Based on the Principle of the Rotation of the Center of the Reuleaux Triangle Water Saving Sprinkler

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Abstract. In this paper, a water-saving sprinkler is designed with the property that Reuleaux triangle can make the center move around the circle and make the curved edge track square. When the sprinkler sprays at a fixed angle, the sprinkler area can be square after a certain period. Through the overall structural design of the sprinkler, the design and analysis of the translation device and the rotation device, the design and analysis of the water supply system, the design and analysis of the support structure and other aspects, the model is built. The utility model can realize the maximization of the water utilization of the sprinkling irrigation system, reduce the waste of water resources caused by over-spraying, can also be used for crops with high requirements on the uniformity of the water environment, and reduce the damage to the growth of species of plants caused by uneven water environment.

1. Project Background and Research Significance

1.1. Project background
Sprinkler irrigation is a widely used water-saving irrigation method with great advantages and potential. At present, the uniformity of sprinkler irrigation system and the utilization efficiency of irrigation water are relatively low. However, rectangular layout and parallelogram layout are widely adopted in northern irrigation districts, which have the problems of low water use efficiency, large overlapping area of spraying and serious waste. No matter the rectangular combination or diamond combination is adopted, the sprinkler irrigation area cannot be equal to the actual land area. In the sprinkler irrigation system, multiple sprinklers work together. When the sprinkler irrigation radius is larger than the distance between sprinklers, there will be intersecting parts in the sprinkler irrigation area, and when the sprinkler irrigation radius is smaller than the distance between sprinklers, there will be parts that cannot be sprinkled. The combination of the following figures shows overlapping spraying.
According to the Notice on Soliciting Water-saving Technologies, Technologies and Equipment for Major Industries of the State (the Third Batch), sprinklers capable of uniform irrigation and reducing water waste are urgently needed in the market.

1.2. Research significance
The system designed in this project is composed of planetary gear train rotating device, reuleaux triangle steering device, rocker arm nozzle and water supply system. The water pressure is provided by a water pump, the spraying angle is adjusted to 120 degrees through a limiting ring, the spraying direction is controlled by a steering device, a tripod acts as a bottom to stabilize, and the device has the characteristics of maximum water flow spraying efficiency and reduction of excessive spraying waste. When spraying the corner part of the plot, the amount of spray outside the boundary of the circular spray area nozzle is reduced by 8.241%. Therefore, the device can realize a square spraying area, reduce the amount of out-of-bounds spraying and reduce the overlap of multiple circular spraying area nozzles during combined irrigation, thus providing a new idea and method for improving the uniformity of sprinkler irrigation and improving the utilization efficiency of water resources.

2. The Innovation of the Project
This project has the following innovations:
(1) Structural innovation: the motor is used to drive the planetary gear train to combine with the reuleaux triangle, so that the nozzle conforms to the center circle motion track of the reuleaux triangle;
(2) Functional innovation: realize square unit sprinkler irrigation coverage area, no longer repeat irrigation for the same position, and sprinkler irrigation uniformity is improved;
(3) Application innovation: It can be applied to ornamental plant planting areas that are sensitive to water quantity and require uniform water distribution.

3. The Research Contents and Objectives of the Project
3.1. Research content
By virtue of the property that reuleaux triangle can make the center move around the circle and make the curved track square, the new type of water-saving sprinkler designed by the project team can make the sprinkler area square after a certain period when the sprinkler is spraying at a fixed angle. Through the overall structural design of the sprinkler of the device, the design analysis of the translation device and the rotation device, the design and analysis of the water supply system, the design and analysis of
the support structure and other aspects, the real objects are built. It is planned to maximize the water utilization of sprinkler irrigation system, reduce the waste of water resources caused by over-spraying, and can also be used for crops requiring high uniformity of water environment, thus reducing the damage to the growth of species of plants caused by uneven water environment.

Therefore, the research content of this project mainly includes the following points:
1) Explore the relationship between the running speed and cycle of the planetary gear and the spraying uniformity in the spraying area.
2) explore the relationship between actual spray distance and water pressure during the operation of the device;
3) explore the actual water saving of spraying unit area grassland with this device;
4) Explore the watering effect of this device on plants sensitive to water such as Hongcaige.

