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Design and experiments of an automatic pipe winding machine

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Abstract

To solve the time-consuming and laborious problem of manual winding and unwinding water pipes by field workers during irrigation or pesticide spraying in agricultural production, an automatic pipe winding machine for winding and unwinding water pipes was designed. The guiding mechanism, pipe winding mechanism, and pipe arrangement mechanism of the pipe winding machine are designed, and the automatic deviation correction control method of pipe arrangement based on PID and the constant tension control method of pipe winding and unwinding is put forward, and the control system of the automatic pipe winding machine is developed. By making a prototype of an automatic pipe winding machine, the effects of pipe winding and unwinding and the constant tension control of the automatic winding machine are tested and analyzed. The test results show that under the condition of 4.0 km/h speed, the maximum angle error of the automatic pipe winding machine is 3.32°, the average absolute error is 0.95°, and the water pipes are arranged neatly and tightly. The maximum relative error of the water pipe tension is 9.3%, and the maximum relative error under the 0~4.0 km/h velocity step variable condition is 16.3%. The speed of the pipe winding and unwinding can adapt to the change of the vehicle's speed automatically, and the tension of the pipe is within a reasonable range. The performance of the pipe arrangement and pipe coiling of the automatic pipe winding machine can meet the operating requirements.

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Introduction

Carbon emissions caused by various energy and material inputs in agricultural production account for about 20% to 35% of global carbon emissions (Fan *et al*., 2020). Carbon emissions caused by the development and utilization of water resources are an important part of agricultural carbon emissions (Zou *et al*., 2013). China is the second largest irrigated agricultural country in the world, agricultural irrigation water consumption accounts for about 65% of the country's total water consumption. The main modes of agricultural irrigation are traditional flood irrigation, sprinkler irrigation, drip irrigation, and rain farming (Cuello *et al*., 2019). There are significant differences in agricultural water consumption and carbon emission intensity under different irrigation modes. Sprinkler irrigation is a comprehensive irrigation method that uses special equipment to transport pressurized water to irrigated land for uniform spraying. Compared with the traditional flood irrigation model, the total water consumption of winter wheat during the growth period under the sprinkler irrigation model is reduced by 41.64% (Ye *et al*., 2019).

Typical mechanized water-saving irrigation equipment at home and abroad are center-pivot irrigator, lateral-moving irrigators, rolling irrigators, hose reel irrigators, and other large and medium-sized mobile irrigation machines. The hose reel irrigator has the advantages of strong adaptability, good mobility, high level of automation, long service life, and low overall investment, which is mechanized and efficient irrigation equipment that can adapt to large, medium, and small plots and different crops (Yuan *et al*., 2015; Ge *et al*., 2020).

Related work

In the 1960s, hose reel irrigators began to be studied in Europe. By the late 1970s, it had been finalized and mass-produced, with more than 120 models. For example, the PLLSMPl80/400 hose reel irrigator produced by CASELLA, Italy, has a water pipe with an outer diameter of 180 m, a length of 400 m, and a flow rate is 240 m^3/h. The reel is driven by a hydraulic motor, and the power of the hydraulic system is provided by a diesel engine. After nearly 50 years of development, Italy has become a gathering place for global manufacturers of hose reel irrigators. At present, the total annual output of hose reel irrigators in Italy has reached 6000 to 7000, with a holding volume of about 150,000, covering dozens of series of hose reel irrigators, which are suitable for agriculture, forestry, urban gardens, and many other fields (Sui *et al*., 2017; Yan *et al*., 2020).

The development of hose reel irrigators in China began in the late 1970s. The first hose reel irrigator named JP90/300 in China was successfully manufactured in 1979, and then JP75/200 hose reel irrigator was developed in 1984. In the late 1990s, the hose reel irrigator made by BAUER Company of Austria was imitated, and the mainstream models of domestic hose reel irrigators of JP50, JP75, and JP90 were formed. By the end of 2017, China had more than 80,000 hose reel irrigators, most of which were used in northern and central China. At present, most of the hose reel irrigators in China still follow the product design of foreign countries 30 years ago, and most of the pipe winding machines use reciprocating screws as the pipe arrangement device of hose reel irrigator, which has to match the reciprocating screws with different leads to winding water pipes with different diameters. When the speed of the screw nut pair is too high, the jammed phenomenon occurred easily. Besides, when the hose reel irrigator is working, without adjusting the winding speed, the speed of winding and unwinding pipe will increase with the increase of the number of winding layers, the stability is poor, and the phenomenon of overload is easy to occur (Tang *et al*., 2018).

The automatic pipe winding machine designed in this paper is the automatic pipe winding and unwinding equipment between the water reservoir of the hose reel irrigator and the spray gun, which is suitable for irrigation and pesticide spraying in farmland, sugarcane field, orchard, forest, and other crop planting land. The automatic pipe winding machine adopts a stepper motor to drive the pipe arrangement device to move precisely. Adjusting the control parameters can be suitable for water pipes of different diameters to ensure that the pipes are arranged neatly and tight. In addition, the constant tension control method is used to realize the speed adaptive control and overload protection during the process of pipe winding and unwinding (Wang *et al*., 2012; Yoneyama *et al*., 2014).

Platform design

Overall structure

The overall structure of the automatic pipe winding machine is shown in Figure 1A, which mainly includes a bracket, pipe winding device, pipe arrangement device, the guiding mechanism, water pipe, and control system. The bracket is used to support the guide device, pipe winding device, pipe arrangement device, control device, *etc*., which is the basis of the automatic pipe winding machine. The guiding mechanism allows the water pipe to pass through the entrance of the center of the guiding mechanism from any angle and is led to the pipe arrangement mechanism to ensure the smooth operation of the reel. The pipe winding device is the most important module of the automatic pipe winding machine, which can realize the function of pipe winding and unwind by switching between the positive and negative running directions of the bracket. The pipe arrangement device is an important part of the automatic pipe winding machine, which is driven by the driving motor and moves back and forth in a straight line according to a certain law. The control device can call the corresponding control program to realize the coordinated work between the pipe arrangement device and the pipe winding device, and to ensure that the water pipes are arranged neatly in the process of pipe winding and unwinding. For better use, the automatic pipe winding machine is installed on a cart driven by manpower or power.

