

Article

Design and Experiment of an Autonomous Docking Device for an Unmanned Replenishment Vehicle for Large Sprayers

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Abstract

In order to address the problems of manual dependence, low replenishment efficiency, and insufficient operational continuity in unmanned field operations of large sprayers, an autonomous docking device for an unmanned replenishment vehicle was designed. The device is composed of three principal components: a robotic-arm docking system, a pesticide delivery system, and a docking control system. RTK positioning information is utilised to determine the relative position between the unmanned replenishment vehicle and the large sprayer. The robotic arm approaches the high-position filling port, and the end effector completes guidance, flexible compensation, and electromagnetic coupling. A geometric model of the robotic arm was established, and its workspace was analysed using the Monte Carlo method. Single-factor tests and response surface optimization tests were conducted to optimize the key parameters of the end effector, and robotic arm control accuracy tests and field collaborative docking tests were carried out to evaluate the performance of the device. The results showed that the workspace of the designed robotic arm covered the elevated filling-port area of the large sprayer and met the docking requirements within a vehicle spacing of 0.25–1.25 m. After parameter optimization, the predicted cumulative docking time of the end effector was 2.051 s. The field collaborative docking test showed that, within a vehicle spacing range of 25–125 cm, 56 of 60 docking trials were successful, giving an overall success rate of 93.33%. Within the medium-spacing range, stable docking was achieved with an average docking time of 44.10–47.89 s. The results indicate that the proposed autonomous docking device can support unmanned vehicle approach, robotic arm positioning, end-effector guidance, and stable pesticide replenishment of large sprayers.

Keywords: large sprayer; unmanned replenishment vehicle; autonomous docking; pesticide replenishment



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1. Introduction

With the development of modern agriculture toward large-scale, precise, and intelligent production, large and efficient plant protection equipment has been increasingly used in field crop production. The employment of large boom sprayers has become a pivotal element in the protection of maize and other field crops, owing to their high operational efficiency, extensive coverage, and aptitude for large-scale field management. Concurrent with this, the continuous development of technologies such as autonomous driving, variable-rate spraying, and boom self-balancing has promoted the transition of large sprayers from mechanized operation to intelligent and unmanned operation [1].

At present, the replenishment of pesticides remains an important factor hindering the implementation of closed-loop operation in the unmanned operation of large sprayers. Conventional replenishment methods usually necessitate manual operations including the cessation of the machine, the opening of the tank cover, the transportation of the pesticide, and the insertion of a filling pipe. These operations not only increase labor intensity, but also engender high pesticide exposure risk, low replenishment efficiency, and insufficient continuous operation capability [2]. When sprayers perform large-area continuous operation, reliance on manual intervention in the replenishment process makes it difficult to achieve a complete unmanned operation chain, thereby limiting the application efficiency of unmanned plant protection equipment.

Therefore, the development of an autonomous docking device for an unmanned replenishment vehicle for pesticide replenishment of large sprayers represents a significant engineering challenge. The docking process for replenishing pesticides on large sprayers is distinguished by several key differences when compared with general vehicle parking tasks. These include high target position, limited operating space, residual parking errors after the vehicle has stopped, and high requirements for end connection accuracy. In the case of large sprayers, the filling port is typically situated at a relatively elevated position on the machine body. The docking space is constrained by guardrails, boom mechanisms, and the overall structure of the sprayer. Conversely, when the unmanned replenishment vehicle and the sprayer complete relative parking in the field, RTK positioning errors, vehicle heading errors, and platform parking errors still exist. Consequently, stable docking cannot be achieved by relying solely on the accurate positioning of the mobile platform. A combination of robotic-arm spatial compensation and end-effector guidance is required to enable autonomous docking from approach to stable connection.

Extensive research has recently been conducted on agricultural robotic arms, end effectors and docking technologies for interfaces. Existing studies have shown that agricultural robotic arms are widely used for harvesting, spraying, pruning and monitoring. Interface-type tasks, meanwhile, place greater emphasis on workspace adaptability, position compensation capability and end-guided connection performance [3–5]. At the same time, studies on fuelling, charging and fluid replenishment have shown that structures combining guided capture and active attraction are helpful in improving the success rate and stability of docking in connection tasks involving position and attitude deviations [6–8]. Although Gao et al.'s study [9] provides a useful reference for autonomous docking in pesticide replenishment, research on autonomous docking for high-position filling ports of large sprayers remains limited, particularly with regard to collaborative docking devices integrating robotic-arm spatial compensation and local error compensation at the end effector.

Compared with previous studies on autonomous docking, replenishment, charging, robotic positioning, and compensation mechanisms, many existing methods rely on visual recognition, high-precision robotic positioning, or active alignment control to complete interface docking. These methods can achieve high positioning accuracy under structured or semi-structured conditions, but they usually place high requirements on target perception, platform positioning accuracy, and environmental stability. For field pesticide replenishment of large sprayers, the filling port is located at a high position, the operating space is constrained by the sprayer structure, and residual parking errors still exist after vehicle stopping. Therefore, relying only on precise positioning or rigid alignment makes it difficult to ensure stable docking.

The main novelty of this study lies in the design and experimental validation of an autonomous docking device that combines robotic-arm spatial compensation with a passive conical guiding interface, flexible compensation, and electromagnetic coupling. In

this system, the robotic arm is used for large-range positioning and compensation, while the end effector and the receiving interface are used to absorb local position and attitude errors during the final docking stage. This design reduces the dependence on chassis parking accuracy and provides a feasible solution for high-position filling-port docking of large sprayers. In addition, the key parameters of the end effector were optimized, and robotic arm accuracy tests and field collaborative docking tests were conducted to verify the feasibility and field applicability of the device.

Therefore, this study provides a feasible technical solution for autonomous pesticide replenishment of large sprayers. The proposed device was evaluated through workspace analysis, end-effector parameter optimization, robotic arm positioning accuracy tests, and field collaborative docking tests, providing a reference for the development of field replenishment from manual assistance toward collaborative unmanned operation.

2. Design of the Autonomous Docking Device and Experimental Methods

To enable stable autonomous docking during pesticide replenishment for large sprayers, the system was designed with regard to its composition, the configuration of the robotic arm, the structure of the end-effector and the docking control strategy. Taking into account the high position of the filling port, the limited operating space, the residual parking errors and the high requirements for a stable end connection, this section first describes the composition and working principle of the autonomous docking system for the unmanned replenishment vehicle. Building on this, the geometric configuration and workspace of the robotic arm are analysed and the end-effector and its guiding structure are designed. Then, according to the requirements of the autonomous docking task, the docking control method and system operation process are proposed. Finally, the experimental schemes and evaluation indices for testing the accuracy of the robotic arm position control, the performance of the end-effector docking, and the field docking are presented. This provides a methodological basis for the subsequent analysis of the experimental results.

2.1. System Composition and Working Principle

2.1.1. System Composition

The autonomous docking system for unmanned large sprayer replenishment vehicles mainly consists of a robotic arm docking system, a pesticide delivery system and a docking control system. The entire system is mounted on an electric chassis (7YJY-4000, Beiqi Foton Motor Co., Ltd., Beijing, China). Figure 1 shows the overall architecture and main components of the system.

As shown in Figure 2, the robotic-arm docking system consists of a rigid, column-type robotic arm and an end effector. Mounted on the frame of the replenishment vehicle, the robotic arm includes a rotary motor, two-stage lifting hydraulic cylinders, a pitching hydraulic cylinder and a horizontal telescopic hydraulic cylinder. These driving units control the horizontal rotation, vertical lifting, fine adjustment of the arm attitude and linear extension of the robotic arm respectively. This ensures that the end effector can move to and cover the position directly above the high-position filling port of the sprayer. The end effector comprises a flexible corrugated pipe, an electric push rod and an electromagnet. On the sprayer side, a conical flared guiding structure, an interface-state sensor and an attraction iron ring are installed to provide physical guidance and error compensation during the final stage of docking.