3.2. Research objectives
The research objectives of this project are: to obtain the planet wheel rotation speed and spray angle that can achieve the highest spray uniformity through experiments, and to obtain the uniformity difference data when using this device to spray the same amount of water compared with the traditional sprinkler head; The dependence of spraying of this device on the stability of water pressure is obtained.

4. The Implementation Plan of the Project Research and the Research Methods and Technical Routes to be Adopted

4.1. Implementation plan
The implementation plan adopted by the project team is as follows:
1) Through the establishment of mathematical models, the changes of spray nozzles during the operation of motor-driven planetary gears are studied, and the overall preliminary scheme design is carried out.
2) Select appropriate auxiliary hardware peripherals such as motors and sensors to design the circuit.
3) Three-dimensional modeling and simulation technology is used to simulate the stress situation of all structures in the whole electromechanical system and perfect the model.
4) Build a real object, carry out experiments, and modify and perfect the model design and parameters according to the experimental data.

4.2. Technical route

4.2.1. Principle of device. It is easy to prove the equal width property of reuleaux triangle. Its width is equal to the side length of the equilateral triangle. When reuleaux triangle rotates in a square whose side length is its width, the trajectory of each corner is basically a regular square.

![Reuleaux triangle](image)

**Figure 3.** Reuleaux triangle

The equal width property of reuleaux triangle is easy to prove, and its width is equal to the side length of the equilateral triangle. When the reuleaux triangle rotates in a square whose side length is
its width, the path each corner travels is basically a square. Therefore, the fan OAB, which connects the center of the reuleaux triangle and the two vertices, is one third of the total shadow area. After rotation, it can still sweep across the entire square area.

4.2.2. Sprinkler structure

![Sprinkler structure](image)

Figure 4. Schematic diagram of main structure of sprinkler
(1, a bracket 2, a steering device 3, a spray head 4, planet wheels, a motor 5 and a water inlet)

The overall structure of the sprinkler is shown in the figure. The top of the sprinkler is a rocker nozzle, the inside of the shell is a steering mechanism, and the middle is a water supply pipe crossing. The hose connected with the upper sprinkler is connected with the nozzle inlet. The tripod structure is to improve the overall stability of the device. Next, the module is introduced.

4.2.3. Nozzle structure

![Nozzle structure](image)

Figure 5. Rocker arm sprayer structure

As shown in fig. 4, the adjustable single spray nozzle commonly used in the market at present can set its spray fan angle to 120 degrees through adjusting the angle of the limiting ring, so as to reach one-third of the ejection area of reuleaux triangle at the same time. However, the main water spray port and the auxiliary water spray port are both provided with water distribution needles, so that the water flow sprayed in the same straight line at the same time can be atomized more uniformly. In order to achieve the best spray uniformity effect of the nozzle, it is decided to use a water pump with a lift of 25M to supply pressure to the nozzle. In the same round of irrigation group of the same project,
a type of nozzle or nozzle with similar performance is selected to facilitate the control of irrigation uniformity and the operation and management of the whole system.

4.2.4. **Steering gear.** The translation device is shown in the figure. The lower planet wheel is driven by a 10W reduction motor with a rated torque of 3.5Kg·cm. The planet wheel is coaxial with the center of the upper reuleaux triangle and drives the sub-wheel to rotate through the rotation of the central female gear. By installing the nozzle shaft on the external gear, the function of circular movement of the nozzle center in the plane is achieved. Moreover, due to the restriction of the square frame on the outside, the reuleaux triangle plate will rotate in the plane, thus changing the spray point and spray direction of the spray head, and realizing square spray irrigation under the condition that the spray radius of the spray head is unchanged.

![Figure 6. Steering device structure](image)

4.2.5. **Bracket design.** The three-leg support is adopted, and the bottom is made of metal, thus reducing the center of gravity of the whole nozzle device. The middle part is hollow polypropylene plastic, which is connected with an external water pipe, so that the device can maintain good stability in the operation process; and a telescopic conical metal rod is additionally arranged at the bottom of the bracket and can be inserted into the soil, so that the anti-dumping energy force of the device is further enhanced.