The guiding mechanism

The guiding mechanism is composed of four polished rods with rollers distributed in a shape of intersecting parallels, which are installed at the front of the bracket and close to the pipe arrangement device. Each polished rod-drum of the guiding mechanism is composed of two bearings, a middle pass pipe, and a fixed shaft. Adjust the distance between the transverse roller and the longitudinal roller by adjustment nut to adapt to the water pipes of different diameters.

Pipe winding device

The pipe winding device realizes the function of winding and unwinding the pipe, which mainly includes outlet pipe, rotating joint, belt, stepper motor, water inlet pipe, and pipe received bracket, as shown in Figure 1B. The water pipe in the outlet end is connected with the pipeline on the bracket through a rotating joint so that the bracket can rotate at any angle. When winding the pipe, the water pipes are wound around the bracket by layer, starting from the connector at one end of the bracket and winding to the empty side. After each winding is full of one layer, the pipe is automatically wound in the reverse direction along the axis of rotation of the bracket by the pipe arrangement mechanism, and so on. When unwinding the pipe, the stepper motor drives the bracket to reverse, the water pipe can be unwound neatly and smoothly from the drum under the external force. When the water pipe of this layer is unfastened over, the pipe arrangement mechanism moves in the opposite direction and continues to release the next layer of water pipe, and so on, until all the water pipes have been unwound.

The length of the receiving pipe is an important index of the pipe winding device, and the length of the pipe is calculated according to the following formula (Cao, 2021).

$$\begin{cases} L = \frac{\pi H}{d} \sum_{n=1}^{N} (D_0 + nd) \\ \quad N = \frac{D_1 - D_0}{d} \end{cases} \qquad (1)$$

where, L is the calculated length of the water pipe, H=450 mm is the width of the drum, D_1=500 mm is the outer diameter of the drum, D_0=160 mm is the diameter of the inner roller, d is the diameter of the water pipe, and N is the number of layers wound around the full winding bracket. When selecting different pipe diameters according to the national standard, the length of the water pipe accepted by the pipe winding mechanism is shown in Table 1.

Pipe arrangement device

As shown in Figure 1C, the ball screw nut mechanism is used to transform the rotational motion of the stepper motor into rectilinear motion, which can accurately drive the reciprocating movement of the support seat of the pipe arrangement device, and drive the reciprocating movement of the guiding mechanism, guiding wheel and water pipe which are installed on pipe arrangement device. A grooved guide pulley and resistance wheel are installed on the support seat. Adjusting the nut of the resistance wheel can change the rotating resistance moment of the guide wheel, to increase the tension force of the water pipe between the bracket and the pipe arrangement mechanism, avoiding the disordered arrangement due to the relaxation of the water pipe. The resistance wheel is installed under the pull pressure sensor. When the water pipe is pulled, the resistance wheel will be subjected to upward force, and the pulling

Table 1. The length of the water pipe accepted by the winding mechanism.

Outer diameter of water pipe, d/mm	Length, L/m
14.0	811.0
17.0	562.0
22.0	324.0
25.0	246.0

force value of the water pipe can be calculated by reading the signal of the pull pressure sensor. To adjust the resisting moment of the resistance wheel, it adopts the structure shown in Figure 1D. A spring and a friction plate are arranged between the resistance wheel and the nut. Rotating the nut clockwise can make the nut close to the resistance wheel, which increases the spring deformation and increases the friction torque between the friction plate and the resistance wheel and gasket (Wang *et al*., 2017).

