Politecnico di Torino

Master Degree in Mechatronic Engineering

THESIS TITLE:

MECHANIZED IRRIGATION CENTER PIVOT ARM CORNER

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ABSTRACT:

THIS THESIS ADDRESSES THE INHERENT LIMITATION OF TRADITIONAL CENTER PIVOT IRRIGATION SYSTEMS IN EFFECTIVELY IRRIGATING SQUARE OR RECTANGULAR FIELD CORNERS DUE TO THEIR CIRCULAR WATERING PATTERN. BY PROPOSING AN ENHANCED SWING ARM SYSTEM INTEGRATED WITH REAL-TIME KINEMATIC (RTK) GPS GUIDANCE AND A U-CHANNEL SYNCHRONIZATION MECHANISM, THE STUDY AIMS TO MAXIMIZE LAND COVERAGE, IMPROVE WATER EFFICIENCY, AND ENSURE PRECISE IRRIGATION IN IRREGULARLY SHAPED FIELDS. THE SWING ARM EXTENDS BEYOND THE MAIN PIVOT'S CIRCULAR PATH, UTILIZING RTK GPS FOR CENTIMETER-LEVEL POSITIONING ACCURACY TO DYNAMICALLY ADJUST ITS MOVEMENT ALONG FIELD BOUNDARIES. A U-CHANNEL MECHANICAL COUPLING SIMPLIFIES SYNCHRONIZATION BETWEEN THE SWING ARM AND THE MAIN PIVOT, REDUCING RELIANCE ON COMPLEX COMPUTATIONAL SYSTEMS WHILE ENSURING ROBUST OPERATION IN AGRICULTURAL ENVIRONMENTS. THE DESIGN INCORPORATES A RACK-AND-PINION STEERING MECHANISM, ELECTROMECHANICAL ACTUATORS, AND VARIABLE-RATE SPRINKLERS TO OPTIMIZE WATER DISTRIBUTION. SIMULATIONS DEMONSTRATE THE SYSTEM'S ABILITY TO ACHIEVE

87.21% CHRISTIANSEN'S UNIFORMITY COEFFICIENT, EXCEEDING THE 70% THRESHOLD FOR

SATISFACTORY IRRIGATION, AND VALIDATE ITS CAPACITY TO COVER 1000×1000-METER FIELDS WITH A 207.1-METER SWING ARM. RESULTS HIGHLIGHT A 15–30% REDUCTION IN WATER WASTE THROUGH ADAPTIVE NOZZLE SPACING, PRESSURE REGULATION, AND GPS-GUIDED PATH PLANNING. THE INTEGRATION OF RTK AND U-CHANNEL MECHANISMS OFFERS A COST-EFFECTIVE, RELIABLE SOLUTION FOR EXTENDING CENTER PIVOT FUNCTIONALITY TO FIELD CORNERS, ENHANCING CROP YIELDS AND RESOURCE EFFICIENCY. THIS RESEARCH CONTRIBUTES SUSTAINABLE AGRICULTURAL PRACTICES BY BRIDGING THE GAP BETWEEN CIRCULAR IRRIGATION SYSTEMS AND RECTANGULAR FIELD GEOMETRIES, PROVIDING ACTIONABLE INSIGHTS FOR FARMERS AND POLICYMAKERS TO MITIGATE WATER SCARCITY CHALLENGES.

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1-Introduction

1.1Introduction to Center Pivot Irrigation

Center pivot irrigation is one of the most efficient and widely used mechanized irrigation systems in modern agriculture. Designed to optimize water distribution across large fields, it consists of a long sprinkler pipeline supported by wheeled towers that rotate around a fixed central point. As the system moves in a circular pattern, it ensures uniform water application to crops, making it particularly valuable in regions with limited water resources or irregular rainfall patterns. (Evans, R.G, Sadler, & E.J, 2008)

1.2Historical Background and Development

The concept of center pivot irrigation was pioneered in the 1940s by Frank Zybach, an American farmer and inventor. His goal was to develop a more efficient irrigation system that would reduce labor while ensuring consistent water application. Over the decades, center pivot technology has evolved significantly, incorporating advancements in automation, precision control, and remote monitoring. Today, center pivot systems are widely used in countries such as the United States, Brazil, China, and Australia, where large-scale agriculture is prominent.

1.3Components and Working Principle

A typical center pivot irrigation system consists of the following key components:

- **Pivot Point**: The stationary hub from which the entire system rotates. It supplies water to the main pipeline and houses the control mechanisms.
- **Sprinkler Pipeline**: The main pipe that extends outward from the pivot point and distributes water through a series of sprinklers. The length of the pipeline can range from a few hundred meters to over a kilometer, depending on field size.

- **Sprinklers and Nozzles**: Attached along the length of the pipeline, these components regulate water flow and distribution. Nozzles can be adjusted based on crop type, soil characteristics, and climate conditions.
- **Towers and Drive Mechanism**: The pipeline is supported by multiple wheeled towers equipped with electric or hydraulic motors, which allow the system to move in a circular pattern around the pivot.
- **Control Panel**: Modern center pivot systems are equipped with automated control panels, which can be programmed for variable water application, speed adjustments, and integration with precision agriculture technologies.

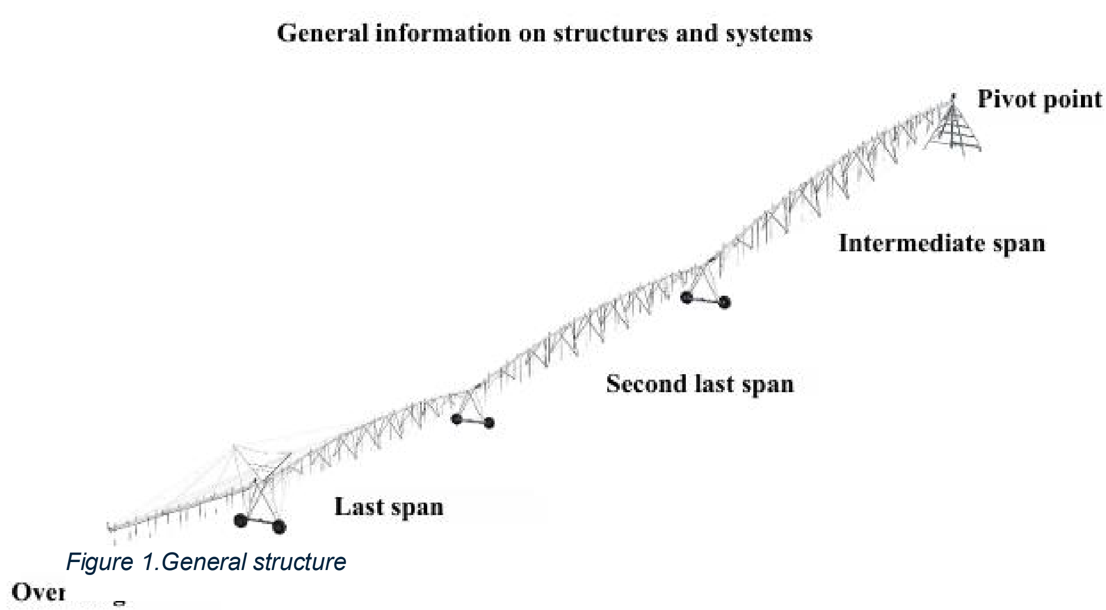

Figure 1.General structure

Water is typically supplied to the system via a pump, which draws water from a well, reservoir, or other sources. As the system moves, sprinklers discharge water at a controlled rate, ensuring even distribution across the field.

1.4Advantages of Center Pivot Irrigation (King, B. A., Bjorneberg, & D. L., 2015)

The widespread adoption of center pivot irrigation is due to several benefits:

1. **Efficient Water Use**: Compared to traditional irrigation methods such as flood or furrow irrigation, center pivot systems significantly reduce water wastage by minimizing runoff, deep percolation, and evaporation losses.
2. **Uniform Water Distribution**: The movement of the system ensures that water is applied consistently, preventing under- or over-irrigation of crops.
3. **Labor Savings**: Once installed, center pivot systems require minimal manual intervention, as they can be automated to operate on preset schedules.
4. **Adaptability to Different Crops and Soils**: Center pivots can be used for a variety of crops, including corn, wheat, soybeans, and alfalfa, and are suitable for diverse soil types.
5. **Integration with Precision Agriculture**: Advanced systems incorporate GPS, soil moisture sensors, and variable rate irrigation (VRI) technology, allowing for precise water application based on real-time field conditions.

1.5 Movable Corner System

The corner system is an extra segment attached to the last span of the center pivot. This arm can pivot independently to cover the corners and irregularly shaped areas of a field. It swings out as the main pivot rotates, extending the irrigated area. The arm can move in and out, adjusting its position to cover more ground. The movement of the arm is typically control by a series of sensors and controllers that adjust its position based on the field's layout. The extended arm corner Maximizes the irrigated area, potentially increasing crop yields by covering previously unwatered corners and irregular field shapes. It also provides water to areas that would otherwise require separate irrigation systems, which improv the overall water use efficiency. The arm corner also reduces the need for additional irrigation infrastructure and labor to manage corner areas separately. The addition of a corner system increases the initial investment and may require more maintenance. The system adds complexity to the irrigation setup, necessitating more 1 sophisticated controls and potentially more frequent adjustments, these are some points that should be taken into consideration before adding the swing arm system. Swing arm in center pivot irrigation use various control systems to manage the movement and water distribution efficiently.

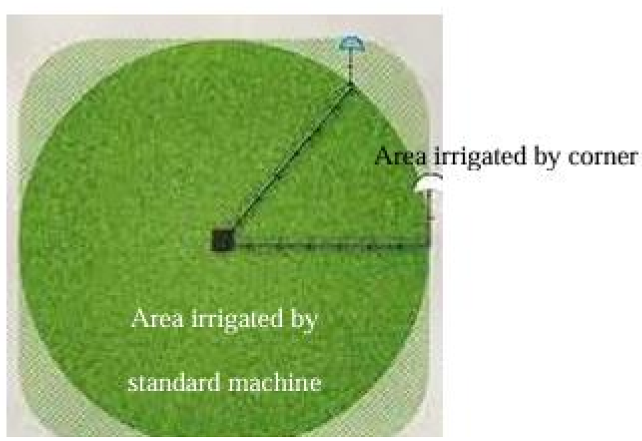

Figure 2.Arm Corner

1.6Mechanical Control Systems

• Cable and Pulley Systems: These systems use cables and pulleys to mechanically guide the swing arm's movement. They are simple and reliable but can be less precise than more advanced systems.