The pesticide delivery system comprises a 4000 L capacity tank, a centrifugal pump, an electromagnetic three-way valve and internal delivery pipelines. The delivery pipelines run through the hollow robotic arm. The electromagnetic three-way valve controls the flow

direction of the pesticide. This enables high-flow pesticide delivery to the target sprayer. After the task is complete, the valve connects the pipeline to the replenishment vehicle's tank so that any residual pesticide in the pipeline can flow back by gravity.



Figure 1. Overall structure and main components of the autonomous docking system of the unmanned replenishment vehicle.

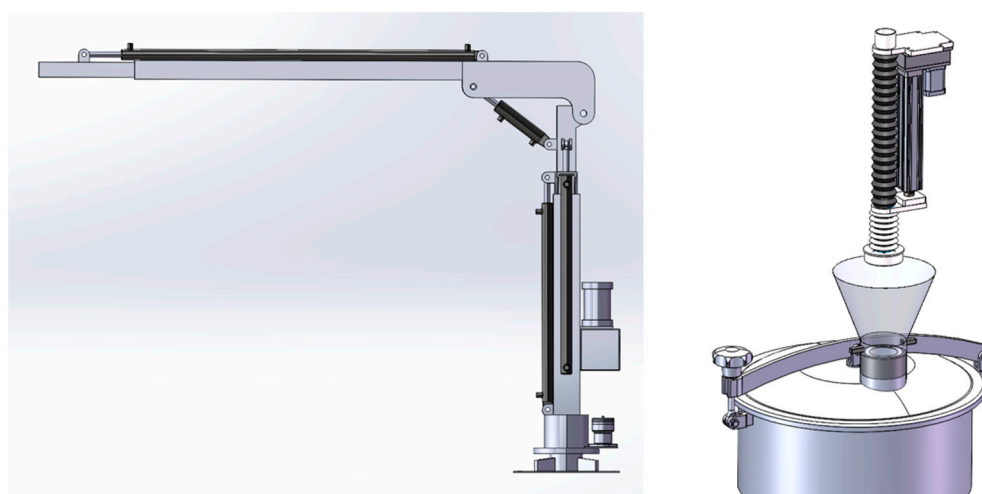


Figure 2. Structural diagram of the robotic arm and end effector.

As shown in Figure 3, the docking control system consists of a main control computer (PD701A tablet computer produced by Shenzhen PDS Technology Co., Ltd., Shenzhen, China), a GNSS RTK positioning unit, a draw-wire displacement sensor, an interface-state sensor and a hydraulic/motor drive box (KM50E-PCU produced by Kalman Navigation Technology Co., Ltd., Wuxi, China). The control modules communicate with each other via the CAN bus and RS232 serial port. The main control computer acquires sensor data and sends pulse-width modulation (PWM) drive signals and switching control signals, thereby enabling coordinated control of all system components.

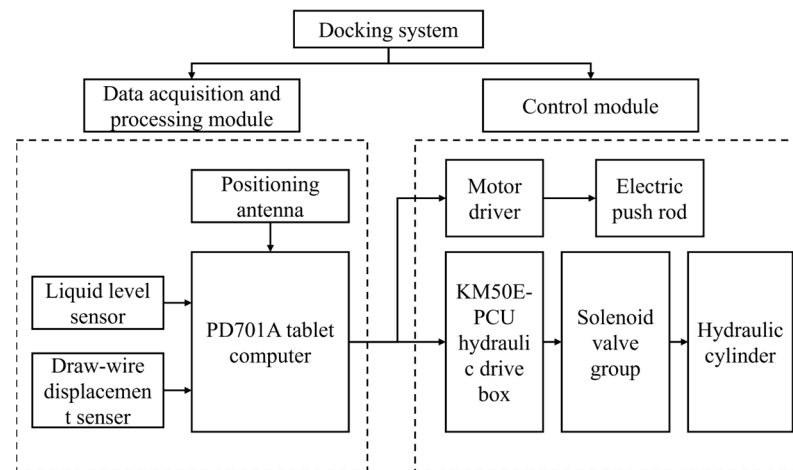


Figure 3. Hardware system structure diagram.

2.1.2. Working Principle

When there is insufficient pesticide remaining in the large sprayer during field operations, the sprayer stops and moves to a preset replenishment area at the edge of the field or alongside a farm road. An unmanned replenishment vehicle then travels along the farm road, guided by RTK positioning information, to approach the preset area near the sprayer. Based on the RTK positioning information of the replenishment vehicle, the robotic arm, and the RTK antenna installed at the sprayer filling port, the system then calculates the relative position between the unmanned replenishment vehicle and the sprayer. According to the filling port's relative direction, height and distance, the system controls the robotic arm to perform lifting, rotation and telescopic motions. This enables the end effector to gradually approach the sprayer's filling port area [10,11]. After reaching the target area, the conical guiding structure corrects the interface position while the flexible compensation mechanism absorbs local position and attitude deviations. A stable connection is then achieved through the attraction mechanism [12]. Once the docking state has been confirmed, the system begins to deliver the pesticide. The pesticide is delivered to the sprayer filling port via the onboard delivery system, the internal channel of the robotic arm and the end effector. Once replenishment is complete, the end effector exits the target interface, the robotic arm returns to its initial position and the system switches back to standby. The sprayer then returns to the field for continued operation while the replenishment vehicle continues along the farm road to perform subsequent replenishment tasks. Thus, the unmanned replenishment vehicle completes a full autonomous docking and replenishment cycle.

2.2. Geometric Configuration and Workspace Analysis of the Robotic Arm

During the autonomous docking process of the unmanned replenishment vehicle for large sprayers, the robotic arm is primarily employed to position the end effector in close proximity to the sprayer's filling port. This facilitates guided insertion, flexible compensation, and attraction-based connection. The filling port of a large sprayer is typically located at a height of over 3 m, with a sprayer width of around 2.9 m. During replenishment, the lateral distance between the vehicle and the sprayer is approximately 0.25–1.25 m.

According to these operating conditions, the robotic arm needs to have the following capabilities [13]:

- A high-position reaching capability of more than 3 m;

- A horizontal extension capability to cover variations in the spacing between the two vehicles;
- A certain range of attitude compensation capability.

Considering the installation space of the unmanned replenishment vehicle platform and the layout requirements of the pesticide delivery pipeline, the simplified structure of the robotic arm used in this study is shown in Figure 4.

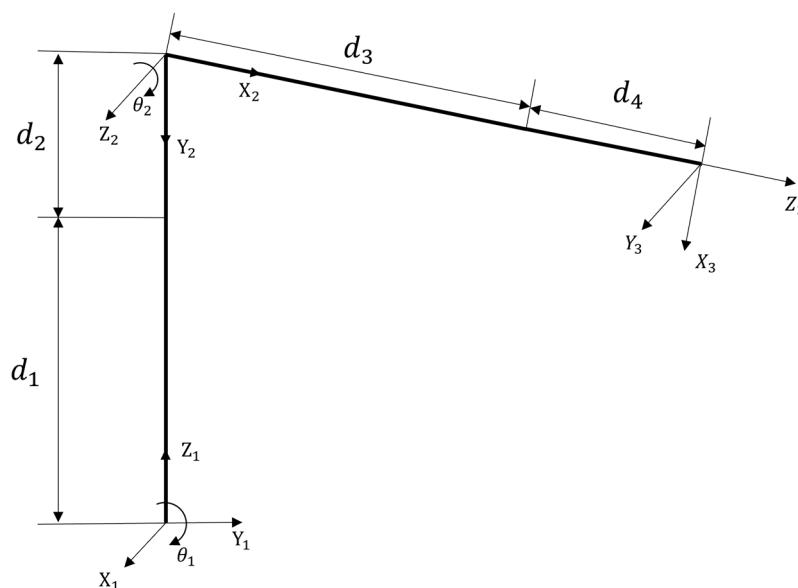


Figure 4. Simplified structural diagram of the robotic arm.