4.2.6. **Water inlet.** The water supply pipeline is the same as the conventional sprinkler irrigation greenbelt. The water pipe is buried underground. After being pressurized by a water pump, the water flows from the pipeline into the water inlet and then directly connects with the nozzle upward.

4.2.7. **Design requirements of booster pump.** The design flow rate of sprinkler irrigation system should be greater than the sum of the flow rates when all sprinklers work at the same time.

\[ Q \geq 3.6nP \]

In the formula

- \( Q \)——The design flow rate of sprinkler irrigation system, L/s;
- \( n \)——The number of sprinkler heads, ge.
- \( P \)——The rated flow rate of a single sprinkler head, \( m^3/(h \cdot ge) \); According to the formula, the specific parameters of the pump can be determined only by calculating the flow rate and lift.

Water quantity of pump:

\[ Q = \sum_{Sprinkler \ head} N q \]

Pump lift:
\[ H = H_{\text{Hypothesis}} + \sum f_i H_j + \sum j H_j + \Delta \] (3)

In the formula

- \( N_{\text{Sprinkler head}} \) — Quantity of nozzles working at the same time
- \( q \) — Quantity of single nozzle
- \( H_{\text{Hypothesis}} \) — Nozzle design working pressure
- \( \sum f_i H_j \) — The sum of the head losses along the pipeline from the pump outlet to the most unfavorable nozzle
- \( \sum j H_j \) — The sum of the local head losses from the pump outlet to the most unfavorable nozzle.
- \( \Delta \) — Height difference between center line of water pump outlet and most unfavorable nozzle.

The working water pressure range of common nozzles on the market is 2.2-4.5 kg force, which is 0.22-0.45 Mpa. The tap water of about 0.1 Mpa cannot provide enough water pressure, so a special booster pump for irrigation needs to be purchased, and a pump body with a lift in the range of 22-45 m is required. The common booster pumps on the market can meet this demand.

4.2.8. Overall system design. Sprinkler irrigation is to form water with a certain pressure through a sprinkler irrigation system or unit composed of sprinkler irrigation equipment. An irrigation method in which small water droplets are sprayed into the air by a nozzle to evenly spray onto the soil surface to provide necessary moisture for the normal growth of plants. Compared with traditional surface irrigation methods, irrigation has the advantages of water saving, energy saving, water saving and high irrigation quality.

The overall design of sprinkler irrigation system shall be determined through technical and economic comparison based on terrain, soil, meteorology, hydrology, and plant conditions. Rectangular combination is suitable for green land with regular and flat terrain, and its design is simple and easy to arrange. The rhombus combination is suitable for greenbelts with irregular and undulating terrain. This form has strong wind resistance, but the water quantity of each road is uneven and the calculation is complicated in design. In order to conform to the property of reuleaux triangle and according to the advantages of rectangular combination, the whole sprinkler irrigation system is set with rectangular sprinklers.

In the design of irrigation system, water sprayed from the nozzle will reach the ground through a certain trajectory, which is the spray trajectory. The specific trajectory of the trajectory is the injection angle when the water leaves the nozzle; According to this situation, the 0-degree trajectory is called a horizontal trajectory, which is generally used for high places such as low shrubs or mountain tops. The 10-degree track is used for shrubs, land and lawns. The 25-degree trajectory is a general standard trajectory, which can be used in most sprinkling irrigation occasions.

After comparing the data, the device will adopt a 25-degree sprinkler irrigation track to adapt to the common green sprinkler irrigation environment.

4.3. Theoretical calculation

![Figure 7. Reuleaux triangle mathematical model](image)
As for the parameter selection of reflex triangle, we should start from its mathematical model. The motion model of reflex triangle is shown in fig. 7. Relying on the internal meshing planetary gear drive, the planetary gear 01 moves along a large ring gear O, and rotates itself while the planetary gear revolves along the ring gear.