• Pivot Point Sensors: Mechanical sensors located at the pivot point can help determine the position of the swing arm and adjust its movement accordingly.

2. GPS-Based Control Systems

• Real-Time GPS: Uses GPS technology to provide real-time positioning of the swing arm. This allows for precise control of the arm’s movement, ensuring accurate coverage of irregular field areas.

• GPS Guidance and Mapping: The system can follow pre-programmed field maps created using GPS data, ensuring that the swing arm covers all necessary areas without overlapping or missing spots.

3. Electromechanical Control Systems

• Electric Motors: Electric motors can be used to drive the movement of the swing arm, providing precise control over its position.

• Sensor Feedback: Electromechanical systems often use sensors (such as potentiometers or encoders) to provide feedback on the arm’s position, allowing for real-time adjustments. 4. Automated Control Systems

• Integrated Control Panels: Centralized control panels can manage the entire irrigation system, including the swing arm. These panels can be programmed to adjust the arm’s movement based on predefined parameters. (Norton, 2020)

2-Literature Review

1. Introduction

Center pivot irrigation has become a dominant method for large-scale irrigation due to its efficiency in water distribution and automation capabilities. However, one of its inherent limitations is its circular coverage pattern, which often leaves the outer corners of rectangular fields unirrigated. To address this issue, swing arm corners (also known as corner irrigation systems) have been developed as an extension of center pivots to maximize land utilization and improve water application uniformity. This literature review explores the existing research on center pivot irrigation, its efficiency, challenges, and the integration of swing arm corner solutions for improved irrigation coverage. (O'Shaughnessy, S. A., & et al, 2016)

2. Center Pivot Irrigation: Efficiency and Performance

2.1 Water Use Efficiency

Numerous studies have evaluated the water use efficiency (WUE) of center pivot irrigation compared to traditional surface irrigation methods. According to Evans and Sadler (2008), center pivot systems can achieve up to 85–95% efficiency due to reduced runoff and deep percolation losses. This is in contrast to furrow or flood irrigation, where efficiency can be as low as 50–70% due to evaporation and uneven water distribution. (Evans, R.G, Sadler, & E.J, 2008)

Precision agriculture technologies, such as Variable Rate Irrigation (VRI), have further enhanced center pivot efficiency. Research by O'Shaughnessy et al. (2016) demonstrated that sensor-based irrigation scheduling under center pivot systems could lead to a 20–30% reduction in water usage while maintaining or increasing crop yield.

2.2 Energy and Economic Considerations

The economic feasibility of center pivot irrigation has been widely studied. According to Fraisse et al. (2019), center pivot systems, while having high initial investment costs, are more cost-effective in the long run due to reduced labor and higher yield potential. However, energy costs associated with pumping water remain a critical factor influencing its overall sustainability, particularly in regions with high electricity or fuel prices.

Studies such as those by Irmak et al. (2012) suggest that optimizing irrigation scheduling and using low-pressure sprinkler nozzles can significantly reduce energy consumption while maintaining adequate water application rates.

2.3 Challenges of Traditional Center Pivot Systems

Despite their advantages, conventional center pivots face limitations in irregularly shaped fields, particularly in rectangular plots where significant portions of the land remain unirrigated. Research by King and Bjorneberg (2015) highlighted that, on average, 20–25% of a rectangular field is left without water, leading to inefficient land use and yield reduction. This has prompted the need for additional solutions, such as swing arm corners, to extend irrigation coverage.

3. Swing Arm Corner Solutions: Enhancing Irrigation Coverage

3.1 Functionality and Design

Swing arm corners, also known as corner arms or end guns with corner extensions, are designed to extend the reach of a center pivot into field corners, thereby maximizing land utilization. These systems consist of an articulated arm that extends outward when needed and retracts as the pivot moves in a circular motion. Studies by Schmidt and Sourell (2018) show that implementing swing arm corners can increase irrigated area by 15–20%, leading to significant improvements in yield potential.

A key challenge in the design of swing arm corners is controlling water application rates dynamically. As the arm extends, the speed and flow rate must be adjusted to maintain uniform distribution. Researchers such as Dukes and Perry (2010) have explored the use of advanced nozzle configurations and pressure regulators to optimize corner irrigation performance.

3.2 Water Distribution Uniformity

The uniformity of water distribution in swing arm corner systems has been a focus of multiple studies. According to Kincaid et al. (2011), traditional corner systems often suffer from over- or under-irrigation due to inconsistent pressure regulation and movement dynamics. Advanced systems now integrate Variable Rate Irrigation (VRI) and GPS-controlled actuators to modulate water application based on soil type and crop requirements (Sadler et al., 2015). (Evans, R.G, Sadler, & E.J, 2008) (King, B. A., Bjorneberg, & D. L., 2015)

3.3 Automation and Control Technologies

Modern swing arm solutions incorporate automation technologies to improve precision and efficiency. Research by Smith and Baillie (2020) highlights the integration of remote sensing, real-time monitoring, and machine learning algorithms for adaptive corner irrigation control. These advancements have enabled better synchronization between the pivot movement and corner arm deployment, reducing water wastage and ensuring uniform coverage. (Hoffmann , H., & Jensen , & R., 2017)

4. Comparative Analysis of Center Pivot with and Without Swing Arm Corners

Several studies have compared traditional center pivot systems with those incorporating swing arm corners. A meta-analysis by Howell et al. (2017) found that fields with swing arm extensions had, on average:

- **12–18% higher crop yield** due to increased irrigated area.
- **15–20% higher water use efficiency**, particularly in precision-controlled systems.
- **Reduced dryland patches**, leading to more consistent field productivity.

However, additional investment and maintenance costs associated with swing arm corners remain a barrier to widespread adoption. Research by Evans et al. (2021) suggests that

while these systems improve land use efficiency, farmers must weigh the cost-benefit ratio based on field size, water availability, and economic constraints.

5.Guiding systems

A-Below-Ground Guidance Systems (BAURE):

Below-ground guidance systems for swing arms in center pivot irrigation use buried infrastructure to guide the movement of the pivot's end gun or corner arm. These systems use buried cables or wires that emit signals, which are detected by sensors mounted on the swing arm. The sensors communicate with the control system, allowing the arm to follow the predefined path accurately. One of the major benefits of below-ground guidance is its ability to provide precise control over irrigation while minimizing interference with farming activities on the surface. Since the guidance components are buried, they are protected from weather conditions and potential damage from farming equipment, making the system highly reliable. Additionally, it offers flexibility, as the buried cables can be installed to suit the specific layout of any field, including those with irregular shapes or obstacles. While the initial installation costs can be higher due to the need for trenching and laying cables, the long-term benefits of durability, precision, and reduced maintenance make it a valuable investment for farmers aiming to maximize irrigation efficiency. While below-ground guidance systems offer great precision, they come with notable disadvantages. The high installation costs can be a significant barrier, as trenching and burying cables require both time and specialized labor. Additionally, maintenance and repairs can be 2 challenging. If the underground cables are damaged, identifying and fixing the problem may involve costly and time-consuming excavation work. There's also the risk of accidental damage from deep plowing or other farming activities, which could disrupt the system and necessitate repairs. Furthermore, limited flexibility in making quick adjustments after installation can be a concern, as repositioning buried components is more complicated compared to surface-based systems. (Hoffmann , H., & Jensen , & R., 2017)

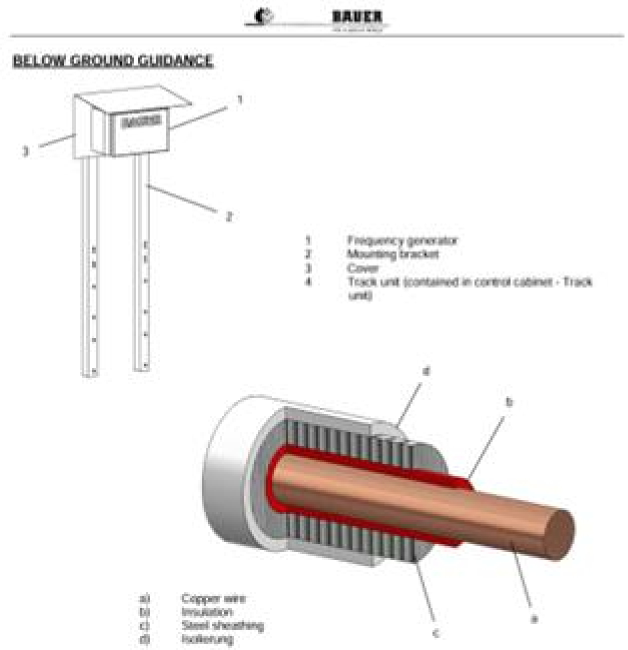

Figure 3.BAUER Guidance System

B-GPS Guidance and Mapping (zimmatic 9500CC) (Zimmatic., 2023)

GPS guidance systems rely on real-time positioning to accurately control the movement of the swing arm in a center pivot irrigation system. GPS receivers gather precise location data by communicating with satellites to determine the exact position of both the swing arm and the entire system. This data is processed by control algorithms within the system's control panel, which guide the movement of the swing arm to ensure it follows the desired irrigation path. The system automatically adjusts the swing arm's position based on pre-set parameters and real time data, ensuring even water distribution across the field. The use of RTK (Real-Time Kinematic) technology in such systems significantly improves accuracy by correcting GPS signals to provide centimeter-level precision, which is crucial for ensuring optimal coverage, especially in irregularly shaped fields. RTK helps maintain consistent irrigation and reduces water waste, making the system more efficient. In addition to real-time positioning, mapping systems play a crucial role in GPS-guided irrigation. Before irrigation starts, a detailed map of the field is generated using GPS data, outlining

