and vertical conveying devices for fruit collection. The boxing system consists of a uniform distribution device and vertical lifting device for intelligent fruit boxing. The fruit box loading/unloading system comprises front and rear fruit box loading/unloading mechanisms and fruit box slide rails for continuous loading/unloading operations.

The inclined conveying devices include four short inclined conveyors and two long inclined conveyors, corresponding to six harvesting stations positioned on both sides of the fruit boxes. The short inclined conveyors transport fruits from the middle and upper parts of trees picked by platform operators, while the long inclined conveyors transport fruits from the middle and lower parts picked by ground operators.

The main parameters of the self-propelled orchard multi-station harvesting equipment are shown in . The diesel engine provides power to drive the crawler chassis while powering a generator to supply electricity for the upper platform fruit conveying and boxing system. Operations require one dedicated driver and six picking workers. The driver handles driving and platform control, while the six picking workers correspond to the six inclined conveyor stations. Each inclined conveyor can rotate horizontally and pitch to required positions, facilitating fruit placement by workers.

2.2 Working Principle

During fruit harvesting operations, the driver first lowers the front fruit box loading/unloading mechanism to ground contact, pushes an empty fruit box onto its track, then hydraulically raises the mechanism to align with the fruit box slide rails before pushing the empty box to the boxing station on the operation platform for positioning and fixation.

The driver operates the machine at working speed while six picking workers harvest fruits at their respective height zones. Picked fruits are collected by corresponding inclined conveyors to the horizontal conveyor, then to the vertical conveyor, and finally fall uniformly into the fruit box through the distribution device. After each fruit layer is filled, the distribution and vertical conveying devices rise a predetermined height to maintain appropriate distance between distribution blades and fruit surfaces, reducing collision damage. When the lifting device contacts the limit switch, signaling a full box, fruit boxing stops.

After boxing completion, picking workers signal the driver to stop. The driver raises the rear loading/unloading mechanism to align with the slide rails; workers release the full box limit and push the full box onto the rear mechanism via slide rails. The driver lowers the mechanism to ground contact, releases the box limit upon ground contact, allowing the full box to slide to ground for subsequent vehicle transport to storage. The driver then loads another empty box from the equipment front via the front mechanism, and workers position and limit the empty box to continue operations.

3.1 Crawler Chassis Design

In crawler chassis system design, ground pressure is closely related to machine mass, crawler contact length, track gauge, and crawler width. Reasonable ground pressure improves machine passability and steering performance, with typical average ground pressure values designed at $p \leq 0.05$ MPa [19, 20].

Wide-row dense planting orchards typically have row spacing of 3-5 m, with some orchards using ridge cultivation. Design must ensure the crawler chassis maintains distance from tree roots and ridge walls while wider chassis improves overall stability. Based on investigation, maximum chassis width was determined not to exceed 1800 mm. Compared with wheeled chassis, crawler chassis has greater self-weight, with total machine mass reaching 3000 kg. The main platform load includes seven personnel and full fruit boxes totaling 4600 kg. Fruit harvesting operates at slow speeds of 1-2 km/h, with maximum walking speed of 2 km/h selected as design parameter. Crawler parameters are calculated using formulas (1)~(3):

$b = (0.9\sim1.1)L = (1.2\sim1.4)$

where b is crawler width (mm), m is total load mass (kg), L is crawler contact length (mm), B is track gauge (mm), and p is ground pressure (MPa). Calculations yielded b = 350 mm, B = 1450 mm, and L = 2028 mm, with verified average ground pressure p = 0.037 MPa, meeting design requirements.

During chassis movement, driving force must be greater than or equal to friction resistance but less than or equal to ground adhesion. Different speeds between the two tracks create varying conditions, generating rolling resistance and turning resistance. When both tracks have no speed difference, chassis system resistance is minimal as rolling resistance of both tracks; when speed differences occur, turning resistance from track contact surface displacement becomes much greater than rolling resistance, requiring consideration of power demands under various complex working conditions. Power selection parameters are calculated using formulas (4)~(6):

$F_1 = mgf$
$P_1 = F \quad v = mgf \quad v$
$P_2 = \quad {}_1\ {}_2$

where F_1 is travel resistance (N), g is gravitational acceleration (9.8 m/s^2), f is rolling resistance coefficient, P_1 is motor maximum power (kW), f is maximum equivalent working condition rolling resistance coefficient (0.69), v is maximum vehicle speed (m/s), P_2 is required engine power (kW), ${}_1$ is motor mechanical efficiency (0.9), and ${}_2$ is pump volumetric efficiency (0.85). Calculations yielded motor maximum power of 17.2 kW and required engine power of 22.6 kW. Considering additional power consumption by platform cylinders and generator, a Yanmar 4TNV88 engine with rated power of 32.3 kW and rated speed of 2600 r/min was selected to meet requirements.

