A logo with green and blue triangles

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**Politecnico di Torino**Master Degree in Mechatronic Engineering

***Mechanized Irrigation Center Pivot Arm Corner***

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Candidate:

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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.**

***\*-Definition***

The center pivots area is a type of mechanized irrigation method that uses a rotating sprinkler system mounted on a central pivot point to water crops. The pivot towers are usually mounted on a set of wheels and are usually designed to rotate around the pivot point in a circular pattern, covering a large area of land as it goes.

Center-pivot irrigation systems are beneficial due to their ability to efficiently use water and optimize a farm's yield. The systems are highly effective on large land fields

\*-Types

-Center pivots, with circular pattern. They represent at least 70% of the world market.

A yellow circular object with black lines

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-Linear or lateral systems, linear or lateral pivots, when the pivot point is replaced by a moving cart and the area irrigated has a rectangular shape. They represent 25% of world market;

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-Hippodromes, if, after a linear movement, the machine can rotate on a circular pattern, such as the original center pivot. They represent 5% of the world market.

A diagram of a basketball court

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\*-Companies and market size

Center Pivot Irrigation Systems Market size was estimated at USD 1,134.8 Mn in 2021, growing at a CAGR of 15.2% during the forecast period 2022-2028.Earlier, most of the center pivot systems are water powered while currently most of them are propelled by electric motors. Center pivot irrigation system was recognized as most preferable method of enhancing distribution of water to the whole crop in the fields.

The Global Center Pivot Irrigation Systems Market Report tracks recent innovations, key developments and startup’s details that are actively working in the market

Leading companies:

Valmont Industries (Valley)

Lindsay Zimmatic

Reinke Manufacturing

Bauer

T-L Irrigation

\*-How a pivot works

The differences between manufacturers mainly relate to:

- Electrical system design (but differences are small); - Spans and structural components design.

- Automation options (most times the design of electrical and automation system is entrusted to third party companies and therefore there are not any updates, also considering the speed and evolution of technology).

- Traction components, for example some companies may prefer bigger or smaller tires, depending on their installations, types of soil etc.

A diagram of a structure

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\*-Movable Corner system study:

In this application, one span (with its tower and span) is added at the end of the center pivot and can rotate freely for opening and closing itself to increase the irrigated area. It can be GPS-guided or below ground guided.

A diagram of a green circle

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Bender (to be installed on center pivots). In this application, the last span(s) can rotate after the end of field to cover more surface

A aerial view of a farm

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The "corner study" in the context of mechanized irrigation systems involves analyzing and optimizing the efficiency and performance of corner systems in irrigation, particularly with center pivot systems. This study focuses on understanding how corner systems can effectively cover areas of fields that traditional pivot systems might miss, such as the corners of square or rectangular fields. Here are some key aspects of a corner study:

**a. Coverage Efficiency:**

* **Objective**: To determine how effectively the corner system covers additional areas that the main pivot arm cannot reach.
* **Analysis**: This involves mapping the coverage patterns and measuring how much additional area is watered compared to a standard pivot without a corner system.

**b. Water Distribution Uniformity:**

* **Objective**: To assess the uniformity of water distribution across the field, including the corner areas.
* **Analysis**: The study may involve using sensors or visual inspection to check for over-watering or under-watering in different parts of the field, including areas covered by the corner arm.

**c. Guidance System Performance:**

* **Objective**: To evaluate the precision and reliability of the guidance system used by the corner arm.
* **Analysis**: This involves testing GPS or buried cable guidance systems under various field conditions to see how accurately the corner arm follows the intended path.

**d. Impact on Crop Yield:**

* **Objective**: To measure the impact of corner systems on crop yield, especially in areas that would otherwise be dry.
* **Analysis**: Yield data is collected from crops in the corner areas and compared to areas covered by the main pivot to assess the added value of the corner system.