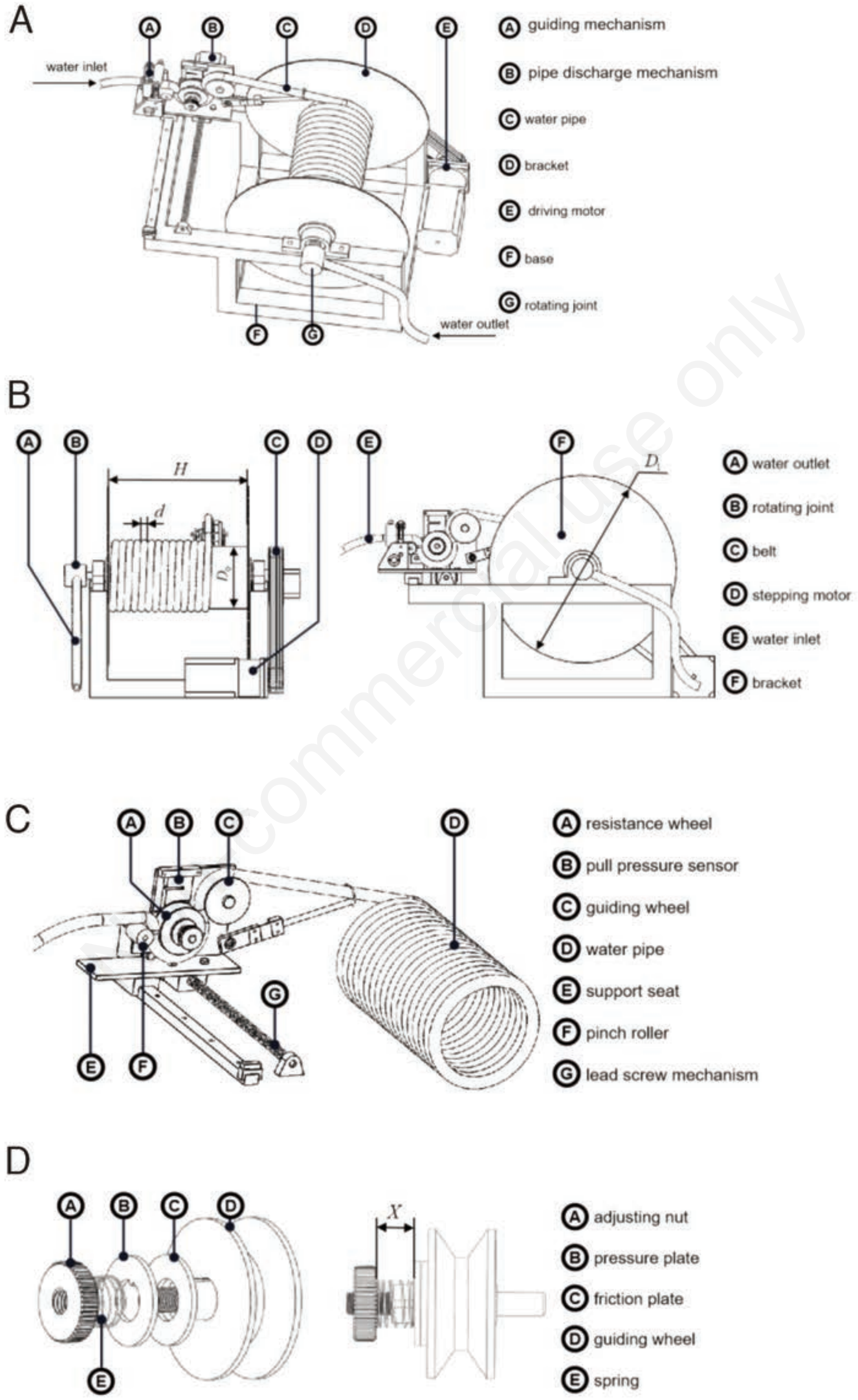


Figure 1. The explanation of each panel is as follows: **A**) mechanical structure schematic of automatic pipe winding machine; **B**) schematic diagram of pipe winding device; **C**) schematic diagram of pipe arrangement device; **D**) schematic diagram of resistance wheel.

Control system

Guideway displacement control

Figure 2A shows a schematic diagram of the movement relations of the pipe arrangement. The lead of the wire is T, the speed of the bracket is ω_1, the speed of the motor of pipe arrangement is ω_2, the diameter of the water pipe is D, and the cut-in angle of the water pipe is θ. To make the pipe in the bracket row tight and flat (without clearance and dislocation), the linear speed of winding to each layer satisfies the following formula (Tao *et al*., 2010):

$$\begin{cases} \frac{\omega_1}{\omega_2} = \frac{T}{d} \\ \theta = 0 \end{cases} \tag{2}$$

In the pipe winding machine, the pipe is deformed under the effect of bending, pulling and supporting, so that the transverse diameter of the pipe is larger than that in the natural state, and the diameter varies with the bending radius and tensile force. Therefore, it is difficult to obtain a neat and tight effect by directly using Eq. (2) to control the pipe arrangement. To improve the control accuracy of pipe arrangement, a control algorithm based on incremental PID is designed. The control model is shown in Figure 2B. In the pipe arrangement control, the control system first collects the angle signal fed back by the angular deviation sensor and compares the actual position with the target position of the pipe arrangement, then calculates the error ek between them. Combined with the target speed of the pipe arrangement control, the PID controller corrects the system error and inputs the corresponding control quantity to the stepper motor of pipe arrangement (Xie *et al*., 2012; Drexler *et al*., 2017).

The principle of pipe position correction control algorithm based on incremental PID is to use a discrete difference equation instead of the continuous differential equation, and its discrete PID control equation (Li *et al*., 2015) is as follows.

$$\mu(m) = K_p \cdot e_k + K_i \sum_1^m e_k + K_d \cdot (e_k - e_{k-1}) \tag{3}$$

where, $\mu(m)$ is the m-th control output, e_k is the error between the k-th target value and the actual value, e_{k-1} is the error between the k–1 target value and the actual value, K_p is the coefficient of proportional control link, K_i is the coefficient of integral control link, K_d is the coefficient of differential control link.

The optimal PID parameter combination is obtained by tuning the parameters, and the control algorithm output of the m-th and m^{-1} th is calculated by Eq. (3), and the difference between the two outputs is carried out to get the control incremental output.

Speed control of winding and unwinding pipes

The schematic diagram of the pipe winding and unwinding of the pipe winding machine is shown in Figure 3. The pipe winding machine is placed on the mobile device, to ensure that the speed of the pipe winding and unwinding can be synchronized with the