The robotic arm consists of a fixed base, a rotary mechanism, a vertical lifting mechanism, a pitching mechanism and a horizontal telescopic mechanism. The fixed base provides an installation foundation, while the rotary mechanism adjusts the robotic arm's orientation in the horizontal plane. The vertical lifting mechanism compensates for the sprayer filling port's height, the pitching mechanism adjusts the horizontal arm's attitude, and the horizontal telescopic mechanism enables the end effector to approach the target along the arm's direction. The main parameters of the robotic arm are listed in Table 1.

Table 1. Main parameters of the robotic arm.

Symbol	Parameter	Value
θ_1	Base rotation angle of the robotic arm/(°)	−180~180
d_1	Basic vertical height of the robotic arm/(mm)	2600
d_2	Vertical lifting displacement of the robotic arm/mm	0~1500
θ_2	Pitch angle of the robotic arm/(°)	−15~15
d_3	Basic length of the horizontal arm/mm	1780
d_4	Telescopic displacement of the horizontal arm/mm	0~1500

A geometric model of the robotic arm was established by taking the centre of the robotic arm base as the origin of the base coordinate system. The position of the end effector is jointly determined by the base rotation angle θ_1 , the vertical height $d_1 + d_2$, the pitch angle θ_2 , and the horizontal arm length $d_3 + d_4$. When θ_2 is defined with respect to the

horizontal state of the arm, the position of the end effector in the base coordinate system can be expressed as follows:

$$\begin{cases} x = (d_3 + d_4) \cos \theta_2 \cos \theta_1 \\ y = (d_3 + d_4) \cos \theta_2 \sin \theta_1 \\ z = d_1 + d_2 + (d_3 + d_4) \sin \theta_2 \end{cases}$$

where x , y , and z are the spatial coordinates of the end effector in the base coordinate system, respectively. It can be seen from the equation that θ_1 mainly affects the orientation of the robotic arm in the horizontal plane, d_2 mainly affects the vertical height of the end effector, θ_2 is used for small-range attitude compensation, and d_4 is used to adjust the extension distance of the end effector along the horizontal arm. Therefore, once the values of the variables are given, a specific end-effector position in space can be obtained using a numerical method.

In this study, MATLAB R2022b combined with the Monte Carlo method was used to analyze the workspace of the robotic arm [14,15]. Random sampling was performed within the allowable range of each joint variable, and the random value of the i -th joint variable can be expressed as follows:

$$q_i = q_{i,\min} + (q_{i,\max} - q_{i,\min})\text{rand}(0,1)$$

where q_i is the random sampling value of the i th joint variable; $q_{i,\min}$ and $q_{i,\max}$ are the minimum and maximum values of this joint variable, respectively; and $\text{rand}(0,1)$ is a uniformly distributed random number between 0 and 1. By randomly sampling the variables θ_1 , d_2 , θ_2 , and d_4 and substituting them into the end-effector position equation, the three-dimensional workspace point cloud and the projected views on the X–Z and X–Y planes were obtained, as shown in Figure 5. It should be noted that the Monte Carlo workspace analysis in this study was a geometric reachability analysis. The purpose was to verify whether the designed structural parameters and joint ranges could cover the elevated filling port area. Actuator acceleration limits, joint-speed-dependent torque bounds, dynamic load variation, and link deformation were not included in this model. However, the robotic arm used in this study has a relatively simple structure, and the docking process is not a high-speed continuous trajectory-tracking process. Instead, the robotic arm adopts a low-speed and stepwise control strategy, including height adjustment, base rotation, and horizontal extension. Each stage is completed before the next motion is executed, which reduces the influence of dynamic coupling and transient effects on target reachability. Therefore, the workspace result should be interpreted as geometric coverage rather than complete dynamic reachability. The practical reachability of the target region was further verified by the robotic arm positioning accuracy test and the field collaborative docking test.

The results of the workspace analysis show that the end of the robotic arm forms a continuous reachable region in three-dimensional space that can cover the height range of the target sprayer filling port. In the X–Z plane, the robotic arm has sufficient reaching capability at a high position to meet the sprayer filling port's height requirement. In the X–Y plane, the robotic arm has a relatively large horizontal coverage range and can adapt to variations in operating distance between the unmanned replenishment vehicle and the sprayer of between 0.25 and 1.25 m. Based on the geometric parameters and workspace simulation results, the designed robotic arm can fulfil the vertical height, horizontal extension distance and local attitude compensation requirements for autonomous docking with the high-position filling port of a large sprayer.

However, for the same target docking point, multiple combinations of joint variables may enable the robotic arm to reach the same position, resulting in a kinematic multi-

solution problem. The fixed-pitch strategy was adopted based on the intended application scenario of the unmanned replenishment vehicle. The system is mainly designed for standardized unmanned farms, where the replenishment vehicle usually travels along paved or relatively flat roads at the field edge, while the sprayer is parked close to the field edge. Therefore, the designed docking condition is generally horizontal, and the attitude variation in the target filling port is relatively small. Meanwhile, the flexible corrugated pipe on the end effector can compensate for a certain range of angular deviations during the final guided docking stage. Therefore, during the subsequent docking control, the pitch angle θ_2 is fixed at a preset value, and the end position is mainly adjusted by the base rotation angle θ_1 , the vertical lifting displacement d_2 , and the horizontal telescopic displacement d_4 . This treatment simplifies the motion control process, reduces the influence of multi-solution selection on system stability, and allows the end effector to tolerate local angular misalignment during guided docking.

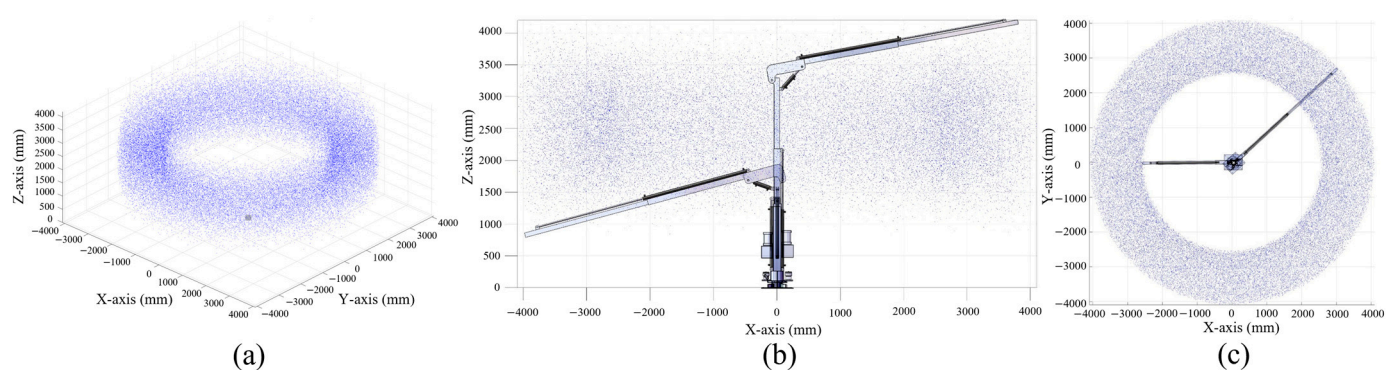


Figure 5. Workspace point cloud of the robotic arm. (a) Three-dimensional reachable workspace of the robotic arm end effector. (b) Projection of the workspace on the X–Z plane, showing the vertical reachable range. (c) Projection of the workspace on the X–Y plane, showing the horizontal coverage range.

2.3. End Effector Design

The unstructured field environment inevitably causes residual position and attitude errors during pre-parking by the unmanned replenishment vehicle. If conventional rigid alignment docking is adopted, small coordinate deviations may easily lead to mechanical jamming, collision, or docking failure. Inspired by the “probe-and-drogue” docking mode used in hose-and-drogue aerial refueling, a flexible end effector with large-range guided capture, local error compensation, and stable locking capability was designed in this study [16–18]. The overall structure of the end effector consists of an active actuator head on the replenishment vehicle side and a passive receiving interface on the sprayer side, as shown in Figure 6.