Figure 4.Zymmatic guidance

boundaries, terrain features, and any obstacles that could impact the swing arm's movement. These precision maps can also include critical information such as soil types, moisture levels, and crop varieties, allowing for tailored irrigation strategies that meet the specific needs of different areas of the field. By incorporating this data, the system can develop an optimized 3 irrigation path, ensuring the swing arm covers the entire field efficiently, avoiding overlaps or missed sections. This precise path planning maximizes water use and ensures uniform irrigation across the field, leading to healthier crops and reduced waste. The GPS-based control system for center pivot irrigation offers several key advantages. It ensures precise water distribution by using real-time data to guide the swing arm accurately, helping to avoid over- or under-irrigation. The system allows for optimized path planning, ensuring that the entire field, including irregular corners, is efficiently covered without gaps or overlaps. Additionally, the system is flexible and adaptable, adjusting to different field shapes, soil types, and changing crop needs. With precision mapping, water levels can be tailored based on factors like soil type and moisture, resulting in better crop health. Automation reduces the need for manual adjustments, saving time and labor while improving overall irrigation efficiency. (Trimble Agriculture., 2022)

C-GPS RTK (Real-Time Kinematic):

GPS RTK (Real-Time Kinematic) is a highly accurate satellite-based positioning system. It enhances the precision of standard GPS by using a fixed base station and one or more mobile receivers (rovers) to correct the GPS signal. A base station is a stationary GPS receiver set up at a known, fixed location. It continuously receives signals from satellites and calculates the corrections needed to account for errors caused by factors like atmospheric conditions and clock inaccuracies. On the other hand, rovers are mobile GPS units that also receive satellite signals. The rover communicates with the base station, either by sending its data or receiving corrections from it, allowing the rover to apply real-time corrections and improve accuracy. The communication link, which can be established through methods such as radio, cellular networks, or the Internet, is essential for transferring correction data from the base station to the rover. Both the base station and the rover receive GPS signals from the same satellites, and the base station, being in a fixed position, calculates the errors in satellite positioning, which are caused by factors like signal delays in the atmosphere or satellite clock errors. It then sends these error corrections to the rover in real-time. By using this information, the rover can adjust its position calculation, achieving centimeter-level accuracy compared to standard GPS, which typically has an accuracy of 3 to 5 centimeters. This is how RTK (Real-Time Kinematic) works, providing precise positioning for various applications. 4 In a center pivot irrigation system with a swing arm (also called a corner arm), installing an RTK system for precise positioning would significantly improve the control and movement of the swing arm to ensure optimal water coverage. (Dukes, M. D., & Perry, C., 2010)

D-RTK in center pivot swing arm (with base station):

The base station should be installed at a fixed location, ideally near the pivot point or close to the irrigation system, where it can have a clear line of sight to the entire field, including the swing arm. One important consideration is to ensure a stable and known location for the base station. It should be placed in an area with good GPS signal reception, away from obstructions like tall buildings, trees, or hills that might interfere with satellite signals. A central location, such as the pivot point (the central tower of the irrigation system), is a good choice because it minimizes the distance between the base station and the swing arm, which helps ensure better accuracy. Additionally, the base station should be positioned at an elevated height, such as on a tall pole or structure, to avoid obstructions and maintain a clear communication path with the swing arm. The rover should be placed on the moving swing arm of the center pivot system. The swing arm is the outermost section of the center pivot, which moves to cover more of the field, so accurate positioning is critical in this area. The rover should be installed at the end of the swing arm, where it extends the most. This placement provides precise positioning data at the point that requires the most accurate control, as the outer part of the arm covers the largest area and moves the most. Additionally, it is important to install a rover on the last tower of the system to monitor its location. Knowing the position of the last tower is essential for effective operation and alignment. Both rovers will communicate wirelessly with the base station to receive correction signals and accurately track their positions. Depending on the size of the field, you might use a radio or cellular connection for this communication, ensuring that both the swing arm and the last tower have accurate positioning data. When using an RTK system for accurate positioning in a center pivot irrigation system, there are several important considerations to keep in mind. First, RTK systems typically maintain accuracy within 10 to 20 kilometers from the base station. Therefore, if the center pivot field is large, it is crucial to position the base station centrally to ensure consistent accuracy across the entire field. Additionally, maintaining a clear line of sight is essential; there should be no major obstructions between the base station and the rover on the swing arm, as a clear communication path is necessary for optimal performance. Finally, if the field has uneven terrain or obstacles, it is important to place the base station in a location where it can effectively "see" the entire path of the swing arm, allowing for reliable signal transmission and accurate positioning.

6. Conclusion

Center pivot irrigation remains a cornerstone of modern irrigation systems, offering high efficiency, automation, and adaptability. However, its limitation in covering rectangular field corners has led to the development of swing arm corner solutions, which significantly improve land and water use efficiency. The integration of advanced technologies, such as VRI, sensor-based control, and automation, has further enhanced the performance of these systems.

Future research should focus on optimizing the energy efficiency of swing arm solutions, improving real-time control algorithms, and assessing long-term economic viability. Additionally, sustainability concerns related to water conservation and energy consumption should drive innovation in smart irrigation solutions.

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3-Methodology

A center pivot irrigation system is a mechanized method of watering crops, consisting of a rotating pipeline mounted on wheeled towers that move around a fixed central point, creating a circular irrigation pattern. This system is widely used due to its efficiency, automation, and ability to provide uniform water distribution across large agricultural fields. However, a key limitation of center pivot irrigation is its inability to fully cover rectangular or irregularly shaped fields, leaving significant portions of land, particularly in the corners, without irrigation. This inefficiency can lead to reduced crop yield in those areas, impacting overall farm productivity. To address this challenge, swing arm corner systems have been developed as an extension to center pivots, allowing the irrigation arm to extend outward when needed and retract as it moves through the circular path. By integrating swing arm corners, farmers can maximize land utilization, reduce water wastage, and ensure more uniform crop growth across the entire field.

This section outlines the approach used to analyze the performance and efficiency of center pivot irrigation systems, with a specific focus on swing arm corner solutions. The methodology includes system design parameters, data collection techniques, simulation models, and evaluation criteria to assess water distribution uniformity, energy consumption, and overall irrigation effectiveness.

First, the study defines the structural and operational characteristics of the center pivot system, including sprinkler spacing, flow rates, and corner arm extension mechanisms.

To evaluate system performance, a combination of field experiments, numerical simulations, and analytical models is employed. Experimental data is collected

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through field sensors measuring water application rates, soil infiltration, and crop response. Additionally, a MATLAB-based simulation is used to model the movement

and operation of the swing arm corner, optimizing sprinkler activation and flow regulation.

The final assessment compares irrigation efficiency, land coverage, and resource utilization between conventional center pivots and those equipped with swing arm corners. By integrating both experimental and computational methods, this study aims to provide a comprehensive understanding of the benefits and limitations of swing arm corner solutions in modern irrigation practices.

3.1Angle calculation

Below is a conceptual explanation (with equations) on how to calculate the angle between the center pivot's last tower and the swing arm using GPS-RTK positions. We assume:

1. GPS Base Station is at the pivot center.

2. GPS Rover A is on the last tower (the end of the main pivot).

3. GPS Rover B is at the tip of the swing arm.

We want the angle between the last tower and the swing arm so that the tip remains on the field boundary.

- (x_pivot, y_pivot) be the pivot center coordinates from the base station (often this is the origin if the base station is at (0,0), but not necessarily).
- (x_tower, y_tower) be the last tower position (rover A).
- (x_arm, y_arm) be the tip of the swing arm position (rover B).

All coordinates come from GPS-RTK measurements.

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To find the angle between the last tower and the swing arm, you can think of two vectors both emanating from the pivot center, or one from the pivot to the tower and another from the pivot to the arm tip

$$\mathbf{v}_1 = \left(x_{\text{tower}} - x_{\text{pivot}},\ y_{\text{tower}} - y_{\text{pivot}}\right)$$

$$\mathbf{v}_2 = \left(x_{\text{arm}} - x_{\text{pivot}},\ y_{\text{arm}} - y_{\text{pivot}}\right)$$

The standard formula for the theta θ between two vectors u and v in 2D is

$$\theta = \arccos\left(\frac{\mathbf{v}_1 \cdot \mathbf{v}_2}{\|\mathbf{v}_1\|\|\mathbf{v}_2\|}\right)$$

3.2 atan2 function

In theory, you can compute the angle α between two vectors v1 and v2 by using the dot product. However, this approach only yields the magnitude of the angle. In practice, we often also need the direction (e.g., whether one vector is to the “left” or “right” of the other). For that, the atan2 function is superior. It automatically accounts for the correct quadrant, returning angles in the range −π to π, so we know not just how large the angle is, but also its rotational sense (clockwise or counterclockwise). Consequently, atan2 is more robust for real-time orientation tasks and when quadrant information is critical. The atan2 function is a mathematical function used to compute the angle θ between a vector and the positive x-axis, considering the vector's x- and y-components. Unlike the standard arctangent function (atan), atan2 takes two arguments (y and x) and determines the angle in the correct quadrant, covering the full range of −π to π (or $-180^{\circ}180^{\circ}$). This makes atan2 particularly important for applications requiring precise directional calculations, such as robotics, navigation, and swing arm control in center pivot systems. It eliminates the ambiguity of 6 quadrants and ensures numerical stability, even when one of the components is zero. In real time applications, atan2 is highly efficient and can dynamically calculate angles based on changing vector coordinates, making it a crucial tool for tasks like determining the orientation of robotic arms, calculating trajectories, or controlling machinery in dynamic environments. Its simplicity and robustness make it ideal for systems requiring real-time performance and accuracy. However, for the behavior of the swing arm (e.g., ramping from 90° to 180° and back), atan2 needs to be supplemented with additional logic to ensure the swing arm behaves as desired. To ensure the swing arm remains between 90° and 180° when using the atan2 function, additional logic is needed to constrain and adjust the calculated angle appropriately. While atan2 provides an accurate angle based on the vector components, it can return values outside the desired range of 90° to 180°, depending on the relative positions of the pivot and the swing arm tip. To address this, after calculating the angle using atan2, a conditional check can be applied to enforce the constraints. If the angle is less than 90°, it should be set to 90°, and if it exceeds 180°, it should be capped at 180°. This ensures that the swing arm behavior aligns with the physical system requirements, where 90° represents the fully retracted position and 180° represents the maximum outward extension. By combining atan2 with these bounds, the system maintains realistic and controlled motion, critical for applications such as center pivot irrigation systems or other machinery with rotational constraints.