3.2 Extended Working Platform Design

Modern orchard row spacing is 3-5 m, with initial manned platform width of 1500 mm insufficient for different row spacing requirements, making platform width extension necessary. The extended working platform designed in this study is shown in [Figure 5: see original paper], composed of C-section steel, guide grooves, platform steel plates, guardrails, guide bearings, support bearings, and hydraulic cylinders. The single-side extended platform width is 600 mm, with both sides capable of stepless extension, achieving a maximum expanded manned operation platform width of 2700 mm.

The front and rear C-section steel of the extended platform slides with support bearings in the main platform bottom groove, with guide bearings on the

C-section steel side providing position limitation. Selected C-section steel dimensions are 85 mm × 48 mm × 6 mm. The main platform connects to the extended platform bottom via hydraulic cylinder hinges to drive extension movement. Thrust force F and hydraulic cylinder parameters are calculated using formula (7):

where is friction coefficient between extended and main platforms (0.4), m is extended platform load weight (kg), m is extended platform self-weight (kg), P is hydraulic system working pressure (MPa), d_1 is cylinder piston diameter (mm), and d_2 is cylinder rod diameter (mm). With cylinder design pressure of 25 MPa, calculated piston diameter d_1 is 40 mm and rod diameter d_2 is 25 mm.

3.3 Fruit Box Loading/Unloading Mechanism Design

The fruit box loading/unloading mechanism consists primarily of frame, hydraulic cylinder, linkage mechanism, slide rails, and limit blocks. Divided into front and rear loading/unloading mechanisms based on installation position, its main functions are loading empty boxes from ground to operation platform and unloading full boxes to ground. As shown in [Figure 6: see original paper], the mechanism moves vertically through hydraulic cylinder-driven linkage mechanisms during operation. Limit blocks at slide rail ends protrude in free state to prevent box sliding; when contacting ground, the protrusion automatically releases, allowing boxes to slide down the rails by gravity.

The slide rails on the loading/unloading mechanism can be raised via hydraulic cylinders to align with dual slide rails on the operation platform, forming a front-to-rear unobstructed fruit box movement channel.

Force analysis of the loading mechanism after simplification is shown in [Figure 7: see original paper]. The moment balance equation (8) yields:

$F\ L_2\sin\alpha = 0$
$F\ \sin\alpha = 0$
$F\ = 0,\ F\ \ - F\ \ = 0,\ F_1 + F\ \cos\alpha = 0$
$M\ = 0,\ F L_4\sin\beta - F\ \ L_3\cos\alpha - F\ \ L_3\sin\alpha = 0$

where F_1 is mechanism load (N), L_1 is slide rail length (m), L_2 is linkage mechanism short side length (m), L_3 is linkage mechanism long side length (m), L_4 is cylinder hinge point to linkage mechanism bottom length (m), F is cylinder pulling force (N), α is linkage mechanism-frame angle (°), and β is cylinder-frame angle (°).

Cylinder pulling force F is calculated using formula (9):

$F\ = L_4\sin\beta$

The maximum cylinder pulling force occurs at the initial lifting stage, calculated as 20.26 kN. Based on this, a double-acting cylinder with piston diameter of 80 mm, rod diameter of 45 mm, and stroke of 400 mm was selected.

3.4 Fruit Inclined Conveying Device Design

As shown in [Figure 8: see original paper], the inclined conveying device consists primarily of conveyor belt, DC motor, horizontal rotation device, and gas spring. The conveyor belt features appropriately spaced baffles to separate and convey fruits, preventing large-scale rolling or dropping. Two gas springs on both sides enable pitching motion, while the horizontal rotation device enables horizontal swinging. Picking workers can push the device to adjust it to required positions, maximizing picking efficiency and comfort.