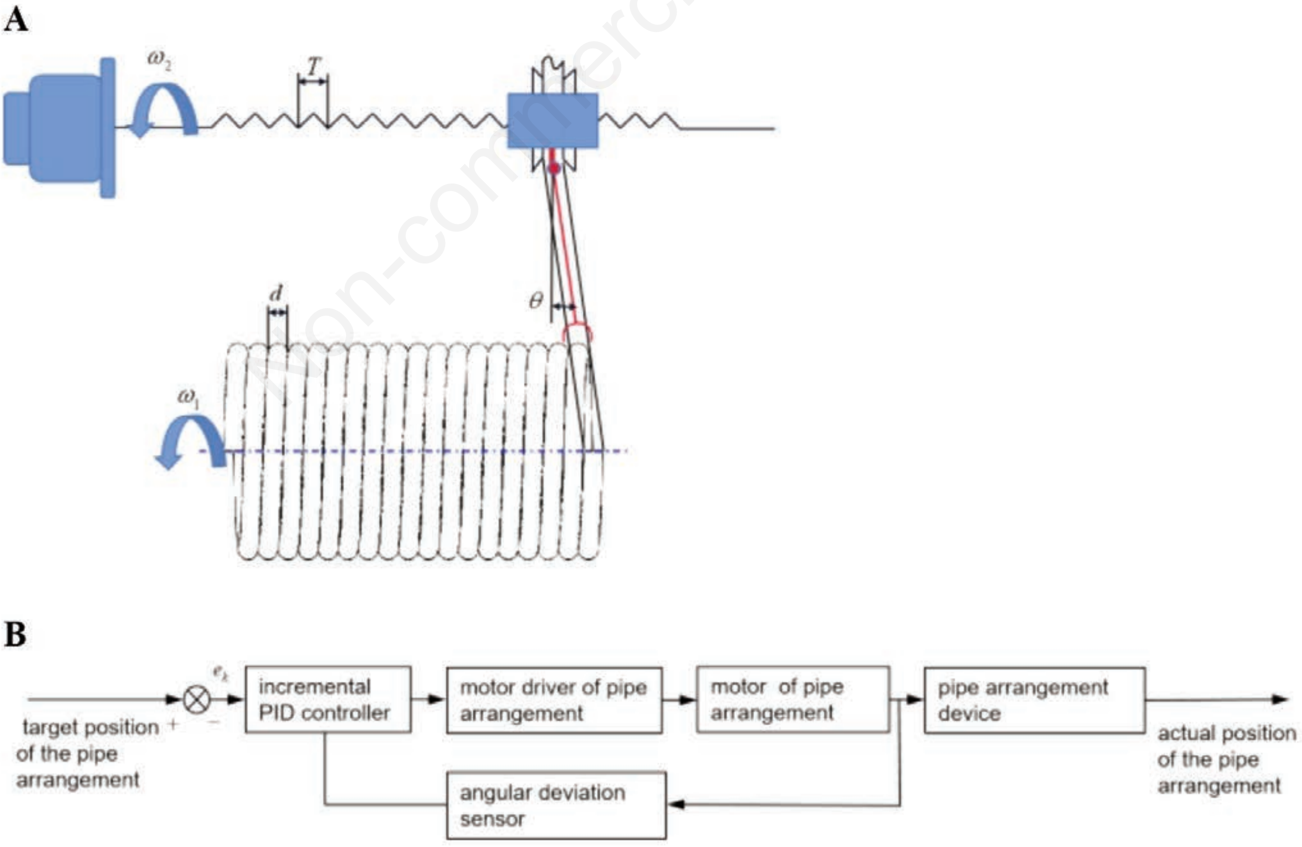


Figure 2. A) Schematic of the movement relations of the pipe arrangement; **B**) schematic diagram of PID deviation correction control for pipe arrangement.

speed of the base, thus the speeds of them must be equal. According to the relationship between the linear velocity of winding and unwinding pipe and the rotate speed of the bracket, the following formula can be obtained easily.

$$\begin{cases} v = R\omega_1 \\ R = D_0 nd \end{cases} \tag{4}$$

where, v is the speed of winding and unwinding pipe, R is the bending radius of the outermost water pipe in the bracket, ω_1 is the rotational speed of the bracket, D_0 is the inner diameter of the bracket, n represents the layer count of water pipes and d is the diameter of water pipe.

It is difficult to keep the speed constant when working in the field, and the diameter R of the reel drum varies with the layer counts of water pipes, so it is also difficult to accurately calculate the value of ω_1, to realize the goal of synchronizing the speed of the pipe winding and the vehicle. Therefore, the control of pipe winding and unwinding adopts the method of constant tension (Valenzuela *et al*., 2006; Xu *et al*., 2018). According to Hooke's law:

$$F = \frac{AE}{L}\int_0^t (V - v)dt \tag{5}$$

where, F is the tension of the roll material, A is the cross-sectional area of the packaging material, E is the elastic modulus of the material, t is the running time of the material, V is the speed of the cart v is the speed of winding and unwinding pipe, and L is the protruding length of the water pipe.

Eq. (5) shows that the tension of the roll material in the winding process is caused by the difference between the driving speed of the cart and the speed of the pipe winding and unwinding. To control the tension at a certain value, it is necessary to control the speed of the pipe winding and unwinding. It can be seen that the winding tension of the water pipe is related to its elastic modulus, the rotation speed of the bracket, the winding radius, and the speed of the cart. Figure 4 is a schematic diagram of PID control of the constant tension of the pipe winding device. To realize constant tension winding, the control system needs to collect the force signal fed back by the tension sensor, compare the actual value of tension with the target value, and calculate the error e_k between them. Then, the PID controller corrects the system error, inputs the corresponding control quantity to the pipe winding motor, and adjusts the rotation speed of the bracket in real-time (Li *et al*., 2015).

Composition and control flow of control system

The structure block diagram of the control system of the pipe winding machine is shown in Figure 5. The control system includes NI myRIO-1900 measurement and control instrument, the motor driver for pipe arrangement, stepper motor for powering pipe arrangement, the motor driver for winding pipe, stepper motor for powering the pipe wound, a deflection detection module, water pipe tension sensor, limit sensor, and man-machine interaction module. Among them, the deflection detection module is BF350-3EB (made in China), the sensitivity coefficient is 2.0 mV, and the range of output analog voltage is DC 0~5V. The tension sensor is TJL-1-50 (made in China), the measuring range is 50 kg, and the accuracy is 0.03% F·S.

The flow chart of the control system is shown in Figure 6. After the system starts, the main control module initializes the program parameters, communicates with the human-computer interaction module, reads the initial control instructions, and obtains the values of each control parameter through the corresponding protocol analysis. The main control module calculates the theoretical rotational speed of the motor for the winding pipe at this time and converts it into the pulse frequency value and direction signal level which control the operation of the stepper motor, to control the winding or unwinding of the pipe. The main control module detects the tension of the water pipe through the tension detection module and compares it with the set target value. The main control module calls the incremental PID algorithm to adjust the speed of the winding and unwinding pipe and enters the next cycle until the tension reaches the target setting value. At the same time, the main control module calculates the theoretical rotation speed and direction of the pipe arrangement motor combined with the speed of the motor for winding pipe and converts it into the impulse frequency value and direction signal level which control the operation of the stepper motor, to control the operation of the stepper motor to drive the left and right translation of the pipe arrangement device. Besides, the main control module obtains the deviation value of the pipe arrangement position through the deflection detection module, calls the incremental PID deviation correction algorithm to adjust the position of the pipe arrangement device, and enters the next cycle until the deviation is 0.

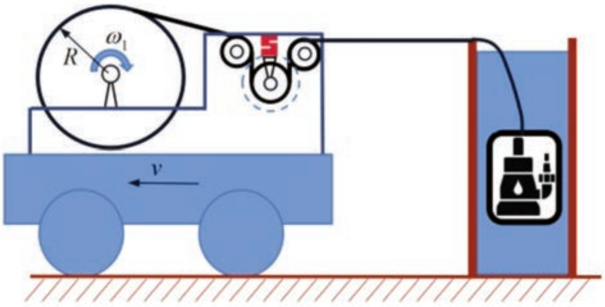


Figure 3. Schematic diagram of winding and unwinding pipe.