To capture a large range of initial errors, a fixed conical receiving interface was installed on the side of the sprayer’s filling port. When the robotic arm moves the end effector towards the target area and the internal electric push rod drives the actuator head downwards, the end effector can still enter the large opening of the conical funnel, even when there are lateral or attitude deviations. During continuous downward motion, the end effector slides along the inclined wall of the conical funnel under contact force, gradually converging towards the centre. This design converts the originally complex, precise-alignment problem into passive mechanical guidance based on geometric constraints [19].

In coordination with the conical guidance process, a flexible corrugated pipe was adopted in the active actuator head to transmit pesticide over a variable distance. During convergence and sliding towards the centre of the conical funnel, the corrugated pipe undergoes adaptive lateral bending and axial compression [20]. This local flexible component

effectively absorbs contact stress and residual pose deviation generated during docking. Consequently, the end effector can smoothly slide into the preset bottom position, even under non-ideal alignment conditions. This greatly improves the system's fault tolerance.

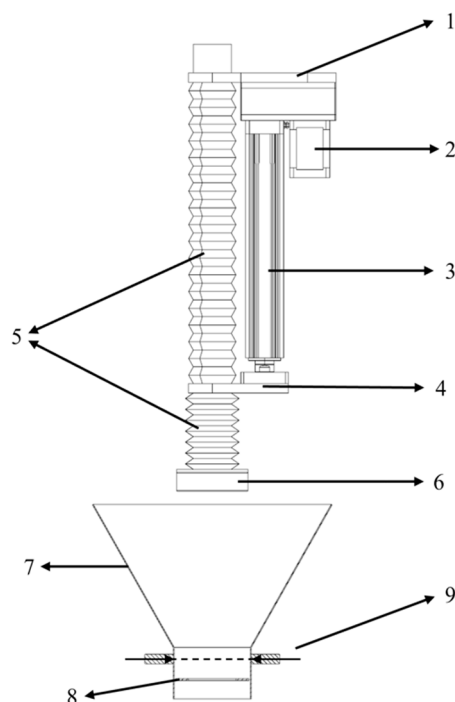


Figure 6. End effector structure. (1) Upper mounting plate; (2) stepper motor; (3) electric push rod; (4) lower mounting plate; (5) flexible corrugated pipe; (6) electromagnet; (7) conical funnel; (8) attraction iron ring; (9) interface-state sensor.

Once the end effector has slid to the bottom of the conical funnel, the annular electromagnet at its base works with the iron ring on the sprayer to ensure a reliable seal and stable connection during the delivery of high volumes of pesticide (≥ 300 L/min). When energised, the electromagnet generates a strong attractive force, which further eliminates small physical gaps and provides reliable mechanical constraint. Meanwhile, the interface-state sensor embedded in the sprayer monitors the docking state. Under normal undocked conditions, the sensor outputs a low-level signal. Once electromagnetic coupling is complete, the structural component blocks the sensor's optical path, causing it to output a high-level signal. To account for transient disturbances such as windblown leaves in the field, the control system incorporates a 1 s delay confirmation mechanism. The system only determines successful docking and starts the centrifugal pump for replenishment when the high-level signal remains valid, effectively avoiding pesticide leakage caused by false triggering.

2.4. Docking Control Method and Operation Process

The docking control system is centred around the upper computer. It receives RTK positioning information, robotic arm displacement feedback and end-state detection signals. It then sends control commands to the hydraulic drive control box, motor driver and end actuator according to the requirements of the docking task. The main program flow is shown in Figure 7.

Following system startup, the sensors, actuators and communication modules are initialised first, after which the position information of the unmanned replenishment vehicle, robotic arm and target sprayer is acquired. When the sprayer enters the preset replenishment area, the system uses the relative position of the two vehicles to determine the

direction and distance of the filling port. It then calls the robotic arm extension subroutine to move the end effector into the guided capture region near the target interface. This subroutine is shown in Figure 8. The motion sequence comprises height adjustment, base rotation and horizontal arm extension. This sequence prevents interference between the robotic arm and the sprayer structure during low-position rotation, thereby improving the stability of the docking process.

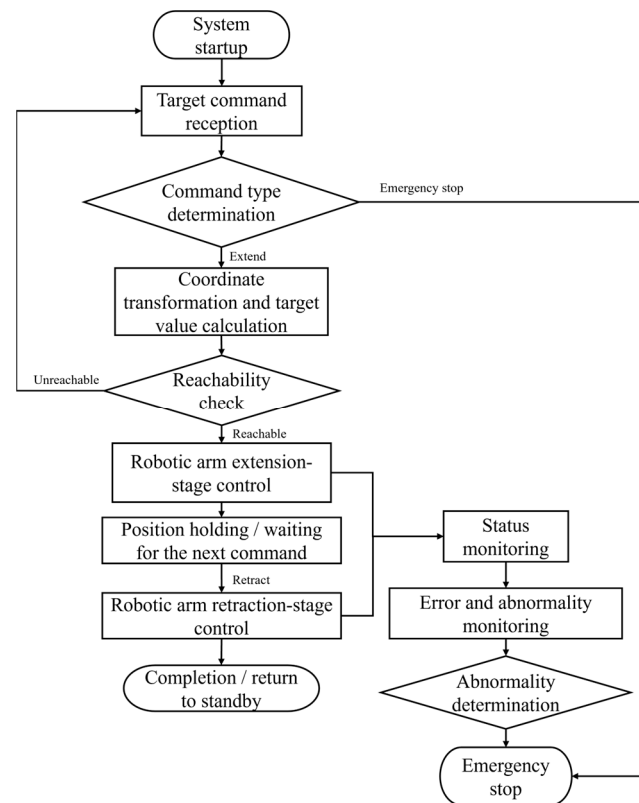


Figure 7. Main program flowchart.

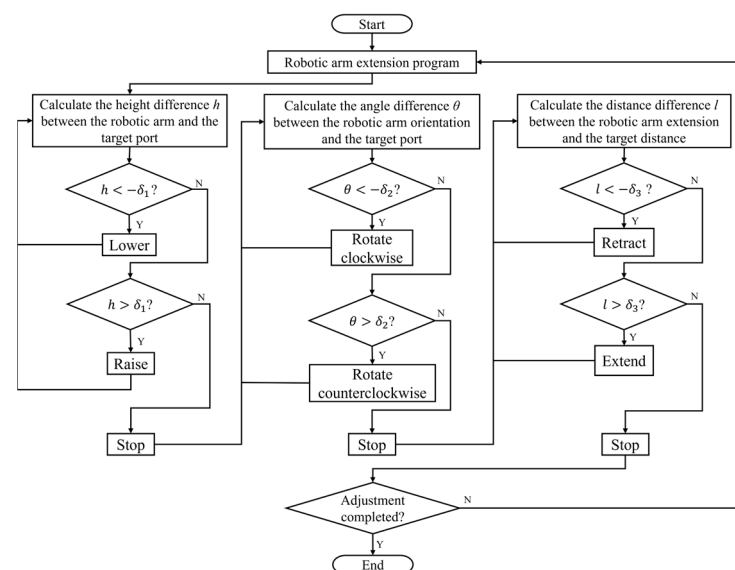


Figure 8. Robotic arm extension subroutine diagram.

During robotic arm positioning, the system sequentially performs compensation control in three directions: height, angle and horizontal distance. First, the lifting mechanism is

controlled by comparing the current height error (h) with the preset threshold (δ_1), so that the end effector enters the target height range. Next, the base rotation is controlled based on the comparison between the angle error θ and the preset threshold δ_2 , which enables the horizontal arm to point towards the sprayer filling port. Finally, the horizontal telescopic mechanism is controlled according to the deviation between the target distance and the actual end length. Once the length error l is smaller than the preset threshold (δ_3), the robotic arm positioning is complete, and the end effector enters the guided docking stage.