- Step 1: Compute α_{raw} Using atan2

$$\alpha_{\text{raw}} = \text{atan2}(y_{\text{tip}} - y_{\text{tower}}, x_{\text{tip}} - x_{\text{tower}})$$

- Step 2: Adjust the Raw Angle α_{raw} Since atan2 provides angles in the range -180 to 180°, convert the angle to a positive range $[0^{\circ},360^{\circ}]$

$$\alpha_{\text{adjusted}} = \text{mod}(\alpha_{\text{raw}} + 360, 360)$$

- Step 3: Restrict the Angle to $90^\circ \le \alpha \le 180^\circ$

$$\alpha = \max(90, \min(180, \alpha_{\text{adjusted}}))$$

3.3 Actuators and motors

The drive motor plays a crucial role in ensuring that the swing arm of a center pivot irrigation system moves forward or backward along its path, maintaining synchronization with the main pivot while controlling its speed. Without the drive motor, the swing arm would be unable to follow the main pivot and provide full field coverage. Each leg of the steerable tower typically contains a conventional electric motor that drives its corresponding wheel through a gearbox, allowing the swing arm to adjust its position dynamically based on the real-time data received 7 from the control system. This setup is essential for maintaining smooth and precise movement of the swing arm across varying field conditions. The steering motor is essential for controlling the wheels of the steerable tower via a gearbox, adjusting the angle of the wheels to steer the tower along the path defined by the buried cable or other control methods. It allows the swing arm to move independently of the main pivot, which is crucial for reaching field corners. Since the swing arm needs to follow a different path than the main pivot’s circular motion, the steering motor adjusts its angle, ensuring that it can navigate field boundaries efficiently and cover areas outside the main pivot's reach.

Motor Type	Advantages	Disadvantages	Best Use Case
AC Induction Motor	Simple, durable, high torque, low maintenance	Limited speed control (without VFD)	Heavy-duty, constant-speed applications
DC Motor	Precise speed/position control, high torque	Higher maintenance (brushed DC), less robust	Systems requiring precise control or variable speed
BLDC Motor	Efficient, low maintenance, precise control	Higher cost, requires controller	Precision control with low maintenance needs
Stepper Motor	Precise positioning, high torque at low speeds	Low speed, reduced torque at high speed	Systems needing precise positioning
Stepper Motor	High precision, closed-loop control, high torque	High cost, complex system	High-precision movement and dynamic control
VFD + AC Motor	High torque, speed control, durable	Requires VFD for precise control	Heavy-duty, high-precision control with ruggedness

Table 1.Data for steering system

In our steering system for the swing arm of the center pivot irrigation setup, a 3-phase motor will serve as the primary power source to drive the swing arm's movement. Its purpose is to provide the mechanical force needed to extend and retract the swing arm along its designated path, ensuring smooth and efficient operation. The motor's direction will be controlled by altering the phase sequence, allowing precise control over the swing arm's forward and reverse motions.

3-phase motor can serve a dual purpose in the steering system for a swing arm

• Power Supply: The motor provides the mechanical force required to adjust the steering mechanism (e.g., moving the steering linkage or rotating the wheels).

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- Direction Detection: The motor can indirectly detect the direction of wheel movement by monitoring its own rotational state, which is linked to the wheels' position.

The direction of a 3-phase motor's rotation is determined by the sequence of the three-phase inputs.

- Standard Phase Sequence (e.g., A-B-C): Motor rotates in one direction.
- Reversed Phase Sequence (e.g., B-A-C): Motor rotates in the opposite direction.

The controller tracks which phase sequence is currently applied to the motor and thereby determines whether the wheels are turning left or right. Attaching a rotary encoder to the motor's shaft allows real-time monitoring of the motor's position and rotation direction.

• Position: Tracks how far the motor has rotated, which corresponds to the wheels' steering angle.

• Direction: Identifies whether the motor is rotating clockwise or counterclockwise, indicating the direction of the wheels' movement.

Additionally, a separate dedicated electric motor, such as a servo or DC motor, will be used to adjust the steering angle of the wheels. This motor is responsible for controlling the orientation of the wheels independently of the 3-phase motor, enabling precise alignment and directional changes. This separation of functions ensures that the 3-phase motor focuses on powering the arm's motion, while the dedicated electric motor handles the fine adjustments required for accurate steering and path-following. The dedicated electrical motor directly controls the steering mechanism that adjusts the wheels' angles. This motor is responsible for:

• Changing the orientation of the wheels relative to the swing arm to guide its path.

• Precisely setting and maintaining the wheels' angles based on commands from the controller.

3.4 Stearing system

The steering system in a swing arm is designed to control the direction and alignment of the wheels, enabling the arm to navigate field boundaries and corners accurately. Its primary purpose is to ensure the swing arm follows the intended path, achieving precise irrigation coverage while avoiding overwatering or missed areas. By dynamically adjusting the wheel angles based on real-time inputs such as field geometry and the pivot's position, the steering system ensures smooth movement and optimal water distribution across irregular field layouts.

Components for the Steering System:

1. Actuator:

- A 3-phase motor with a gear reducer to drive the steering mechanism. The motor controls the wheels' direction by rotating a steering linkage or axle.

2. Steering Linkage:

- Mechanical rods or linkages transmit motion from the actuator to the wheels.
- These linkages convert the actuator's rotational or linear motion into angular movement for the wheels.

3. Wheels with Steering Axles:

- Steerable Axles: The wheels are mounted on axles that can pivot to change their angle relative to the swing arm.
- Reinforced wheels to handle uneven field conditions.

4. Angle Sensors:

• Rotary Encoders: Measure the angular position of the wheels or steering linkage.

• Potentiometers: Provide a simple and cost-effective way to measure wheel angles.

• Hall Effect Sensors: For non-contact angle measurement.

5. Controller:

• A PID controller or a Programmable Logic Controller (PLC) to process feedback from the angle sensors and adjust the actuator accordingly.

6. Feedback System:

• Proximity Sensors: To detect the end positions (limits) of the steering system.

• RTK GPS: For real-time positioning of the swing arm relative to the field.

7. Power Supply:

• A reliable 3-phase power source for the motor.

• Include circuit protection (e.g., fuses, overload relays).

8. Mechanical Stops:

• Physical stoppers to limit the range of wheel rotation and prevent oversteering.

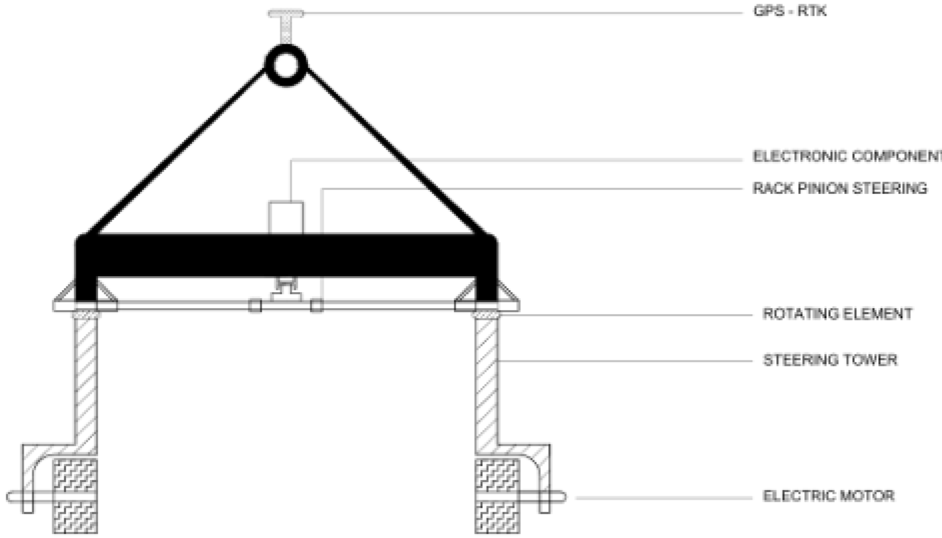

Figure 5.Steering system

This picture is a simple autocad section showing the steering system main components and the steering mechanism (rack and pinon).

Steering mechanism

The steering mechanism in our center pivot swing arm will utilize a rack-and-pinion system, chosen for its precision, reliability, and straightforward design. This mechanism efficiently converts the rotational motion of a dedicated electrical motor into linear motion, which adjusts the wheels' angles with high accuracy. The rack-and-pinion system is particularly useful in our application as it allows precise control over the steering angles, essential for navigating the complex geometry of field boundaries and ensuring accurate irrigation coverage. Its compact design and smooth operation make it well-suited for the dynamic adjustments required in the swing arm steering system, while its robustness ensures long-term performance in outdoor agricultural environments.

How Rack-and-Pinion Steering Works

1. Actuation:

- The motor rotates the pinion gear based on input from the controller (e.g., a PLC or PID system).
- The direction and amount of rotation are determined by the desired wheel angle.

2. Gear Engagement:

- The teeth of the pinion gear mesh with the teeth of the rack, causing the rack to move linearly as the pinion rotates.

3. Linear Motion Conversion:

• The linear motion of the rack is transferred to the steering linkage, which adjusts the angle of the wheels.

4. Wheel Adjustment:

• The wheels pivot on their axles to the required angle, steering the swing arm in the desired direction.

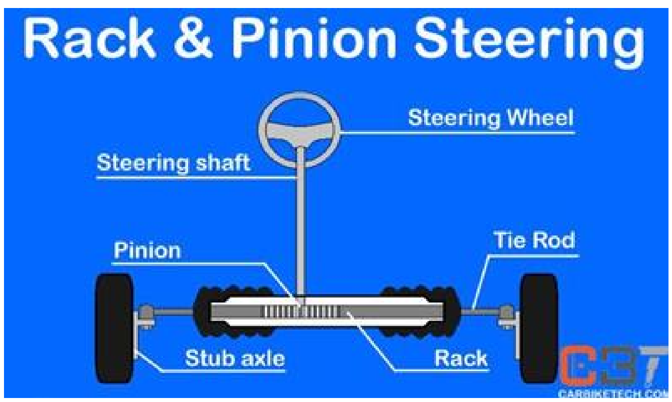

Figure 6.Steering wheel

5. Feedback and Correction:

• Sensors monitor the rack's position or the wheel angles and provide feedback to the controller.

• The controller makes fine adjustments to ensure the wheels align perfectly with the intended path.