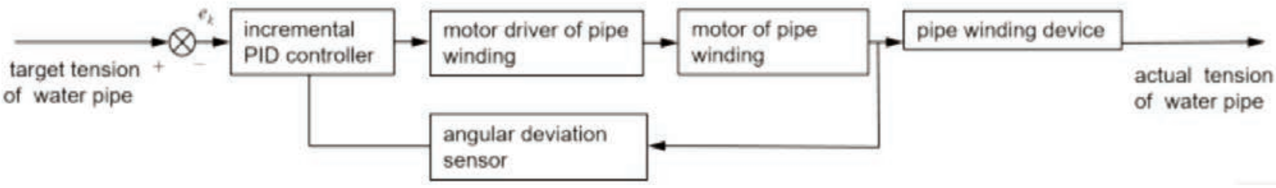


Figure 4. Schematic diagrams of PID control of constant tension of the pipe winding device.

Experiments

To verify the actual operating performance of the automatic pipe winding machine, we first introduced the hardware and software configuration, then we made a prototype machine. Carrying out the automatic pipe arrangement experiments and constant tension control experiments in the planting area validate the effects of pipe winding and unwinding.

Experimental equipment

The automatic pipe winding machine test platform is shown in Figure 7, which includes the prototype body, carrier, NI myRIO-1900 measurement, and control instrument, computer. The NI myRIO-1900 measuring and controlling instrument collects the data measured by the deflection detection module and the tension detection module and controls the pipe arrangement and pipe winding and unwinding after calculation. At the same time, the NI myRIO-1900 measuring and controlling instrument also can transmit the measured tension data and the rotation speed data of the bracket to the upper computer and analyze and record the test data through the Lab-view program of the upper computer (Yu *et al.*, 2014). The automatic pipe winding machine can walk in the field with tractors, trolleys, and electric vehicles as carriers. To analyze the performance of the automatic pipe winding machine more accurately and obtain the test data, the electric crawler chassis carrier is used for the test.

The crawler chassis is driven by a servo motor, and the precise speed control and acceleration and deceleration control can be realized by the controller, and its parameters are shown in Table 2.

Experimental condition

The experiment purpose of the automatic pipe winding machine is to test the performance and effect of winding or unwinding pipe, including the speed range of pipe winding and unwinding, the effect of pipe arrangement, and the control performance of constant tension under different working conditions. To obtain the real test results, the test site is selected in the agricultural planting base of Guangxi University in Nanning City, Guangxi Zhuang Autonomous Region. The experimental plot is trapezoidal, the long side is 165 m, the short side is 165 m, the terrain is gentle, and the plant in the experimental plot is longan. The PE water pipe is used in the experiment, the diameter of the pipe includes Ø14 mm and Ø25 mm, both of which are 200 m in length. The automatic pipe arrangement test and constant tension control test are carried out. Referring to the relevant China's national standards (GB/T 21400.1, GB/T 25405, and GB 10395.18; National standard of the People's Republic of China, 2008, 2010a, 2010b) of sprinkler irrigation machines, the velocity of the chassis is set to 2.0 km/h at low speed and 4.0 km/h at high speed.

Table 2. The length of the water pipe accepted by the winding mechanism.

Parameter	Value
Size (length×width×height)	960×580×420 mm
Velocity range	0~6 km/h
Cruising ability	20 km
Carrying capacity	80 kg
Weight	102 kg

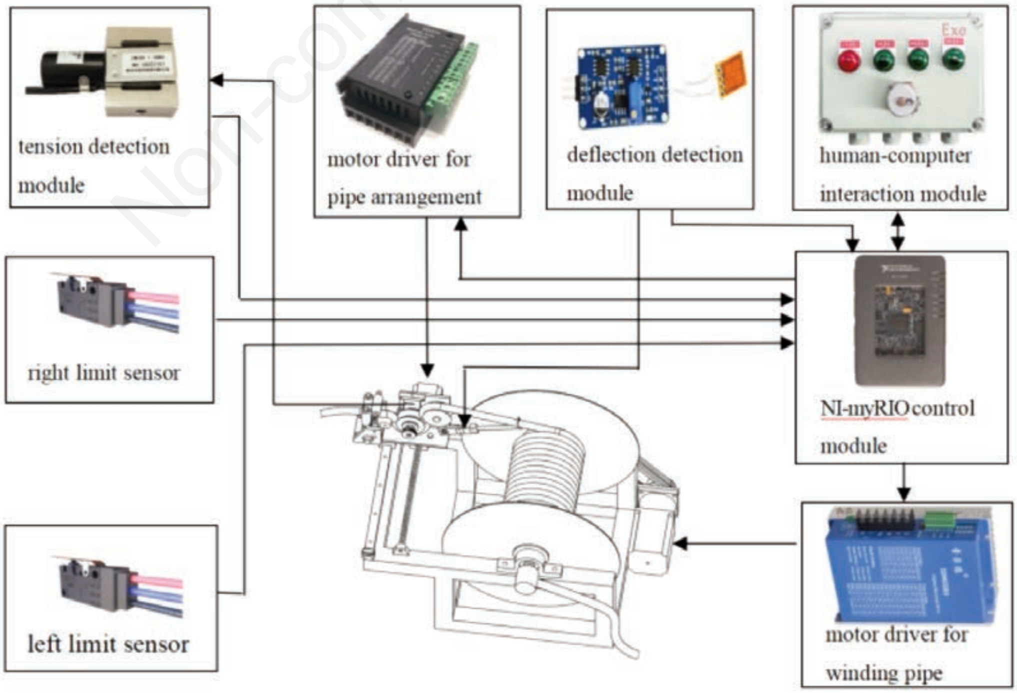


Figure 5. Schematic diagram of control system composition.