To clarify the control parameters and stage-completion criteria, the RTK positioning data were updated at a frequency of 10 Hz. The allowable thresholds for height adjustment, base rotation, and horizontal distance adjustment were set as $\delta_1 = 2$ cm, $\delta_2 = 0.8^\circ$, and $\delta_3 = 2$ cm, respectively. When the corresponding height error, angle error, or length error was smaller than its preset threshold, the current adjustment stage was considered complete, and the system entered the next stage. The response delay of the hydraulic valves was approximately 200 ms. The draw-wire displacement sensor was used to measure the horizontal extension of the robotic arm, and the interface-state sensor was used to determine the docking state of the end effector.

Once the end effector has entered the target area, the electric push rod is activated to extend downward. The interface position is corrected by the guiding structure on the sprayer side, and local position and attitude deviations are absorbed by the flexible compensation mechanism. After the electromagnetic attraction mechanism is energized, a stable connection is established with the target interface. To avoid false triggering caused by transient disturbances, the system judges docking to be successful only when the interface-state sensor maintains a high-level signal for 1 s. Then, the liquid delivery command is issued. Once replenishment is complete, the system turns off the liquid delivery signal, controls the end effector to exit the target interface, and retracts the robotic arm to its initial standby position, thereby completing one full operation cycle.

2.5. Experimental Design

2.5.1. End-Effector Docking Performance and Parameter Optimization Test

To evaluate the performance of the end effector during guided insertion, flexible compensation and electromagnetic attraction, and to optimise the combination of key structural and motion parameters, a test was conducted to evaluate the performance of the end effector during docking and to optimise its parameters. As the end effector is primarily responsible for the final connection once the robotic arm has reached the target position, its docking performance directly impacts the efficiency and success rate of the autonomous docking process. Therefore, the cumulative docking time of the end effector under the condition of the first successful docking was used as the main evaluation index to analyse the key factors affecting the docking process.

The test was carried out on an end-effector docking test bench, as shown in Figure 9. During the test, the end effector was mounted on a fixed support structure, and the target interface and guiding components were arranged according to the actual docking relationship. The final connection process after robotic arm positioning was simulated by controlling the electric push rod, guiding structure, and electromagnetic attraction mechanism. To ensure the comparability of different test results, the initial position of the end effector, the installation position of the target interface, and the test environmental conditions were kept consistent in all tests.

First, preliminary single-factor tests were conducted. The extension speed of the electric push rod, the height of the conical funnel, the half-cone angle of the conical funnel, and the driving voltage of the electromagnet were selected as the main influencing factors, and their effects on the cumulative docking time of the end effector were analysed. During

the single-factor tests, the cumulative docking time was recorded for each tested parameter level. If a parameter level caused docking failure or required repeated docking attempts, it was considered to have entered an unstable or failure-prone range and was therefore not included in the subsequent response surface design range. Therefore, the response surface test was designed within the parameter range in which stable first-attempt docking could generally be achieved. This treatment ensured that the response surface model was established based on the stable parameter range screened by the single-factor tests, rather than by selectively removing failed data from the response surface test. Based on the single-factor tests, response surface optimisation tests were conducted. According to the results of the single-factor tests, the factors with the most significant effect on the cumulative docking time were selected for the response surface design [21]. The factor levels are listed in Table 2. The values -1.682 , -1 , 0 , $+1$, and $+1.682$ represent the coded levels used in the central composite design.

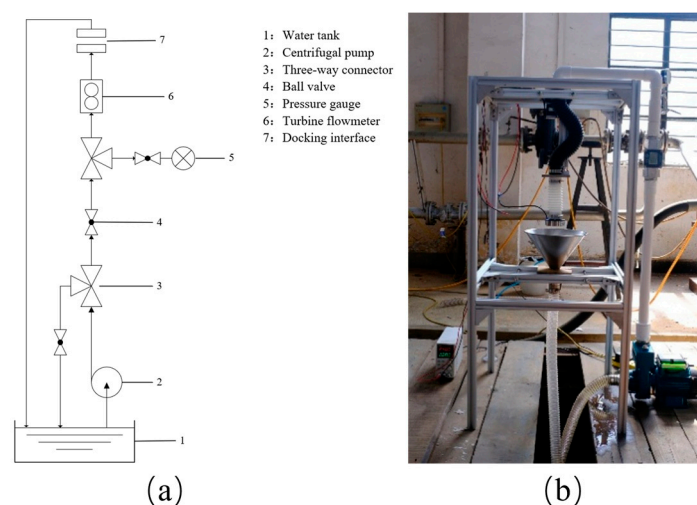


Figure 9. End-effector docking test bench. (a) Schematic diagram of the test bench. (b) Photograph of the physical test bench used for the end-effector docking performance test.

Table 2. Factors and levels of the end-effector response surface test.

Factor	Symbol	-1.682	-1	0	$+1$	$+1.682$
Half-cone angle of the conical funnel/(°)	A	27	30.243	35	39.757	43
Driving voltage of the electromagnet/(V)	B	13	15.838	20	24.162	27
Extension speed of the electric push rod/(cm/s)	C	6	7.622	10	12.378	14

The response surface model was established to analyse the effects of each factor and their interactions on end-effector docking performance, and to obtain an improved combination of key parameters for the end-effector. The test results provide a basis for selecting end-effector parameters for the subsequent collaborative docking field test.

2.5.2. Robotic Arm Control Accuracy Test

To verify the positioning accuracy of the robotic arm during autonomous docking, a test was conducted to assess the control accuracy of the robotic arm. Prior to docking, the robotic arm primarily adjusts the position of the end effector via vertical lifting, base rotation and horizontal telescopic motion. Therefore, the accuracy of the robotic arm's height control, angle control and horizontal extension control was tested to evaluate whether they could meet the requirement for the end effector to enter the capture region of the target interface.

The test was conducted in Wuxi, Jiangsu Province, China, and the test setup is shown in Figure 10.



Figure 10. Robotic arm position control accuracy test.

During the test, the variation in height of the robotic arm was obtained by measuring the difference in height between the RTK antenna on the robotic arm and the RTK antenna on the roof of the vehicle. The horizontal extension of the arm was measured using a draw-wire displacement sensor and the base rotation angle was obtained from rotary mechanism feedback. To verify the accuracy of the system's feedback data, the final position of the robotic arm was also measured using a laser rangefinder and an angle measuring device, and the system's feedback values were compared with the measured values.

According to the typical motion requirements of the robotic arm during autonomous docking, the test was conducted under vertical lifting, horizontal extension and base rotation conditions. Different target values were selected for vertical lifting, horizontal extension and base rotation, with different heights, distances and angles respectively. Each condition was repeated three times. The system feedback values and the actual measured values after the robotic arm reached the target position were recorded and the corresponding errors were calculated.

The evaluation indices included the error between the target and system feedback values, and the error between the target and externally measured values. The feedback error was used to evaluate the accuracy of the control system's internal position feedback, while the actual error was used to evaluate the robotic arm's final positioning accuracy. Statistical analysis of the errors under different conditions was used to evaluate the control accuracy of the robotic arm in lifting, rotation and extension, and to determine whether it meets the requirements for autonomous docking with the high-position filling port of a large sprayer.

2.5.3. Field Collaborative Docking Verification Test

To verify the performance of the proposed autonomous docking device in collaborative operations in a real working scenario, a field test was conducted to verify collaborative docking. This test centred on the actual docking process between the unmanned replenishment vehicle and the large sprayer. The main focus was on evaluating the feasibility of robotic arm positioning, end-effector-guided connection and the coordinated operation of the entire system. The main evaluation indices were docking success and total docking time. The test took place in Shuangyashan, Heilongjiang Province, China, and the field test site is shown in Figure 11. The field test was conducted on a horizontal dirt road after rainfall. Due to the muddy road surface, the sprayer had an approximate lateral attitude deviation of 10° . During the test, the ambient temperature was approximately 6°C , and the wind condition was northwest wind at level 4. According to the recorded positioning

data, the lateral parking error of the unmanned replenishment vehicle ranged from 5.56 cm to 10.23 cm.