According to the model, the radius of the driving ring gear is set to be \( r \), the radius of the planetary gear is set to be \( r \), and a is a point fixed with the row of planetary gears, i.e. a vertex of a triangle. The distance is \( e = O1A \). Based on the principle of kinematics, when the planetary gears do meshing rolling, the coordinates of point A can be expressed as

\[
x = (R-r)\cos \alpha + e \cos \beta
\]

\[
y = (R-r)\sin \alpha - e \sin \beta
\]

Since the arc length of the pitch circle of the internal ring gear and the arc length of the pitch circle of the planetary gear are equal when the planetary gears are engaged and rolled, there are

\[
R \times \alpha = r(\alpha + \beta)
\]

\[
\beta = \frac{R-r}{r} \alpha
\]

Substituting it into the formula, and then making \( \xi = \frac{R}{r} \), \( \eta = \frac{e}{r} \), \( \xi = \frac{e}{r} \), \( \eta = \frac{e}{r} \), the trajectory mathematical model of the outer boundary can be obtained.

\[
x = (\xi - 1) \cos \alpha + \eta r \cos(\xi - 1) \alpha
\]

\[
y = (\xi - 1) \sin \alpha - \eta r \sin(\xi - 1) \alpha
\]
If $\xi$ is 4/3, it not only meets the size requirements of planetary gear and ring gear, but also ensures the structural strength requirements.

![Figure 9. Trajectory diagram with different coefficients](image)

The value of $\eta$ must be determined by two factors: first, it is determined by the structure: if $\eta$ is too small, point a will shrink within planet gear O1 or ring gear o, and the outermost side will not be able to finish the nearly square sweeping; Second, it is determined by the line type: if $\eta$ is too small or too large, the trajectory of point A is not ideal. When $\eta=1.5$, all four sides of the locus of point A are depressed inward. When $\eta=3.5$, all four sides of the locus of point A are convex outward. Only when $\eta=2.5$, the locus line of point A is ideal, which is closest to the square.

5. Research Foundation and Feasibility Analysis of the Project

5.1. Research foundation

Our country's agricultural cultivation scope is large. Sprinkler irrigation has strong adaptability to various terrains. It does not need to level the land like surface irrigation. Sprinkler irrigation can be carried out on sloping land and uneven ground. Especially in sandy soil with thin soil layer and strong water permeability, sprinkler irrigation is very suitable. In addition, sprinkler irrigation is not only suitable for all field crops, but also can obtain good economic effects for various economic crops, vegetables and grasslands. By means of the improved sprinkler irrigation system, it can achieve both sprinkler irrigation efficiency and water saving effect.

| Irrigation technology         | Advantages                                      | Disadvantages                                                                 |
|------------------------------|------------------------------------------------|-------------------------------------------------------------------------------|
| Shallow wet drying irrigation technology | Reduce irrigation                              | Fields with high fertilization level need complete irrigation and drainage systems. |
| Intermittent irrigation technology | Can reduce irrigation and drainage times and enhance soil aeration | It is not suitable for clay and sandy soil, and has extremely high requirements on the slope and length of furrows. |
| Controlled irrigation technology | Reduce irrigation times                        | Need special fields, not suitable for salt and alkali                        |
| Rain storage irrigation technology | Can make full use of rainfall, reduce irrigation times and irrigation amount | Local weather survey is required to be accurate                               |
Compared with the original round nozzle, square sprinkler irrigation can reduce water consumption better under the premise of meeting the requirements of "Technical Specification for Sprinkler Irrigation Engineering".

From Table 2, we can see that different green space environments have different requirements for the types of sprinkler heads.