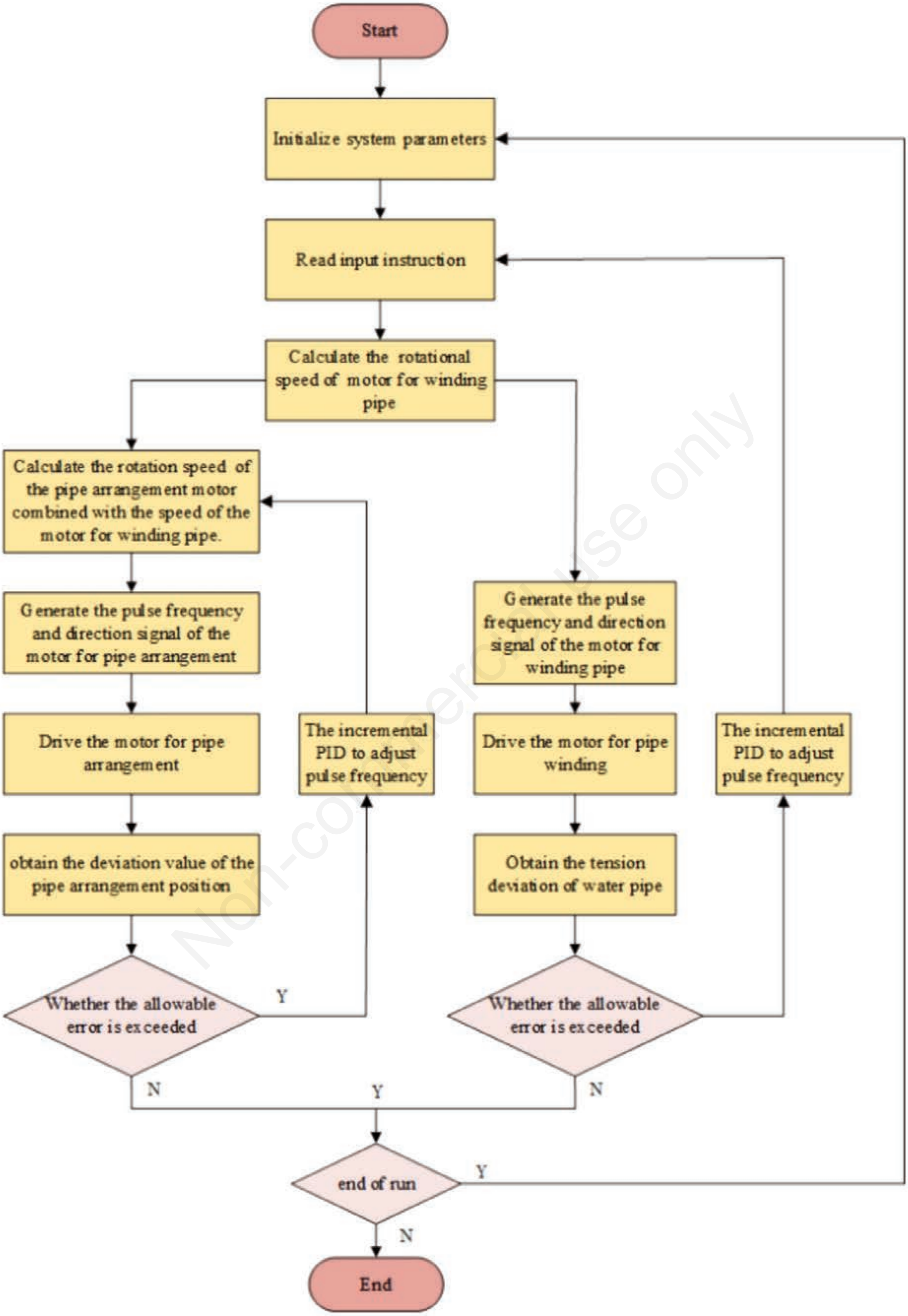


Figure 6. Schematic diagram of control flow.

Analysis of experimental results of automatic pipe arrangement

Taking the complete emptying of the water pipe as the initial state, the experiment was carried out according to the mode of unwinding the pipe first and then winding it. Control the speed of the cart at a constant predetermined speed and observe and record the uniformity and stationarity of the water pipes in the process of winding or unwinding. After the reel is full of one layer, it automatically accumulates into the next layer of winding, or after the pipe is reduced by one layer, it automatically decreases to the next layer, and continues to observe and record. Repeat the above experiments according to different speeds.

The dynamic deviation correction test results of automatic pipe arrangement are shown in Figure 8. The diameter of the pipe used in the test is Ø14 mm. Figure 8A shows the result of automatic pipe arrangement control under the condition of 2.0 km/h speed. The maximum angle error of pipe arrangement is 3.78°, the average absolute error is 0.91°. Figure 8B shows the deviation correction control result of automatic pipe arrangement under the condition of 4.0 km/h speed. The maximum angle error of pipe arrangement is