Figure 11. Field collaborative docking test site.

Prior to the test, the end-effector parameters were adjusted to the improved combination obtained from the previous parameter optimisation test. The unmanned replenishment vehicle and the large sprayer were then positioned near the preset docking area. During the test, the sprayer was parked on one side of the farm road and the unmanned replenishment vehicle entered the designated area near the sprayer, guided by RTK positioning information. The system then used the relative position of the two vehicles to control the robotic arm, completing height, angle and horizontal distance compensation so that the end-effector entered the capture region near the sprayer filling port. The end-effector then completed the final connection with the help of the guiding structure, flexible compensation mechanism and electromagnetic attraction mechanism, and the docking state was confirmed by the interface-state sensor.

The docking success rate and the total time required to complete one autonomous docking operation were recorded during the test under different conditions. Each condition was repeated several times and the success rate and average time for docking were calculated in order to evaluate the adaptability of the proposed autonomous docking device to errors in vehicle parking, deviations in the position of the interface and external disturbances in the field environment. These results will inform the subsequent analysis of the engineering applicability of the collaborative docking device.

3. Results and Analysis

3.1. End-Effector Docking Performance Test and Optimization Results

3.1.1. Single-Factor Test Results

To identify the main factors affecting the docking performance of the end effector, single-factor tests were conducted and the results are presented in Figure 12. Each condition was repeated five times, and the error bars represent the standard deviation of the repeated trials. Figure 12a shows that, as the extension speed of the electric push rod increased from 6 cm/s to 14 cm/s, the cumulative docking time generally decreased. However, when the extension speed increased to 16 cm/s, the docking time increased significantly. This was primarily due to the increased impact when the end effector entered the guiding structure at an excessively high extension speed. One docking failure occurred during the test and re-docking was required, which resulted in an increase in the cumulative time. Figure 12b shows that the height of the conical funnel had a relatively small effect

on the cumulative docking time. Although appropriately increasing the height of the conical funnel may enlarge the capture range of the guiding structure to some extent, the installation space above the sprayer filling port is limited in the proposed device. If the conical funnel is too high, interference may occur during robotic arm motion. Meanwhile, the final compensation of lateral and angular errors mainly relies on the deformation of the flexible corrugated pipe on the end effector, and the flexible corrugated pipe itself has a limited deformation range. Therefore, even if increasing the conical funnel height geometrically enlarges the capture range, the positional or angular deviation generated during the guiding process may exceed the compensation capability of the corrugated pipe, resulting in docking failure. Considering the single-factor test results, installation space, and the compensation range of the flexible corrugated pipe, the conical funnel height was fixed at 15 cm and was not selected as a main optimization factor in subsequent tests. Figure 12c shows that the half-cone angle of the conical funnel obviously affects the docking time. When the half-cone angle was too small, the guiding entrance was narrow and local contact or slight interference could occur when the end effector entered the guiding structure. Conversely, when the half-cone angle was too large, the guiding structure's centring ability was weakened. Therefore, there was an appropriate range for the half-cone angle. Figure 12d shows that, as the driving voltage of the electromagnet increased, the cumulative docking time initially decreased significantly before gradually stabilising. This indicates that under low-voltage conditions, the electromagnetic attraction force was insufficient to form stable coupling quickly, whereas once the voltage reached an effective attraction level, increasing the voltage further had a limited effect on reducing the docking time. The extension speed of the electric push rod, the half-cone angle of the conical funnel and the driving voltage of the electromagnet all had a significant effect on the cumulative docking time, whereas the conical funnel height had a relatively weak effect. Consequently, the first three factors were selected as the response surface optimisation factors and the conical funnel height was fixed at 15 cm.

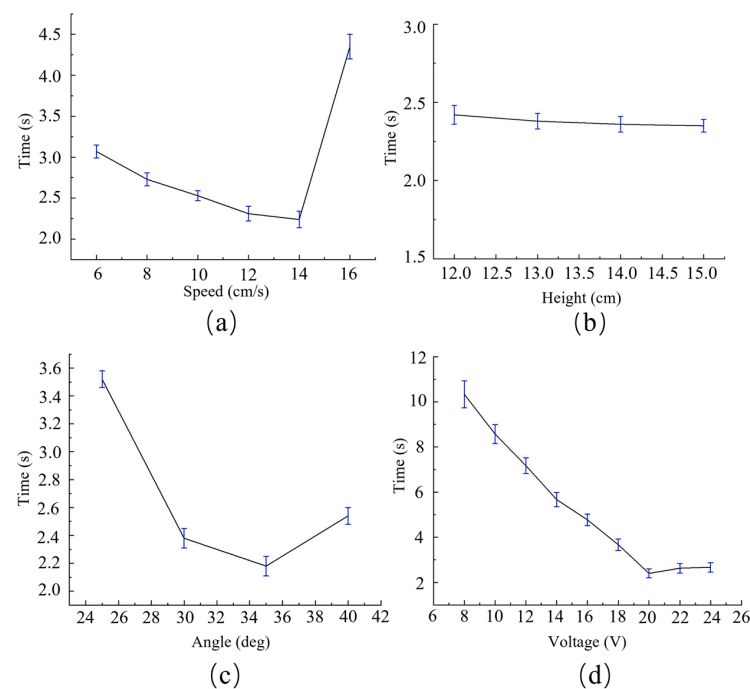


Figure 12. Single-factor test results of the end effector. (a) Effect of electric push rod extension speed on cumulative docking time. (b) Effect of conical funnel height on cumulative docking time. (c) Effect of conical funnel half-cone angle on cumulative docking time. (d) Effect of electromagnet driving voltage on cumulative docking time.

The results of the single-factor test showed that the extension speed of the electric push rod, the half-cone angle of the conical funnel and the driving voltage of the electromagnet obviously affected the cumulative docking time of the end effector. In contrast, the height of the conical funnel had a relatively small effect. Consequently, the extension speed of the electric push rod, the half-cone angle of the conical funnel and the driving voltage of the electromagnet were chosen as the factors to be optimised in the subsequent response surface test, while the height of the conical funnel was fixed at 15 cm. The objective of the parameter optimisation was to minimise the cumulative docking time of the end effector.

3.1.2. Response Surface Optimization Results

Based on the results of the single-factor test, the half-cone angle of the conical funnel, the driving voltage of the electromagnet and the extension speed of the electric push rod were selected as the factors for the response surface optimisation test and denoted as A, B and C, respectively. The cumulative docking time of the end effector (T) was used as the response value and a central composite design test was conducted [22,23]. The factors and levels of the response surface test are shown in Table 2 and the test scheme and results are shown in Table 3.

Table 3. Central composite design test scheme and results.

Test No.	A Angle (°)	B Voltage (V)	C Speed (cm/s)	Cumulative Docking Time of the End Effector (s)
1	27	20	10	2.71
2	30	24	8	2.44
3	43	20	10	2.85
4	35	20	10	2.15
5	40	16	13	2.80
6	40	24	13	2.71
7	30	16	8	2.45
8	35	13	10	2.46
9	30	24	13	2.56
10	35	20	14	2.52
11	35	20	10	2.20
12	35	20	10	2.14
13	30	16	13	2.68
14	40	16	8	2.64
15	40	24	8	2.56
16	35	27	10	2.43
17	35	20	10	2.11
18	35	20	10	2.17
19	35	20	10	2.13
20	35	20	6	2.48

Quadratic polynomial regression analysis was performed on the test results using Design-Expert 13 software, and the regression model for the cumulative docking time of the end effector was obtained as follows:

$$T_e = 12.34533 - 0.506931A - 0.103623B + 0.050510C - 0.000568AB - 0.000994AC - 0.010480BC + 0.007715A^2 + 0.004974B^2 + 0.006483C^2$$

where T is the cumulative docking time of the end effector, s; A is the half-cone angle of the conical funnel, °; B is the driving voltage of the electromagnet, V; and C is the extension speed of the electric push rod, cm/s.