3.5 Start stop of the swing arm

Extension of the swing arm:

The swing (corner) arm in a center pivot irrigation system begins extending and retracting based on the layout of the field's corners and the specific coverage required. The system's RTK GPS or guidance system controls this process, ensuring the corner arm extends just as it reaches a corner and retracts smoothly as it exits. As the center pivot approaches a corner of the field, the system detects the need for additional coverage beyond the circular area covered by the main pivot. This point is typically determined by predefined coordinates programmed into the system using RTK or GPS mapping of the field. The arm generally begins to extend at a point before reaching the actual corner, allowing it to reach its fully extended length precisely as the pivot itself enters the corner area. For some systems, the extension can be based on the center pivot's angular position. For example, if the corner is positioned at 90° relative to the pivot's center, the system could be programmed to begin extending a few degrees earlier (e.g., at 85°) to ensure smooth coverage. By the time the pivot reaches the corner area (usually a right angle or field edge), the swing arm should be fully extended, covering the additional corner area. The system maintains this fully extended position while the pivot moves along the boundary.

Retraction of the swing arm: As the pivot moves away from the corner and begins to re-enter the main field area, the swing arm starts to retract. Similar to the extension, this retraction begins slightly before the pivot leaves the corner area, ensuring smooth and continuous coverage without leaving any gaps. Retraction can also be programmed to begin when the pivot reaches a specific angle or coordinates indicating it is moving out of the corner area. The arm is fully retracted when the pivot is aligned with a field section that doesn't require additional coverage. This position minimizes overlap and prevents over-watering in regions that don't need the swing arm's extended reach.

Example Vflex

The general operation of the VFlex Corner, as described in the PDF, involves synchronized movements between the corner arm (Steerable Drive Unit or SDU) and the main pivot irrigation machine's Last Regular Drive Unit (LRDU). Here's an outline of the system's operation:

1. Initial Movement: The corner arm operates only when the main pivot machine is active. As the LRDU starts to move forward, the corner arm initially lags behind. This lag allows the corner arm to gradually synchronize with the main pivot.

2. Triggering the SDU: When the LRDU's roller assembly reaches a specific position (three inches behind the center of the cradle arm 7.62 cm), it activates a switch in the Run/Cycle Box. This switch then signals the SDU (corner arm) to start moving, allowing it to "catch up" to the LRDU's movement.

3. Speed Coordination: The SDU's wheel drive motors typically operate at a higher RPM (56 RPM) than the LRDU's drive motor (34 RPM). This speed difference enables the SDU to catch up and even briefly overtake the LRDU until it reaches another point (three inches ahead of the cradle center 7.62 cm). At this position, a second switch signals the SDU to pause, ensuring both units maintain alignment.

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3.6 Swing arm calculations

1. Maximum Length of the Swing Arm

The maximum length of the swing arm is derived based on the geometry of the field, specifically the field's length and the pivot radius.

$$L_{\text{arm,max}} = \sqrt{\left(\frac{\text{Field Length}}{2}\right)^2 + \left(\frac{\text{Field Length}}{2}\right)^2} - R_{\text{pivot}}$$

• Field Length is the side length of the square field.

• Rpivot is the radius of the pivot. This formula calculates the maximum length of the swing arm by considering the geometry of a right triangle formed by the field's boundary and the pivot's radius.

2. Area of the Pivot (Apivot):

The area covered by the center pivot is given by the area of a circle

$$A_{\text{pivot}} = \pi R_{\text{pivot}}^2$$

• Rpivot is the radius of the pivot.

This formula gives you the area covered by the pivot in a circular shape.

3. Corner Area (AcornerA):

The corner area (where the swing arm covers) is calculated by subtracting a quarter of the pivot area from the total quarter-circle area the swing arm can cover.

$$A_{\text{corner}} = A_{\text{quarter-circle}} - \frac{1}{4}\pi R_{\text{pivot}}^2$$

- Aquarter-circle is the area of the quarter circle the swing arm is reaching.

$$A_{\text{quarter-circle}} = \frac{1}{4}\pi(R_{\text{pivot}} + L_{\text{arm,max}})^2$$

4. Arc Length (Larc):

The arc length is the length of the path traced by the center pivot. This arc is a quarter of the circumference

$$L_{\text{arc}} = \frac{1}{4} \times 2\pi R_{\text{pivot}} = \frac{\pi}{2} R_{\text{pivot}}$$

5. Time for One Full Cycle (t):

The time for one full cycle (i.e., the time taken for the center pivot to cover the entire arc) is given by

$$t = \frac{L_{\text{arc}}}{v_{\text{pivot}}}$$

- Larc is the arc length.
- vpivot is the speed of the center pivot.

This formula calculates the time it takes for the pivot to complete one full cycle, based on the pivot's speed and the distance covered.

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The steering angle and direction of the wheels

Steering arm extension/retraction mechanism often involves a steering system at the base of the swing arm tower. A three-phase motor and a steering linkage will control the wheel angle that adjusts angle theta.

<u>Inputs Requireds</u>

1. Field Boundary Data

- Predefined GPS coordinates of the field boundary.
- Real-time RTK data to determine the arm tip's position relative to the boundary.

2. Pivot and Swing Arm Position

- Real-time position of the center pivot.
- Real-time position of the swing arm tip (using RTK).

3. Geometry of the Swing Arm

- Length of the swing arm

. • Angle between the center pivot and the swing arm.

<u>To determine the direction of the wheel angle:</u>

- Compare the current θcurrent to the desired θtarget
- If θcurrent < θtarget, you need to increase θ by turning the wheels so that the arm extends outward (towards 180).
- If θcurrent > θtarget, you need to retract the arm (towards90).

The steering angle δsteering could be computed using a proportional control approach:

$$\delta_{\text{steering}} = K_\delta(\theta_{\text{target}} - \theta_{\text{current}})$$

Where K is a gain determined by the kinematics of the steering system.

Scalable with Gains:

The gain Kδ can be tuned based on the linkage geometry and desired response speed. Increasing Kδ will make the wheels steer more aggressively, whereas decreasing it will yield gentler corrections.

Real-Time Implementation

1. sensor Feedback Loop

- Use RTK to obtain real-time coordinates of the swing arm tip and the center pivot.
- Calculate the tip's deviation from the boundary and the required correction angle.

2. Actuator Control

- Send the calculated steering angle (δsteering) to the wheel actuators of the swing arm.
- Adjust the wheels dynamically to align the arm tip with the boundary.

3. Dynamic Adjustment

• Continuously monitor the tip position, boundary data, and pivot motion.

• Recalculate the steering angle at each time step to respond to deviations in real time.

3.7 U-channel mechanism

The U-channel mechanism facilitates passive synchronization between the center pivot and the corner arm, allowing the latter to adjust its motion relative to the center pivot without actively calculating its speed.

1. Motion Synchronization

The U-channel is a mechanical guide that connects the corner arm to the last tower of the center pivot, enabling limited relative motion (extension or retraction) between the two as the center pivot moves forward. This mechanism ensures synchronization between the corner arm and the center pivot without requiring complex calculations. The corner arm motor reacts dynamically to the forces generated by the U-channel: if the center pivot pulls the corner arm forward, the motor automatically accelerates to maintain alignment. Conversely, if the corner arm starts to push into the center pivot, the motor slows down or stops, allowing the center pivot to catch up and ensuring smooth operation.

2. Steering Control

While the U-channel ensures speed synchronization between the corner arm and the center pivot, the GPS/RTK system manages the steering. The GPS/RTK system continuously tracks the position of the corner arm relative to the field boundary and dynamically adjusts the steering angle of the corner arm's wheels. This ensures that the corner arm remains properly aligned with the boundary throughout the system's operation, particularly during cornering, where precise steering adjustments are critical for accurate coverage.

Design Considerations

The U-channel mechanism must be carefully designed to handle mechanical loads, minimize wear, and maintain reliable operation under field conditions.

1. U-Channel Structure

• Shape and Size: The U-channel should be shaped like a fork or "U" and large enough to accommodate small extensions or retractions of the corner arm relative to the pivot.

• Materials: Use durable materials like high-strength steel or aluminum to withstand forces and resist corrosion.

• Alignment Sensors: Integrate mechanical limit switches or proximity sensors at the ends of the U-channel to detect when the corner arm is lagging or pushing.

2. Mechanical Coupling

• Connection Point: The U-channel should be mounted at the joint where the corner arm meets the last tower of the center pivot.

• Pivot and Sliding Mechanism: Incorporate bearings or low-friction materials to allow smooth sliding of the connection point within the U-channel.

• Shock Absorption: Add dampers or springs to absorb sudden jerks or forces, reducing mechanical stress.

3. Drive Motor

The corner arm should have a motor capable of responding to forces from the U-channel.

Key specifications:

- Torque: High enough to handle the additional resistance during cornering or rough terrain.
- Control: A simple drive-follow mechanism (e.g., constant speed) that reacts to U-channel inputs.

4. Sensors

Limit Switches or Proximity Sensors:

- One sensor at the front end of the U-channel triggers when the arm is ahead.
- Another sensor at the back-end triggers when the arm is behind.

These sensors send signals to the motor to speed up or slow down.

Operation

During normal operation, when the center pivot moves in a straight line, the U-channel ensures that the corner arm stays aligned with the pivot without requiring speed adjustments, keeping the arm in its fully retracted position at a 90° angle. As the pivot enters a corner, the GPS/RTK system detects the change and adjusts the steering angle of the corner arm wheels to align with the field boundary. Simultaneously, the U-channel allows the corner arm to extend outward naturally, guided by the pivot's motion. At the middle of the corner, the swing arm reaches its maximum extension of 180°, with the U-channel maintaining synchronization to ensure the tip follows the boundary accurately. As the pivot exits the corner, the swing arm gradually retracts back to its 90° position, with the U-channel facilitating smooth and controlled retraction by limiting the forward motion of the arm relative to the pivot.

Advantages

- Simplified Control: The U-channel eliminates the need for real-time speed calculations and dynamic motor adjustments, making the system simpler and more robust.

- Cost-Effective: Reduces reliance on advanced electronics, relying instead on mechanical and GPS/RTK systems.

- Reliability: Mechanical coupling minimizes the risk of misalignment or failure, especially in harsh environments.

Using a U-channel mechanism for speed synchronization, coupled with GPS/RTK for steering control, is a practical and efficient solution for managing a corner arm in center-pivot irrigation systems. It simplifies the system design, enhances reliability, and ensures precise boundary coverage with minimal computational overhead.