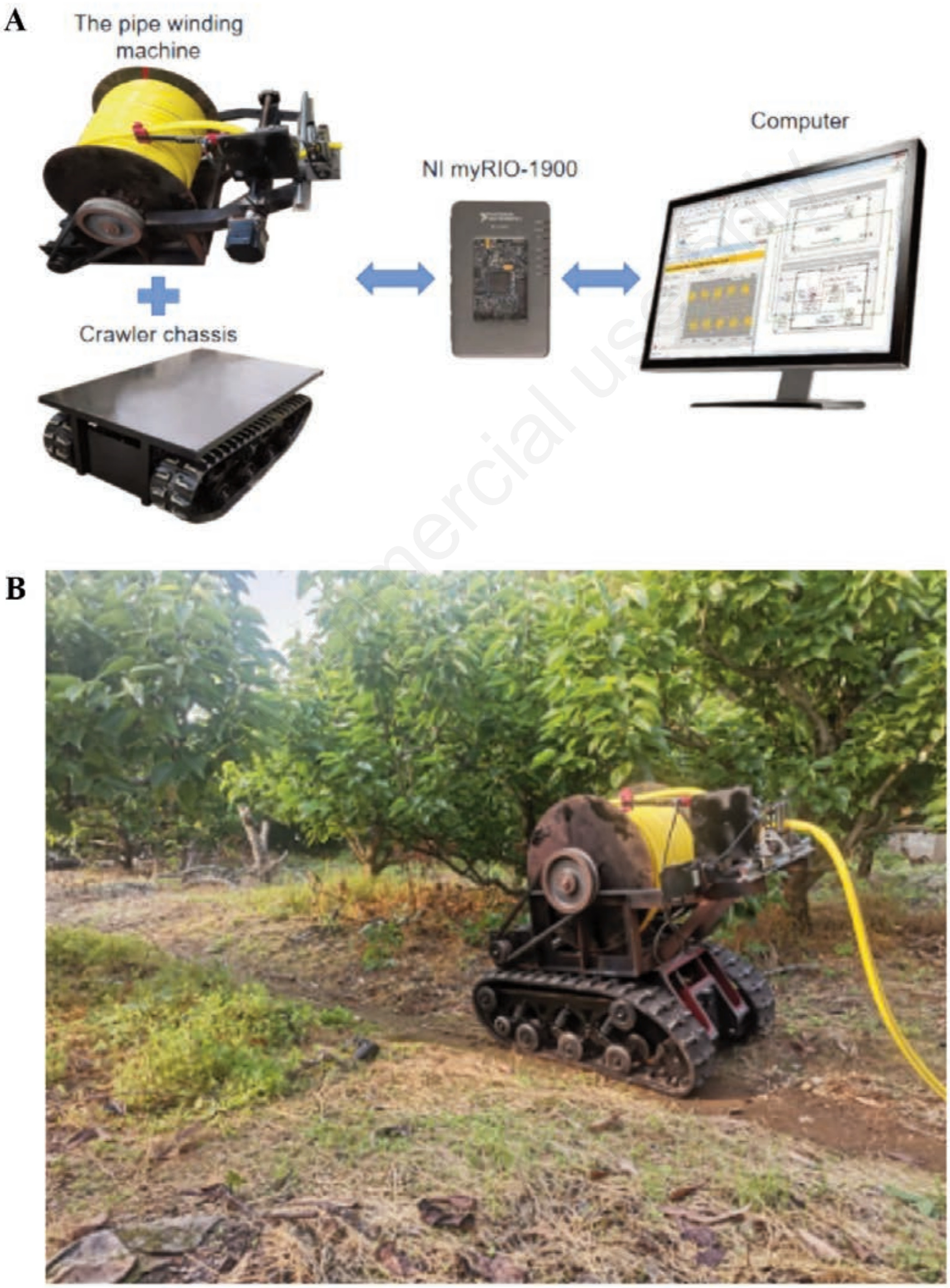


Figure 7. A) Test system of automatic tube winding machine; **B**) test site.

3.32°, the average absolute error is 0.95°. Under the different speed conditions, the automatic deviation correction method based on PID can ensure that the error of pipe arrangement can be controlled in a small range.

The pipe arrangement effect diagram of two different pipe diameters is shown in Figure 9. Compared with the effect pictures, it can be concluded that the automatic pipe winding machine can adapt to the water pipes of different diameters with excellent effect, the water pipes are arranged tightly and neatly, achieving the expected goals and functions.

Analysis of experimental results of constant tension control

The diameter of the water pipe used in the constant tension control test is Ø 14 mm, and the tension of the water pipe is set as 60.0 N, the test conditions include the cart drive at 4.0 km/h constant velocity and the cart under 0~4.0 km/h velocity step variable condition. The field test results of winding and unwinding pipes are shown in Figure 10. Figure 10A is the test result of 4.0 km/h constant speed condition. During the experiment, the car traveled in the field at a constant speed of 4.0 km/h under the control of the

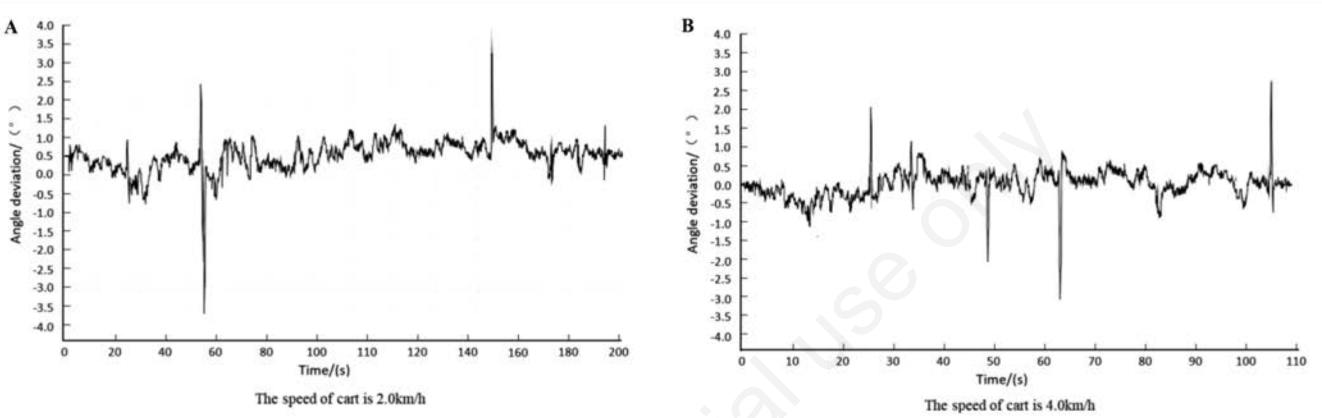


Figure 8. Deviation correction results from automatic pipe arrangement at different speed of cart: **A**) 2.0 km/h; **B**) 4.0 km/h.