An analysis of variance was performed on the regression model. The overall model was highly significant ($p < 0.0001$), and the lack-of-fit term was not significant ($p = 0.0989$),

indicating that the model fitted the experimental data well. The values of R^2 , adjusted R^2 , and CV were 0.9613, 0.9264, and 2.76%, respectively, suggesting that the established quadratic regression model had good fitting accuracy and could be used to describe the relationship between the half-cone angle of the conical funnel, the driving voltage of the electromagnet, the extension speed of the electric push rod, and the cumulative docking time of the end effector. The significance analysis showed that A, B, C, BC, A^2 , and B^2 were significant terms, whereas AB, AC, and C^2 were not significant.

It should be noted that this quadratic polynomial model is an empirical response-surface fitting model established based on the central composite design. It was mainly used to predict the cumulative docking time of the end effector under different parameter combinations and to optimize the parameter combination, rather than to represent a strict physical mechanism of the docking process. The interaction terms were used to describe the combined effects of different factors on the response value, and the quadratic terms were used to describe the nonlinear variation in the response with individual factors. Although AB, AC, and C^2 were not statistically significant, the full quadratic model was retained to maintain the completeness of the response-surface model and the consistency of parameter optimization. The results of the response surface analysis are shown in Figure 13. Figure 13a shows that the half-cone angle of the conical funnel and the driving voltage of the electromagnet jointly affect the cumulative docking time of the end effector. When the half-cone angle was at a medium level and the driving voltage was relatively high, the docking time was shorter. Figure 13b shows that there was an interaction between the half-cone angle of the conical funnel and the extension speed of the electric push rod. An excessively low extension speed increases the forward extension time, whereas an excessively high extension speed increases the guiding impact, resulting in an increase in cumulative docking time. Figure 13c shows that the driving voltage of the electromagnet and the extension speed of the electric push rod obviously affect the cumulative docking time. A higher voltage was beneficial for forming stable attraction, while a moderate extension speed helped to shorten the docking process. Overall, the cumulative docking time was smaller in the middle region of the parameter space and increased near the boundary region. This indicates that end-effector docking performance is affected by the guiding angle, attraction capability and motion speed. Therefore, comprehensive optimisation through the response surface model was required.

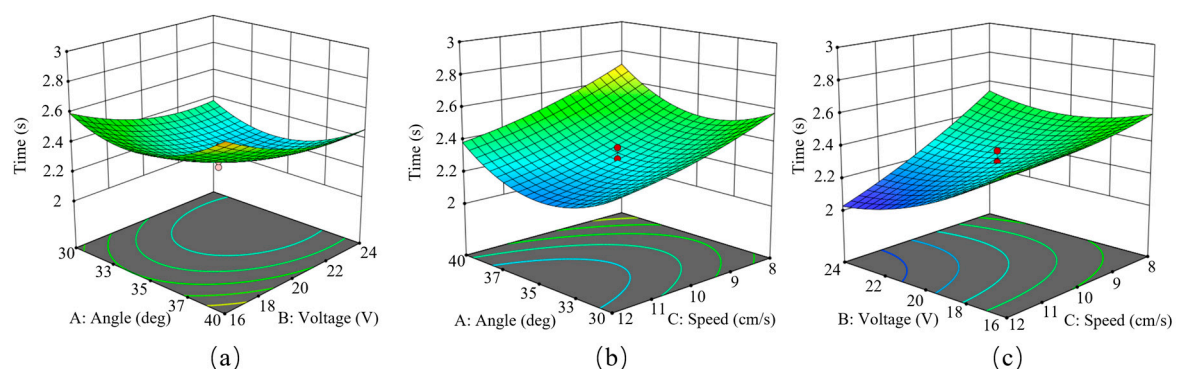


Figure 13. Response surface analysis results for the cumulative docking time of the end effector. (a) Interaction effect of conical funnel half-cone angle and electromagnet driving voltage. (b) Interaction effect of conical funnel half-cone angle and electric push rod extension speed. (c) Interaction effect of electromagnet driving voltage and electric push rod extension speed.

To minimise the cumulative docking time of the end effector, parameter optimisation was performed using a response surface model. The predicted cumulative docking time of the end effector was 2.051 s when the half-cone angle of the conical funnel was 33.332°, the

driving voltage of the electromagnet was 23.407 V and the extension speed of the electric push rod was 12.329 cm/s. This parameter combination could shorten the cumulative docking time while ensuring stable end-effector docking and could be used as the basis for setting the parameters for the end effector in subsequent field collaborative docking tests.

3.2. Robotic Arm Positioning Accuracy Test Results

The test involved setting typical target conditions, including horizontal extensions of 80 and 100 cm, vertical extensions of 50 and 100 cm, and base rotations of 60° and 90°. Each condition was repeated three times. Once the robotic arm had completed the control action, the system feedback value and the externally measured value were recorded and the corresponding errors were calculated. The experimental data are shown in Table 4.

Table 4. Position control accuracy test data of the robotic arm.

Test Condition	Group	Target Value (cm or °)	System Feedback Value (cm or °)	Actual Measured Value (cm or °)	Feedback Error (cm or °)	Measured Error (cm or °)
Horizontal extension	1	80	78.0	77.8	−2.0	−2.2
	2	80	77.9	77.7	−2.1	−2.3
	3	80	78.1	77.7	−1.9	−2.3
	1	100	97.6	97.4	−2.4	−2.6
	2	100	97.5	97.2	−2.5	−2.8
	3	100	97.7	97.1	−2.3	−2.9
Vertical extension	1	50	48.7	48.4	−1.3	−1.6
	2	50	48.2	48.0	−1.8	−2.0
	3	50	48.5	47.5	−1.5	−2.5
	1	100	94.6	94.8	−5.4	−5.2
	2	100	94.7	94.5	−5.3	−5.5
	3	100	94.5	94.1	−5.5	−5.9
Base rotation	1	60	59.4	59.2	−0.6	−0.8
	2	60	59.5	59.5	−0.5	−0.5
	3	60	59.3	59.3	−0.7	−0.7
	1	90	89.4	89.2	−0.6	−0.8
	2	90	89.5	89.4	−0.5	−0.6
	3	90	89.3	89.1	−0.7	−0.9

Based on the data, the average system feedback value, average actual measured value, and errors under each condition were statistically analyzed. The results are shown in Table 5.

Table 5. Statistical results of position control errors of the robotic arm.

Test Condition	Target Value (cm or °)	Average System Feedback Value (cm or °)	Average Actual Measured Value (cm or °)	Average Absolute Feedback Error (cm or °)	Average Absolute Measured Error (cm or °)	Average Difference Between Feedback and Measured Values (cm or °)
Horizontal extension	80	78.00	77.73	2.00	2.27	0.27
	100	97.60	97.23	2.40	2.77	0.37
Vertical extension	50	48.47	47.97	1.53	2.03	0.50
	100	94.60	94.47	5.40	5.53	0.27
Base rotation	60	59.40	59.33	0.60	0.67	0.07
	90	89.40	89.23	0.60	0.77	0.17

The experimental data showed that the robotic arm had relatively high control accuracy in the horizontal direction and that the fluctuation among repeated tests was small. This indicates that the telescopic mechanism operated stably. As the target extension increased from 80 cm to 100 cm, the error margin increased slightly, but remained within acceptable limits, indicating that the system was adaptable and consistent under different horizontal extension conditions. In the base rotation direction, the target values, feedback values and measured values were very close, suggesting that base rotation exhibited high control accuracy and consistent results in repeated tests.