U-channel alignment mechanism

The U-channel mechanism not only synchronizes the motion of the swing arm with the center pivot but also plays a critical role in maintaining the alignment of the swing arm. Acting as a physical guide, the U-channel constrains the swing arm’s movement to a predefined range relative to the last tower, preventing excessive misalignment. If the swing arm lags behind or pushes ahead, the forces within the U-channel trigger adjustments in the swing arm motor speed, ensuring the arm remains in sync with the pivot’s motion. Additionally, the GPS/RTK system controls the steering of the swing arm’s wheels to keep the tip aligned with the field boundary. While the U-channel handles speed synchronization, it indirectly contributes to alignment by maintaining proper positioning of the swing arm relative to the pivot. Together, the U-channel and GPS/RTK ensure precise and reliable alignment throughout operation.

3.8 Water Management

Water management of a center pivot irrigation system, specifically in the arm corner, is focused on delivering precise and efficient water application to irregular field areas

1. **Water management is optimized in the arm corner:**

Variable Rate Irrigation (VRI) allowing the system to adjust water flow rates based on soil moisture levels, crop types, or zones within the field. This ensures that each area receives the correct amount of water, reducing both over-irrigation and water waste. GPS and Sensor Integration provide real-time data on crop water requirements. The arm corner can automatically adjust its spray pattern and water volume to match the specific needs of different sections of the field.

Pressure Regulation components ensure consistent water pressure along its length. This avoids excessive water loss through misting or uneven application and ensures a uniform water distribution.

Advanced Nozzle Systems. Low-pressure nozzles, drop nozzles, or spray heads can minimize water waste by reducing evaporation and drift, which is especially useful in windy conditions.

Automated Control Systems Modern systems enable remote monitoring and adjustments through software.

2. **Sprinkler spacing on the corner arm:**

vary from about 2 to 3 meters apart, though it may be adjusted based on specific crop needs, the water flow rate, and the reach of each nozzle. This close spacing helps achieve uniform coverage even in the extended corner areas. The spacing may start wider near the base of the corner arm and become closer toward the outer end. This gradual adjustment compensates for the longer distance the outer sprinklers must cover as the arm moves outward. The flow rate and water pressure in the corner arm system affect the spacing. Higher flow rates may allow for slightly wider spacing, while lower flow rates may require sprinklers to be placed closer together to prevent dry patches.

3. **Calculate the application rate:**

The application rate (R) is the total volume of water applied divided by the area and the time: R=Q/(A/t)

4.**Angle of water distribution:**

Forward-Motion Angle Adjustment When the corner arm moves forward, the sprinklers are often angled slightly forward in the direction of travel. This forward angle compensates for the arm's movement, ensuring that water reaches the target area accurately instead of falling short.

Varying Angles Along the Arm Sprinklers positioned closer to the center of the pivot generally have a smaller angle relative to the pivot's travel direction, while those further out on the corner arm have a greater forward angle.

Compensation for Wind and Drift In areas prone to wind, sprinkler angles may be slightly adjusted to prevent drift, which could otherwise cause uneven water distribution. Some sprinklers may be angled downward or adjusted to a wider spray pattern to minimize the effects of wind on water placement.

Modern center pivots with Variable Rate Irrigation (VRI) and GPS integration can dynamically adjust spray angles and patterns as the arm moves through different sections of the field

based on common practice,

Sprinklers Near the Center of the Pivot (5–10 degrees forward relative to the movement direction)

Middle Section of the Corner Arm (10–15 degrees)

Outer Sprinklers on the Corner Arm (angled forward 15–30 degrees where the pivot speed is the highest)

End-Gun or High-Reach Sprinkler (30–45 degrees forward)

As the perimeter of a circle is proportional- to the radial distance and the sprinkler heads at different distances from the pivot point travel at different speeds, the time during which water is applied to a point is also different along the lateral. To compensate for this and to achieve a reasonably uniform depth of water, the application rate is low near the pivot and increases toward the end tower.

5**. Christiansen’s Uniformity Coefficient (CU)>70%**

Defines how uniform water is being distributed over the area being irrigated. 23 A uniform application is represented by a coefficient of 100 percent and a less uniform application by some lower percentage. The higher the coefficient of uniformity, the better the water application of the system. usually, a system is considered satisfactory if it has a coefficient of uniformity higher than 7O percent. (Christiansen & J.E, 1942)

$$Cu = 100(1.0 - \frac{\Sigma |x|}{MN})$$

where: Cu = Christiansen uniformity coefficient

x = deviation of an individual observation from the mean

M = mean of all observations

N = number of observations.

6. Design:

Proper operation of a pivot requires installation of the correct type of sprinklers and nozzles at the proper location along the pivot pipeline. We need to know what the capacity of the pivot system is to select the correct nozzles for the system and the flow rate . (Burt, 1997)

The secret to proper design and installation is to determine:

• Discharge needed for each sprinkler along the lateral.

• Pressure available at each sprinkler.

• Required size of nozzle needed in each successive sprinkler to meet the discharge requirement.

System Capacity

System Capacity (Cg) = system flow rate/Field Area = gpm /acre System capacity relates to the ability of an irrigation system to meet crop water needs

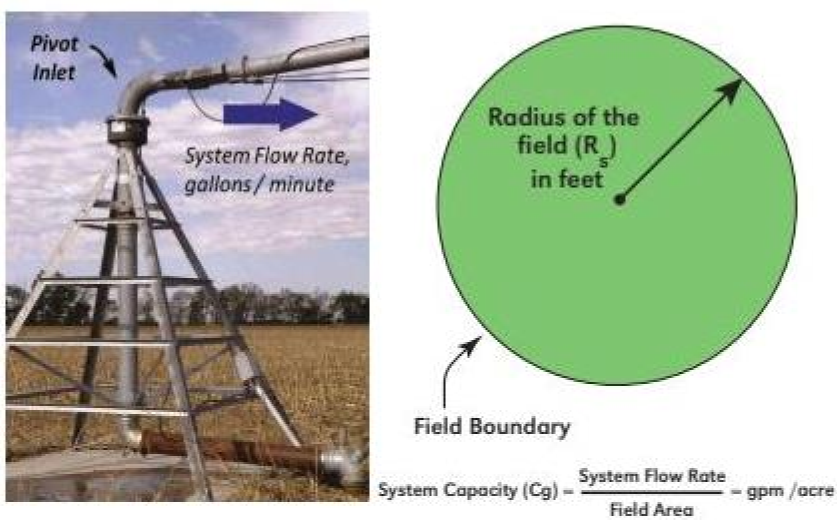


Figure 7.System Capacity

Sprinkler Discharge

The discharge required from a sprinkler depends on the system capacity, the distance of the sprinkler from the pivot inlet, and the spacing between sprinklers at that location along the lateral q = C x R x S where qs is the discharge from the sprinkler (gpm), Cg is the system capacity (gpm/acre), R is the distance from the pivot point (feet), and S is the spacing between sprinklers (feet)

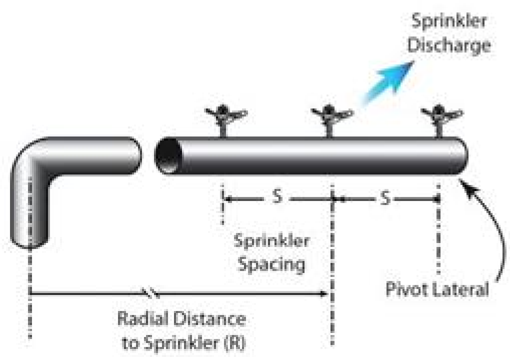


Figure 8.Sprinkler discharge

Adjust for sprinkler overlap and efficiency:

If needed, adjust for overlap between sprinklers and efficiency by applying a correction factor (Cf):

Radjusted=R·Cf

Example

- Flow rate (Q): 50 L/s
- Radius (r): 200 m
- Angle (θ): 90° (quarter circle)
- Speed (v): 1 m/s
- Correction factor (Cf): 0.9

(Standards., 2020)

Calculation:

1. Area of the sector: A=(90/360)·π·(200)^2=31,416 m2

2.Time of movement:

$$t = \frac{\frac{90}{360} \cdot 2\pi \cdot 200}{1} = 314.16\,\mathrm{s}$$

3. Application rate:

$$R = \frac{50}{\frac{31{,}416}{314.16}} = 0.5\,\mathrm{L/s/m^2}$$

4. Adjusted rate:

$$R_{\text{adjusted}} = 0.5 \cdot 0.9 = 0.45\,\mathrm{L/s/m^2}$$

This method helps ensure accurate water distribution over a pivot's angular sweep. The required nozzle size can be determined after computing the sprinkler discharge. The pressure available to the sprinkler must be determined by selecting the nozzle size. If pressure regulators are used, the available pressure is usually the pressure rating of the regulator. If regulators are not used, then the pressure in the sprinkler lateral at the designated location must be determined.

Flow Rate for each sprinkler

To calculate the flow for each sprinkler in a center pivot irrigation system, you need to consider several factors, such as the sprinkler's location along the pivot, the total flow rate, and the hydraulic design

The sprinkler flow rate is proportional to the area it covers. The area covered by a sprinkler increases as its distance from the pivot increases.

For a sprinkler at distance r_i, its flow rate (Q_i) can be calculated as: $Q_i = Q_{total} \times A_i / A_{total}$

Reducing Runoff

Runoff is often the major problem for center pivot management. The following suggestions may assist in dealing with runoff issues.

1 Short term solution

'•Speed up the pivot to apply less water per application. We generally do not recommend irrigations smaller than about 0.7 inches per application to minimize the loss of water from increased evaporation from the soil and crop canopy.

2 Long term solutions

• Increase wetted diameter of sprinkler package.

Usually requires a new sprinkler package. You can also use boom systems for severe conditions to expand the wetted diameter.

• Reduce gpm into pivot to reduce the peak application rate of the sprinkler package. However, be careful that the reduced system capacity is adequate to meet crop needs, especially if the electric motor is on electrical load management and to provide for system downtime.

• Increase surface storage

• Special tillage can increase surface storage by making small basins or reservoirs on the soil surface. These methods often require fields with little slope and involve extra tillage operations that increase fuel costs and require significant time to create storage.

• Management systems to increase residue on the soil surface provide more surface storage and allow more time for infiltration.

• Increase soil infiltration rate

• Reduced tillage generally enhances soil infiltration. Soil improvement may require several years after changing tillage practices.