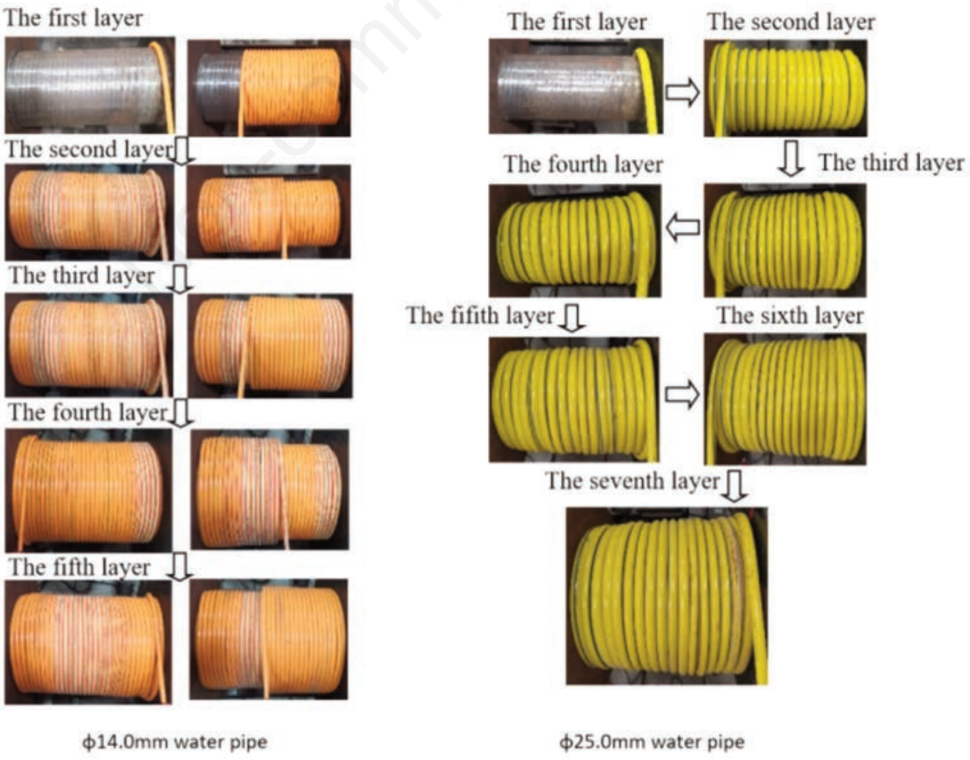
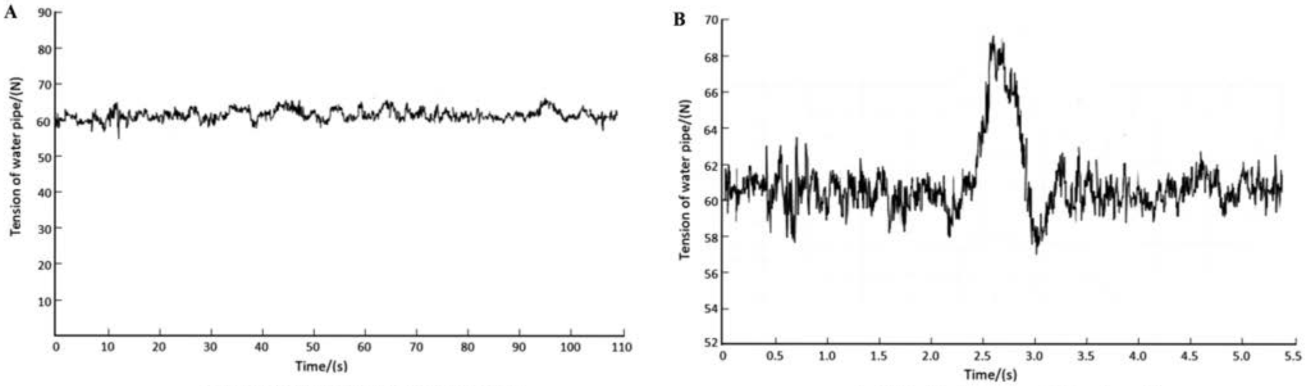


Figure 9. Effect diagram of pipe arrangement.



under the 4.0km/h constant velocity work condition.

under 0~4.0km/h velocity step variable work condition

Figure 10. Field test results of winding and unwinding pipe, at different velocity conditions (**A, B**).

operator, the maximum water pipe tension is 64.6 N, the maximum relative error is 7.6%, the average tension is 60.9 N, and the average relative error is 0.15%.

Figure 10B is the test result of 0~4.0 km/h velocity staging change condition. In the beginning, the cart remained stationary, and at 2.3 s, the cart began to accelerate rapidly to 4.0 km/h and remained constant until the end of the test. From the tension curve of the pipe, it is known that the tension of the pipe is kept at the present value of 60 N during the period of 0-2.3 s. Starting from the 2.3 s, due to the sudden acceleration of the cart, the water pipe tension increased rapidly, resulting in a maximum tension of 69.8 N at 2.7 s, with a maximum relative error of 16.3%. After the tension monitor detects the increase of tension, it rapidly increases the angular velocity of the pipe bracket, which reduces the water pipe tension and finally stabilizes at the set 60 N.

In the whole experiment, the speed of winding and unwinding pipe can automatically adapt to the change of the cart's speed and the tension range of the water pipe is in a reasonable range, no overload occurred. The pipe winding machine can meet the requirements of automatic winding and unwinding pipe under different working conditions and achieve the preset goal.

Conclusions

The automatic pipe winding machine developed in this paper can complete the pipe winding and unwinding work through the coordinated movement of the pipe winding module and the pipe arrangement module, and the experiments are carried out according to different experimental modes, obtaining the following conclusions:

- The deviation correction method of automatic pipe arrangement based on PID makes the pipe arrangement system can automatically adapt to different diameter water pipes and control the deviation in a small range. Under the condition of 4.0 km/h speed, the maximum angle error of the automatic pipe winding machine is 3.78°, the average absolute error is 0.95°, and the water pipes are arranged neatly.
- By adopting the self-adaptive control method of the speed of winding and unwinding pipe based on tension feedback, the speed of winding and unwinding pipe can automatically adapt to the change of the vehicle speed and ensure that the tension of the water pipe is in a reasonable range. The maximum relative error of water pipe tension under constant speed conditions of 4.0 km/h is 9.3%. The maximum relative error of water pipe tension under the velocity staging change condition of 0~4.0 km/h is 16.3%.
- In addition, the structure of the automatic pipe winding machine is simple and compact, and the always existed time-consuming and laborious problems in the process of manual winding and unwinding water pipes can be solved by using low-cost equipment and realize the automatic control of winding and unwinding the water pipes. This machine is suitable for popularization with strong adaptability and is easy to be manufactured.

'*A kind of automatic tube winding the machine which is easy to disassemble and assemble*' (Patent No.: ZL201611004723.4), which developed in this research has obtained the China invention patent.

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