However, in the vertical extension test, the average absolute feedback errors were 1.53 cm and 5.40 cm, while the average absolute measured errors were 2.03 cm and 5.53 cm respectively. These results suggest that the robotic arm exhibited good control accuracy for small lifting strokes, but errors increased during large-stroke vertical lifting. This was primarily due to the effects of assembly clearance, structural deformation under load and transmission hysteresis on the end position becoming more apparent as the lifting height of the column increased, resulting in under-positioning to a certain degree under the large-stroke condition. To address this issue, a height compensation coefficient could be incorporated into the vertical target value during the control process. The compensated target lifting height is denoted as L'_t , which can be expressed as follows:

$$L'_t = k_h L_t$$

where L_t is the original target lifting height, m; k_h is the height compensation coefficient; and L'_t is the compensated target lifting height.

According to the test results, the actual error of the robotic arm under the 100 cm lifting condition was approximately 5 cm, with an average measured error of 5.53 cm. Although this error was relatively large, it was still acceptable for the proposed docking system because the robotic arm performs coarse positioning and large-range spatial compensation rather than rigid, precise insertion. The final connection is achieved through the conical guiding structure and flexible compensation mechanism of the end effector. Therefore, as long as the end effector enters the capture region of the receiving interface, the residual vertical error can be absorbed during the guided docking stage. To further reduce the under-positioning error under large-stroke lifting conditions, the height compensation coefficient k_h was set to 1.05 and applied in the subsequent field collaborative docking test. This coefficient is an empirical correction factor obtained from the robotic arm positioning accuracy test and can be further optimized through additional tests under different operating conditions. The field collaborative docking test also verified that, after applying this compensation, the remaining positioning error did not prevent successful docking under the tested conditions. To further evaluate the positioning repeatability of the robotic arm under the actual segmented docking process, an end-effector repeated positioning test was conducted. In this test, the robotic arm was controlled according to the lifting–rotation–extension sequence used in the docking process. The lifting height was set to 100 cm, the horizontal extension was set to 100 cm, and the base rotation angle was set to 90°. The results showed that the repeated positioning accuracy of the end effector was 2.6 cm after completing the segmented positioning process. This indicates that, under the actual segmented control strategy, the robotic arm could provide stable repeated positioning performance for the end effector to enter the capture region of the guiding interface. However, the complete three-dimensional position and orientation error distribution under more complex motion conditions was not independently quantified in this study and will be further investigated in future work.

3.3. Field Collaborative Docking Verification Results

Vehicle spacing was set at 25, 45, 65, 85, 105 and 125 cm. Each condition was repeated ten times. The number of successful dockings, the success rate and the average docking time were recorded, and the results are shown in Table 6.

Table 6. Field collaborative docking test results.

Condition	Set Vehicle Spacing/cm	Number of Tests	Number of Successful Dockings	Success Rate/%	Average Docking Time/s
1	25	10	8	80	38.93
2	45	10	9	90	41.78
3	65	10	10	100	44.10
4	85	10	10	100	46.21
5	105	10	10	100	47.89
6	125	10	9	90	50.27

Within the set vehicle spacing range of 25–125 cm, the autonomous docking device was able to complete the entire process, including the approach of the unmanned replenishment vehicle, the positioning of the robotic arm, the guided docking using the end-effector, and confirmation of the docking state. A total of 60 tests were conducted, 56 of which were successful, giving an overall success rate of 93.33%. Based on the Wilson score interval for binomial proportions, the 95% confidence interval of the overall docking success rate was approximately 84.1–97.4%. Since only 10 repeated tests were conducted for each individual spacing condition, the success rate under each spacing condition was mainly used to reflect the variation trend under different vehicle spacings. When the vehicle spacing was 65, 85 or 105 cm, all ten tests under each condition were successfully completed. These results suggest that the proposed collaborative docking device exhibits good operational stability within the medium vehicle spacing range. Docking failures at 25 cm and 45 cm were mainly due to insufficient operating space at short distances. When the vehicle spacing was small, the adjustment margins for the robotic arm's lifting, rotation and extension were limited and the end-effector was more easily affected by initial parking deviation when entering the guiding structure. The docking failure at 125 cm was primarily due to the discrepancy between the set parking distance of the automatic navigation chassis and the actual parking distance. When the actual parking distance exceeded the robotic arm's compensation range, the end effector could not enter the capture region of the target interface. Therefore, factors affecting the field docking success rate include chassis parking accuracy, the workspace boundary of the robotic arm, and the limited adjustment space at short distances.

In terms of docking time, an overall upward trend was observed as the set vehicle spacing increased from 25 cm to 125 cm, with the average docking time rising from 38.93 s to 50.27 s. This was primarily due to the increased horizontal extension distance and attitude adjustment of the robotic arm with greater vehicle spacing, resulting in a longer positioning process for the robotic arm. While the average docking time was shorter with smaller vehicle spacing, insufficient operating space reduced the docking success rate. Conversely, larger vehicle spacing provided more adjustment space but increased the robotic arm's extension distance and made the process more susceptible to chassis parking errors. Taking into account both the success rate and the docking time, the docking process was found to be most stable within a vehicle spacing range of 65–105 cm. This range ensured a high success rate while maintaining good operational efficiency. Although no direct comparison with manual or semi-automatic replenishment was conducted in this study, the proposed system reduced the need for direct operator involvement in interface

alignment and connection operations. This is beneficial for reducing pesticide exposure risk and improving the continuity of unmanned field operations.

4. Conclusions

- (1) In order to address the issues of manual dependence, low replenishment efficiency and inadequate continuity of unmanned operation during the replenishment of pesticides for large sprayers in field operations, an autonomous docking device for an unmanned replenishment vehicle was designed. This device consists primarily of a robotic arm docking system, an end effector, a docking control system and a pesticide delivery system. It enables an autonomous approach, robotic arm positioning, end-effector-guided connection and pesticide replenishment between the unmanned replenishment vehicle and the large sprayer's filling port.
- (2) According to the replenishment requirements, including the height of the filling port, the width of the machine, and the operating distance between the two vehicles, a dedicated robotic arm was designed. A geometric model was established to analyse the end-effector position and the workspace of the robotic arm was analysed using the Monte Carlo method. The results showed that the robotic arm's workspace could cover the target filling port region and meet the docking requirements of the high-position filling port at different operating distances between the unmanned replenishment vehicle and the sprayer.
- (3) An end effector with guiding, flexible compensation and electromagnetic attraction functions was designed and end-effector docking performance and parameter optimisation tests were conducted. The results of these tests showed that the extension speed of the electric push rod, the half-cone angle of the conical funnel and the driving voltage of the electromagnet were the main factors affecting the cumulative docking time of the end effector. An improved parameter combination was obtained using the response surface method. These improved parameters enhanced the efficiency of end-effector docking and provided a basis for the field collaborative docking test.
- (4) Robotic arm positioning accuracy tests and field collaborative docking tests were conducted to evaluate the actual docking performance of the autonomous docking device. The robotic arm positioning accuracy test showed that the average measured error under the 100 cm vertical lifting condition was 5.53 cm, and the base rotation angle error was approximately $\pm 0.9^\circ$, corresponding to an end-position error of approximately ± 5 cm. These errors could be further absorbed by the conical guiding structure and flexible compensation mechanism of the end effector. The field collaborative docking test showed that, under a vehicle spacing range of 25–125 cm, 56 out of 60 docking tests were successful, with an overall success rate of 93.33%. Within the vehicle spacing range of 65–105 cm, the docking success rate reached 100%, and the average docking time was 44.10–47.89 s. These results indicate that the proposed device has good field applicability within the medium vehicle-spacing range.
- (5) The tests in this study were mainly conducted on relatively flat field roads and under fixed filling-port conditions. The effects of uneven ground, large vehicle attitude variations, wind disturbance, and different parking errors were not fully evaluated. Future work will further investigate the robustness of the docking process under more complex field conditions. In addition, visual perception or pose feedback will be incorporated to improve target localization, active correction, and end-effector docking robustness, thereby further improving the stability and operational efficiency of the autonomous docking process.

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