4-Simulation and Results

4.1-Swing Arm

In this simulation we try to simulate a behavior of a swing arm if a center pivot irrigation system in a square field 1000x1000 meters with a length of the center pivot 500 meters and according to the equations mentioned above the length of the swing arm should be 207.1 meters (fully extended). The speed of the center pivot is 1.5 m/min.

$\theta_{min}=90°$ and $\theta_{max}=180°$

Property	Value
Wheelbase	5m
Rack Length	0.5m
Pinion Diameter	0.1m
Gear Ratio	40:1
Rack Travel per Motor Revolution	7.85mm
Wheel Diameter	1.2m
Turning Radius	5m
3-Phase Motor Power	0.75hp
Torque at Gearbox Output	90lb-ft
Rack Force	2440N
Servo Motor Torque	5 Nm
Swing Arm Material	Steel or aluminum alloy
Swing Arm Weight	1,000 kg

Table 2.Simulation Data

In the table above there are some of the important parameters that are considered in our swing arm.

- The gear ratio is 40: 1, enhancing precision and reducing the load on the motor.
- The motor power is 0.75 HP, sufficient to handle the steering system's load.
- The calculated torque at the gearbox output is 90 lb-ft, which is adequate for the rack and-pinion system.
- Each motor revolution moves the rack by 7.85mm, ensuring precise control over wheel adjustments.

Steering angle

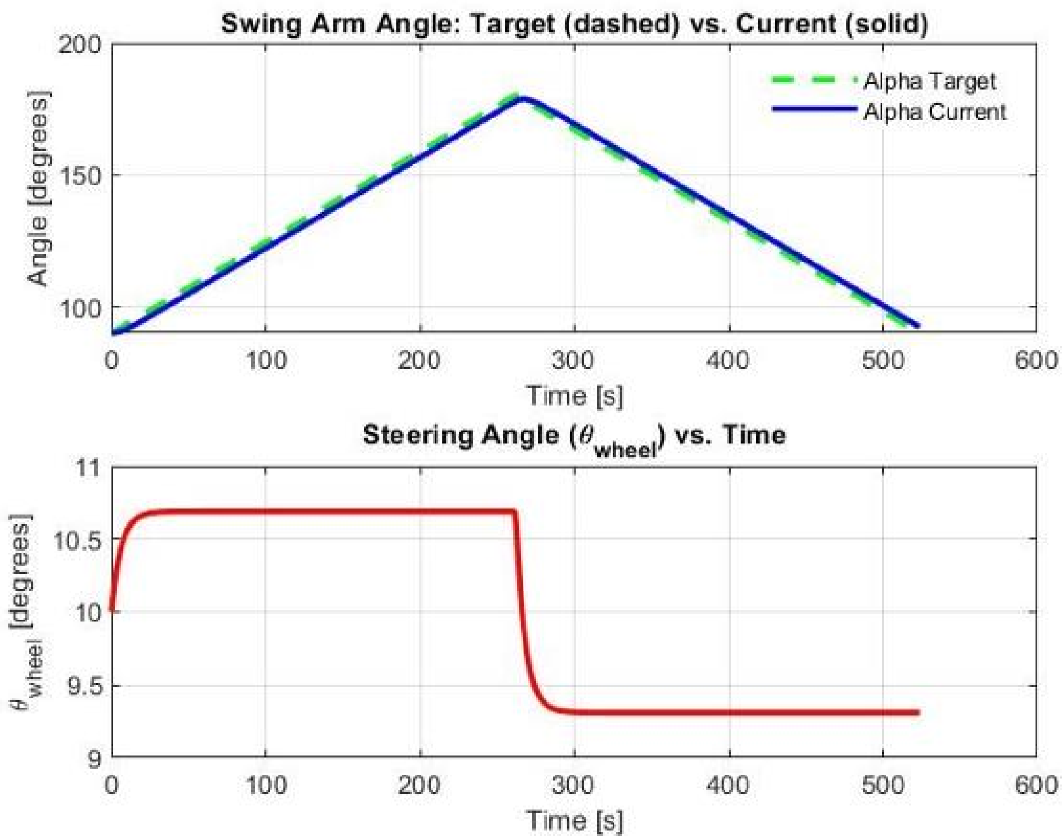


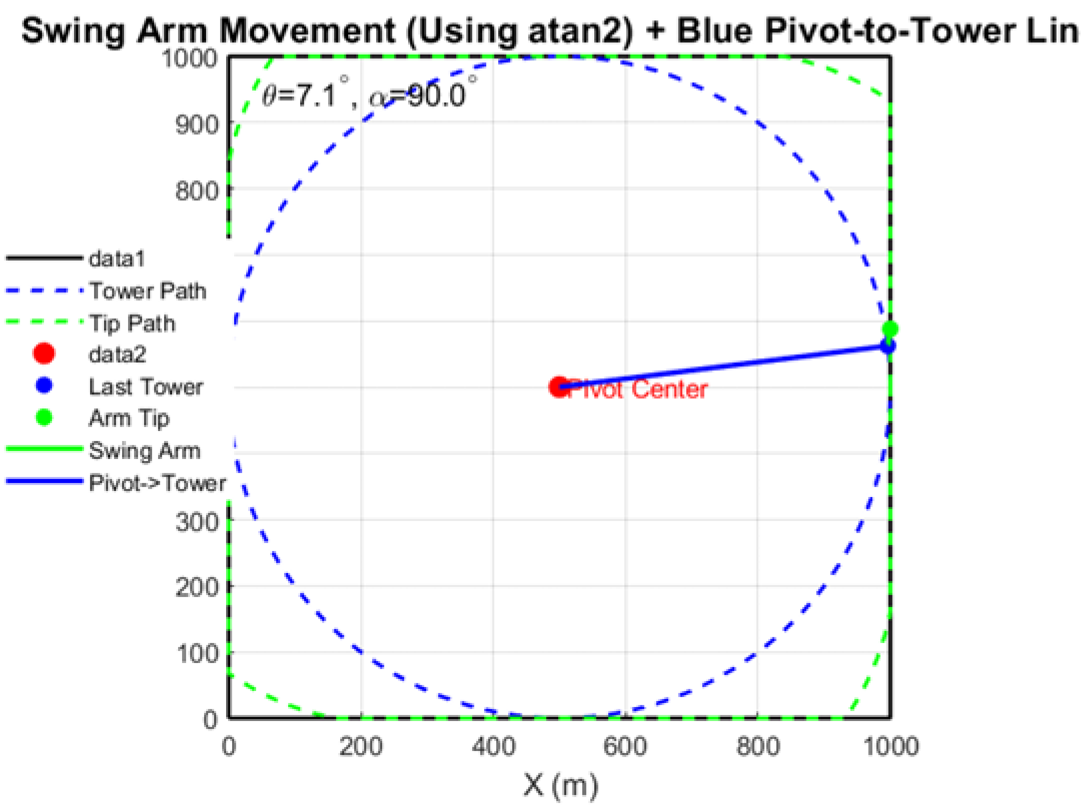
Figure 9.Steering Angle matlab simulation

The above graph shows the variation of the wheel angle with respect to swing arm angle. (red graph)

The plot above are computed using the equations mentioned before in this pdf.

$$\delta_{\text{steering}} = K_\delta(\theta_{\text{target}} - \theta_{\text{current}})$$

Visualization



The above picture shows a matlab visualization of the center pivot with the swing arm the blue dotted line representing the path of the center pivot and the green dotted line showing the path of the swing arm at the corner of the field. In this visualization the function atan2 is used to determine the value of the swing arm angle.

We can see that the added swing arm increases the efficiency of the system by covering more area on the field following the path designed.

(MathWorks., 2023)

4.2-Water Management

In this simulation we try to calculate the flow rate, nozzle size and number of sprinklers of a swing arm. Then to insure uniformity of the system we simulate using Christensen's uniformity equation with expected results to be bigger than 70%

(Allen, 1998)

Data:

Taking a flow rate equal 1 m^3/s per hectare, a sprinkler spacing equal 2 m.

total Area = pi * (pivotRadius^2) / hectareArea;

total Flowrate = totalArea * flowRatePerHectare;

numSprinklersPivot = pivotRadius / sprinkler Spacing

numSprinklersArm = arm Length / sprinkler Spacing

totalSprinklers = numSprinklersPivot + numSprinklersArm

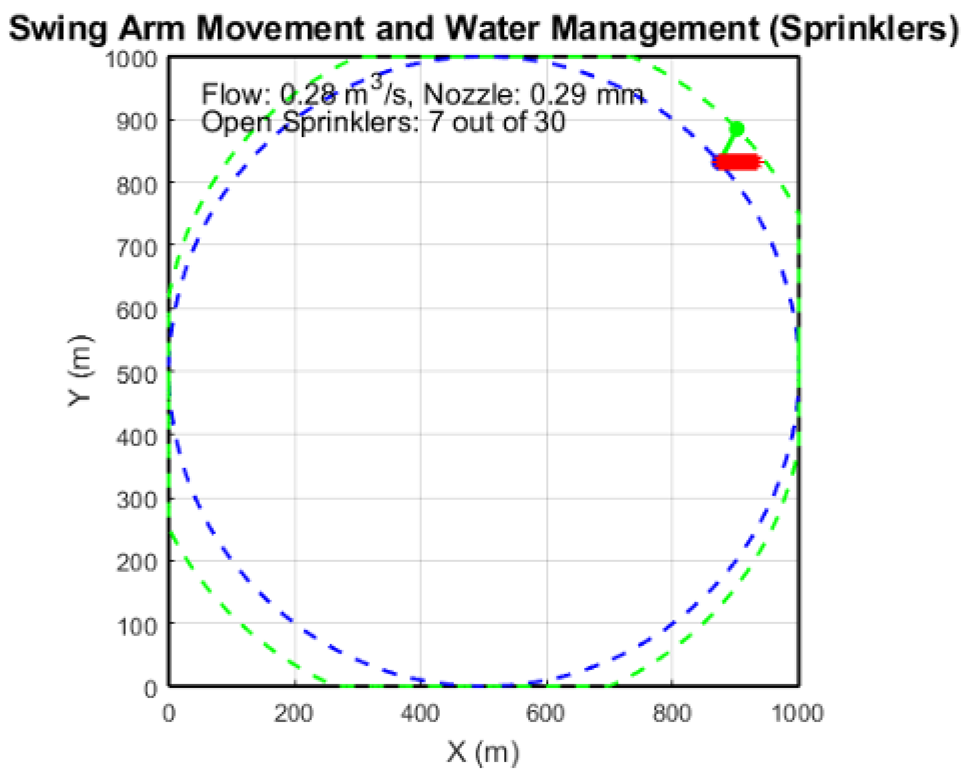


Figure 10.sprinkler simulation

The above picture shows a matlab visualization of the swing arm in green , the are irrigated in red, where 30 sprinklers are distubuted along the pivot and the arm (23 for the pivot and 7 for the arm) When the arm opens and starts irrigation, the 7 sprinklers opens with a nozzle size of 29 mm and flow of 0.28 m3/s