### Table 2. Classification of garden sprinkler heads

| Nozzle name          | Applicable object                                         | Characteristics                                                                 |
|----------------------|-----------------------------------------------------------|--------------------------------------------------------------------------------|
| Micro sprinkler      | Garden, greenhouse and roof green space                   | The atomization effect is good and can be used for cooling and humidifying.     |
| Buried sprinkler     | Head park, public green space and playground lawn          | Circular or spraying at the required angle; Spray evenly, not easy to form surface runoff; |
| Impact driven sprinkler | Large area lawn and shrubs                                 | Wear resistance, corrosion resistance and stable performance; It has good wind resistance and sand prevention characteristics. |
| Spray gun            | Farmland, large area lawn and forest green land             | Long range, good atomization effect and difficult blockage.                     |

5.2. Benefit analysis

5.2.1. Benefit analysis of emission reduction. The device adopts common materials in the market and a mechanical structure which is easy to complete, so that the overall cost is low and the realization is strong; the device can save a certain amount of water during normal operation and has actual economic benefits. If the length of the square is $r$ and the radius of the concentric circle is $r$, the ratio $p$ of the difference between the area of the circle and the square to the area of the square is

$$A = \pi r^2, \quad P = \frac{\pi r^2 - (r-1)^2}{r^2} = \pi - 1$$

In the formula

- $A$——Circumferential area, m$^2$
- $B$——Square area, m$^2$
- $P$——Area ratio
- $R$——Circular nozzle spray radius, m

Therefore, the saving ratio can be calculated by the irrigation water quantity formula to be 13.53%. When the system works, as shown in the figure, the center of reuleaux triangle formed by two motion mechanisms will reciprocate in a small circle track. The radius of the inner circle track is $r = \frac{3\sqrt{2} - 2\sqrt{3}}{3}$, after calculation, the theoretical saving ratio minus the repeated irrigation area of the inner circle results in the actual reduced coverage area of 8.241%×R2.

Apart from the water pump, the estimated cost of the unit is 120 yuan if there is assembly line production. According to the nozzle data, it can be seen that when the working pressure is 2.5Mpa, the spraying diameter is 10M and the flow rate is 0.8-1.2 tons/hour. According to the above formula, it takes 337 days to recover the extra cost compared with ordinary sprinklers based on the urban water charge of one ton of 0.6 yuan and intermittent irrigation of 6 hours a day.

According to the calculation, the device can save 8.241% of the original sprinkler irrigation water in the same area. The amount of water used by sprinkler irrigation in our country is about 18 billion m$^3$, 10% of which will be worked by this device, which can reduce 148.3 million m$^3$ of water waste in a year.
5.2.2. Economic benefit analysis. Take the square layout of wheat planting spray points as an example, each spray point can be irrigated with 0.09 hm$^3$, calculated by five rounds of irrigation per day, the daily irrigation area of a single nozzle is 0.45 hm$^3$, the irrigation period is 16 days, and the irrigation is 5 times a year. One hectare of land can save 38.62 yuan a year. By the end of 2010, China's sprinkler irrigation area accounted for 5.01% of the irrigated area, about 500,000 hectares, and the amount of water used for sprinkler irrigation was about 18 billion m$^3$. 10% of the sprinkler irrigation area could save 1.9308 million yuan in water charges a year by using this device.

$$0.09 \times 5 \times 16 \times 5.01\% \times 180 \times 10^{10} \times 10\% = 193.08 \text{ (Ten thousand yuan)} \quad (11)$$

5.2.3. Benefit analysis. According to the Notice on Soliciting Water-saving Technologies, Technologies and Equipment for Major Industries of the State (the Third Batch), this device can produce better water-saving benefits for long-term large-scale users, and is in line with the national water-saving trend. It has an exemplary role in actively responding to the government's call.

The irrigation system needs to adjust the irrigation water quantity according to different site requirements, and the irrigation water quantity can be calculated according to formula (12):

$$m_{\text{Hypothesis}} = 100 \gamma (\beta_1 - \beta_2) \frac{1}{\mu} \quad (12)$$

In the formula

$m_{\text{Hypothesis}}$ —— The design irrigation amount of green land, kg/cm$^2$;

$\gamma$ —— Soil capacity, kg/m$^3$;

H —— Planned wetting depth, cm;

$\beta_1, \beta_2$ —— Suitable upper and lower limits of soil water content (mass fraction);

$\mu$ —— The effective utilization coefficient of spraying water is generally 0.7–0.9

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