The gas spring supporting the inclined conveying device must satisfy both up-down rotation and positioning at any predetermined location. Force analysis is shown in [Figure 9: see original paper]. The moment balance equation (10) is:

$2F_2 a \cos(\beta_1)$ - a $\sin(\alpha_1) = 0$

where F is gas spring supporting force (F_1 for low position, F_2 for high position) (N), G is total conveyor weight (N), a is gas spring support point to fixed end length (m), b is fixed support height (m), l is gas spring length (l_1 for original length, l_2 for limit length) (m).

With G = 200 N, a = 0.45 m, b = 0.2 m, and L = 0.81 m, analysis shows minimum gas spring force at lowest point l_1 = 0.31 m and maximum at highest point l_2 = 0.55 m. Substituting into formula (10) yields F_1 = 140.2 N and F_2 = 195.3 N, giving a gas spring force range of 140.2~195.3 N within the 200 N self-locking range, enabling “adjust-and-lock” functionality.

As shown in [Figure 10: see original paper], the horizontal rotation device of the fruit inclined conveying device consists of a rotating base and fixed base. The fixed base mounts on the frame, while the rotating base connects to the fixed base via two deep groove ball bearings with interference fit for rotation. A directional ring in the rotating base’ s center groove controls friction between the ring and balls by adjusting universal ball bearing bolts, achieving directional positioning for horizontal adjust-and-lock functionality.

3.5 Horizontal and Vertical Conveying Device Design

The horizontal conveying device, shown in [Figure 11: see original paper], primarily collects and transports fruits from six inclined conveyors to the vertical conveyor. Requiring sufficient length and width to aggregate from six sources, it mounts on the gantry frame upper end via bolts, connecting to inclined conveyors on both sides.

The horizontal conveyor belt uses polyvinyl chloride material with width of 590 mm, drum center distance of 980 mm, drum outer diameter of 80 mm, baffle height of 50 mm, and baffle spacing of 100 mm. The horizontal conveyor speed correlates with vertical conveyor and distribution device speeds. With distribution device speed set at 40 r/min (carrying fruits from three vertical conveyor baffles per revolution), both vertical and horizontal conveyor speeds are set at 0.2 m/s.

The vertical conveying device transports fruits from the horizontal conveyor to the distribution device. As shown in [Figure 12: see original paper], it consists primarily of a stepper motor, outer cover, vertical conveyor belt, drums, telescopic plates, and feed chute. The vertical conveyor belt, telescopic plates, and outer cover form an enclosed space to prevent fruit dropping during transport. Vertical conveyor belt width is 590 mm, drum center distance is 840 mm, drum outer diameter is 80 mm, baffle height is 80 mm, and baffle spacing is 100 mm. The feed chute divides fruits into two-side feeding to improve boxing uniformity and reduce fruit damage.

3.6 Fruit Uniform Distribution Device and Fruit Surface Detection System Design

The distribution device ensures fruits falling from the hopper are uniformly distributed into the fruit box, enabling layer-by-layer boxing to reduce collision damage between fruits and boxes or among fruits.

As shown in [Figure 13: see original paper], the distribution device consists primarily of motor, spoke plate, spoke support bars, distribution blades, proximity switch, rubber rods, and fixed rings. Driven by an upper motor connected to the spoke plate via coupling, spokes with distribution blades are installed along the spoke plate axis, fixed by spoke support bars and spokes. The device features 350 mm spoke length, 200 mm × 20 mm spoke support bars, 50 mm diameter 4-hole spoke plate, four distribution blades of 400 mm length made of 3 mm thick foam with soft, smooth, and flexible characteristics. Blades are installed in a concave trumpet shape with spacing greater than apple diameter to avoid collision damage while facilitating fruit rolling. During operation, the motor drives blade rotation, allowing apples to slide from the outlet through the concave blade channel into the box. Rotating blades sweep across the fruit surface, spreading and leveling accumulated apples.

The fruit surface detection system, comprising proximity switch, rubber rods, and fixed rings, rotates with the distribution device to detect when fruit surface reaches lifting criteria. The fixed ring mounts on spoke support bars, while rubber rods sleeve inside distribution blades and pass through the fixed ring. As fruit height increases and lifts distribution blades, rubber rods move vertically to trigger the proximity switch, transmitting signals.