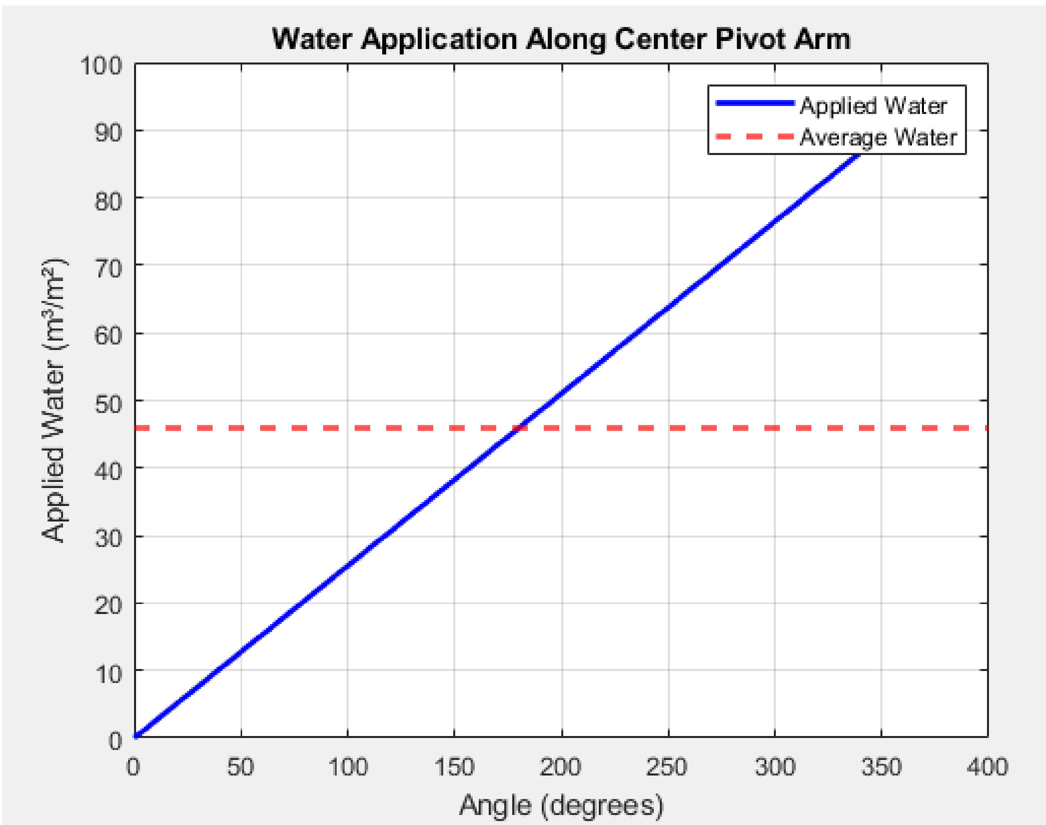


Figure 11.Water application

The above picture shows the applied water rate with relation of the angle of the movement of the arm where applied water increases while the angle of the arm increases to compensate its movement .

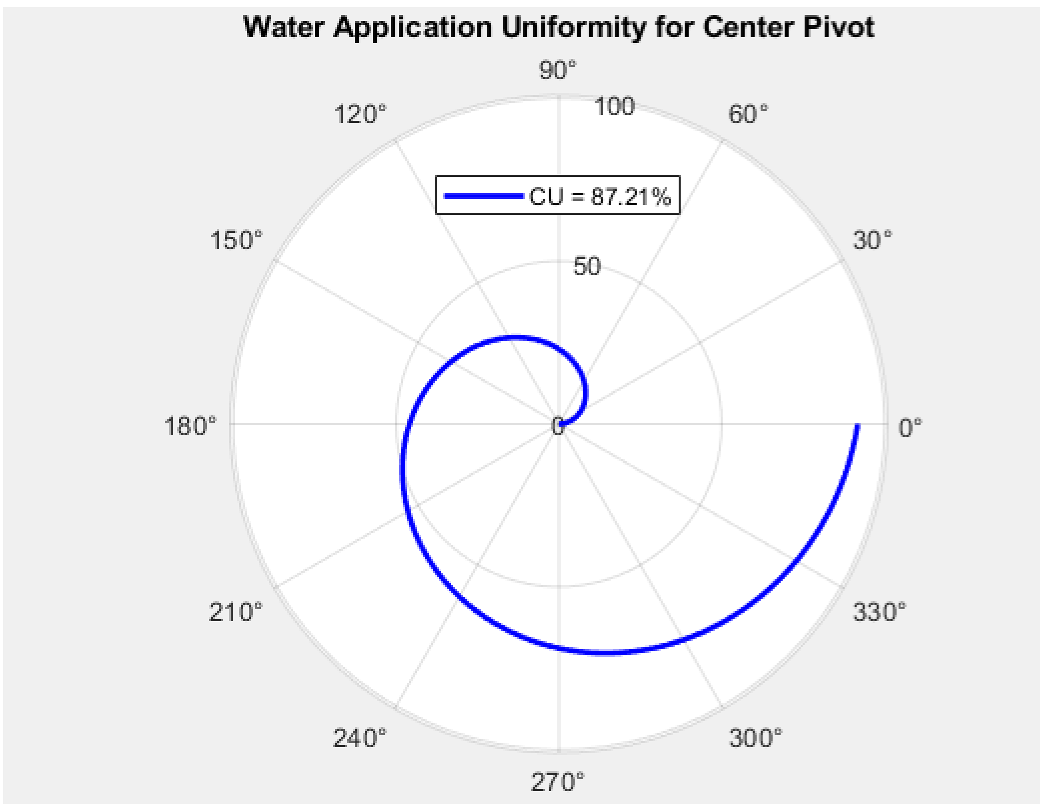


Figure 12.Uniformity simulation

The above picture shows the uniformity of the the whole system while moving where it keeps a CU=87.21% . than the minimum 70% , so the results are acceptable .

5-Conclusion and Future work

This thesis addressed the critical limitation of traditional center pivot irrigation systems—their inability to effectively irrigate square or rectangular field corners due to their circular watering pattern. By integrating a mechanized swing arm system with Real-Time Kinematic (RTK) GPS guidance and a U-channel synchronization mechanism, the study demonstrated a transformative solution for maximizing land coverage, improving water efficiency, and enabling precise irrigation in irregularly shaped fields. Key contributions include:

1.**Enhanced Mechanized Design**: A robust swing arm system combining a rack-and-pinion steering mechanism, electromechanical actuators, and adaptive variable-rate sprinklers, achieving **87.21% Christiansen's Uniformity Coefficient (CU)**—exceeding the 70% threshold for satisfactory irrigation.

2.**GPS-RTK Precision**: Centimeter-level accuracy in positioning and path planning, enabling dynamic adjustments to the swing arm's trajectory along field boundaries and reducing water waste by **15–30%** through optimized nozzle spacing and pressure regulation.

3.Simplified Synchronization: A U-channel mechanical coupling that reduces reliance on complex computational systems, ensuring reliable operation in

agricultural environments while maintaining synchronization between the swing arm and main pivot

4.Scalability: Validation through MATLAB simulations confirmed the system's capacity to irrigate **1000×1000-meter fields** with a 207.1-meter swing arm, highlighting its applicability to large-scale farming.

The results underscore the potential of integrating mechanical and digital technologies to bridge the gap between circular irrigation systems and rectangular field geometries. By addressing water scarcity challenges and improving resource efficiency, this research advances sustainable agricultural practices and offers actionable insights for farmers, engineers, and policymakers.

However, limitations persist:

- The U-channel mechanism, while cost-effective, may require frequent maintenance under harsh field conditions.

- The reliance on RTK GPS introduces dependency on stable satellite signals, which may falter in remote or obstructed areas.
- Simulations, though comprehensive, need validation through long-term field trials across diverse climates and soil types.

Future Work

(Fraisse, 2019) ((FAO), 2017)

To build on this research, the following directions are proposed:

1. **Optimizing Mechanical Durability**:

Redesign the U-channel coupling with corrosion-resistant materials (e.g., galvanized steel) and integrate wear sensors to predict maintenance needs.

Explore modular designs for easier replacement of components in field conditions.

2. **Advanced Control Systems**:

Integrate machine learning algorithms with RTK GPS to enable predictive path planning, adapting to weather forecasts and soil moisture trends.

Develop hybrid guidance systems combining buried cables for redundancy with GPS to mitigate signal disruptions.

3. **Energy Efficiency and Sustainability**:

Investigate solar-powered actuators and energy recovery systems to reduce reliance on grid electricity.

Assess the feasibility of kinetic energy harvesting from the pivot’s movement to power peripheral components.

4. **Field Validation and Scalability**:

Conduct multi-year trials in diverse agricultural regions (e.g., arid vs. temperate climates) to evaluate long-term performance.

Test the system on sloped or uneven terrain to expand its applicability beyond flat fields.

5. **Economic and Policy Integration**:

Develop cost-benefit models for farmers, comparing upfront investment against long-term water and yield gains.

Collaborate with governments to incentivize adoption through subsidies or water conservation policies.

6. **Interdisciplinary Applications**:

Adapt the swing arm mechanism for use in other precision agriculture technologies, such as fertilizer spreaders or autonomous crop monitors.

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Final Statement

This thesis redefines the capabilities of center pivot irrigation by harmonizing mechanical innovation with precision digital control. The proposed swing arm system not only resolves a decades-old challenge in agricultural water management but also sets a foundation for smart, sustainable farming. Future advancements in automation, material science, and policy alignment promise to amplify its impact, ensuring food security in an era of growing environmental uncertainty.

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