As shown in [FIGURE:14(a)], fruits fall from the hopper onto the distribution device and rotate with blades into the box. Lower fruits contact and lift the blades. When fruit height is insufficient to trigger the proximity switch, boxing continues. As shown in [FIGURE:14(b)] and [FIGURE:14(c)], when fruits reach specific height, they lift the blades enough for rubber rods to trigger the proximity switch, which signals the vertical lifting device to raise the distribution device a predetermined height, creating space for continued boxing until the box is full [FIGURE:14(d)].

4 Field Operation Performance Test

To verify the field operation performance of the designed self-propelled orchard multi-station harvesting equipment, apple harvesting field tests were conducted in October 2020 at a location in Shandong Province. The apple variety was Yantai Fuji, with single tree rows of 50 m length, average tree height of 3.55 m, row spacing of 3.8 m, and average plant spacing of 1.0 m. As shown in [Figure 15: see original paper], before testing, the driver extended left and right extension platforms by 20 cm each according to tree row spacing. To ensure complete fruit harvesting, the equipment operated at low speed (1 km/h). Six workers stood at six inclined conveyor stations, rotating and adjusting the inclined conveyors to meet picking requirements.

4.1 Test Indicators and Methods

This study proposes a uniformity coefficient method to evaluate fruit boxing uniformity. Fruit boxes are divided into 5$×5×$1 unit grids per row, column, and layer. The uniformity coefficient is calculated using formulas (11) and (12), where smaller coefficients indicate better uniformity with smaller differences in apple count between layers and grids.

During apple conveying from inclined conveyors to boxes, inevitable compression and collision cause mechanical damage, with collision being a primary damage source. Formula (13) calculates fruit boxing damage rate. Boxing speed is calculated as fruit count per full box divided by time required, using formula (14).

Based on response surface parameter optimization, the optimal low-damage boxing parameter combination was: distribution device speed 29.169 r/min and height 200 mm. Three fruit harvesting and boxing tests were conducted using these parameters. Workers picked fruits and placed them on inclined conveyors, which aggregated to horizontal and vertical conveyors and finally fell into boxes through the distribution device. When fruit accumulation triggered the upper limit switch, the test ended for box replacement. Each test calculated uniformity coefficient, damage rate, and boxing speed, with three-test averages as final results.

4.2 Test Results

[Test results table would appear here with TABLE:2 marker]

The results in show that during harvesting, all components of the self-propelled orchard multi-station harvesting equipment operated stably. After platform extension, workers could reach apples throughout the canopy. The automatic conveying and boxing system adapted to picking speed without congestion. Mean apple harvesting damage rate was 4.67%, mean boxing uniformity coefficient was 1.475, and mean collection/boxing speed was 72.9 fruits/min, meeting design requirements.

5 Conclusions

To address labor intensity and low harvesting efficiency in modern orchard production, this study designed a self-propelled orchard multi-station harvesting equipment integrated with dwarfing rootstock wide-row dense planting modes and agronomic requirements. The equipment automatically collects and boxes manually harvested fruits through multi-stage conveying devices. Field harvesting tests were designed, proposing the uniformity coefficient method to evaluate boxing uniformity, with comprehensive performance evaluation combining damage rate and boxing speed. Results showed the equipment meets design requirements and can be applied in actual orchard harvesting. Main conclusions are:

1. Based on fruit canopy characteristics and the "two sides, two heights, six stations" picking mode, an expandable working platform based on crawler chassis was designed. Key components including fruit box loading/unloading structure, fruit inclined conveying device, horizontal/vertical conveying devices, and fruit distribution and surface detection systems were structurally designed.
2. Field tests demonstrated stable operation of all components. The automatic collection and boxing speed synchronized with six-station manual harvesting speed, with apple harvesting damage rate of 4.67%, boxing uniformity coefficient of 1.475, and boxing speed of 72.9 fruits/min.

The designed self-propelled orchard multi-station harvesting equipment can collect and box manually harvested fruits, effectively reducing labor intensity and improving production efficiency.

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Note: Figure translations are in progress. See original paper for figures.