**e. Energy and Water Use Efficiency:**

* **Objective**: To evaluate the efficiency of water and energy use when using corner systems.
* **Analysis**: This includes calculating the water applied per unit area and energy consumption, comparing the data with fields irrigated without a corner system to determine cost-effectiveness.

**f. Technical Challenges and Solutions:**

* **Objective**: To identify technical challenges associated with corner systems, such as mechanical reliability, maintenance needs, and potential for system failure.
* **Analysis**: Gathering data on common issues and evaluating solutions, like improved materials or updated software for guidance and control.

**g. Economic Analysis:**

* **Objective**: To perform a cost-benefit analysis of using corner systems.
* **Analysis**: This involves looking at the initial investment costs, ongoing maintenance, and potential increase in revenue from higher yields due to better coverage.

\*- **Corner Guidance System**

Corner guidance systems are crucial components of mechanized irrigation systems, particularly in center pivot systems with corner arms. They guide the corner arm as it extends and retracts to cover field areas that are outside the reach of the main pivot's circular path, like field corners. Here’s a detailed overview of the different types of corner guidance systems and how they function:

**1. GPS-Based Guidance Systems:**

* **Overview**: These systems use Global Positioning System (GPS) technology to navigate the corner arm along the intended path.
* **Functionality**:
  + The system includes a GPS receiver mounted on the corner arm or the pivot.
  + It continuously tracks the position of the corner arm relative to the field boundaries.
  + The GPS data is processed in real-time to adjust the extension and retraction of the corner arm, ensuring it follows the desired path and covers the maximum possible area.
* **Advantages**:
  + High accuracy, especially in large and irregularly shaped fields.
  + Flexibility to easily update field boundaries and paths through software without physical alterations.
  + Reduced need for physical infrastructure like buried cables.

**2. Buried Wire or Cable Guidance Systems:**

* **Overview**: These systems rely on a wire or cable buried around the field perimeter, which emits a low-frequency electromagnetic signal.
* **Functionality**:
  + Sensors mounted on the corner arm detect the signal from the buried wire.
  + The strength and direction of the signal help guide the arm's movement along the field boundary.
  + As the corner arm moves, it adjusts its extension based on the signal strength to ensure proper coverage of the corner areas.
* **Advantages**:
  + Reliable in fields with consistent boundaries and few changes.
  + Less affected by signal disruptions that might impact GPS systems.
* **Disadvantages**:
  + Installation of buried cables can be costly and time-consuming.
  + Less flexible to changes in field boundaries compared to GPS systems.

**3. Smart Soil Sensors and Feedback Loops:**

* **Overview**: Advanced corner systems may integrate soil moisture sensors and feedback loops to optimize the guidance and watering process.
* **Functionality**:
  + Sensors monitor soil moisture levels in real-time and send data back to the control system.
  + Based on soil moisture readings, the system adjusts the irrigation pattern and corner arm movement to ensure even water distribution.
* **Advantages**:
  + Enhances precision irrigation, reducing water waste and ensuring uniform coverage.
  + Can adapt to varying field conditions dynamically.

**4. Hybrid Systems:**

* **Overview**: Some systems use a combination of GPS and buried wire guidance for enhanced accuracy and reliability.
* **Functionality**:
  + GPS provides general guidance and path planning, while the buried wire offers precise boundary adherence, especially in critical zones.
* **Advantages**:
  + Combines the flexibility of GPS with the reliability of buried wire systems.
  + Provides redundancy, minimizing the risk of guidance failure.

**5. Control and Monitoring:**

* **Central Control Unit**: All guidance systems connect to a central control unit that processes data and commands the corner arm movements.
* **User Interface**: Farmers can interact with these systems via user interfaces such as control panels, tablets, or smartphones, which display real-time positioning and performance metrics.
* **Alerts and Alarms**: Systems are equipped with alerts for deviations, obstacles, or errors in guidance, allowing for quick intervention.

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 3 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.

A diagram of a copper tube

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GPS Guidance and Mapping (zimmatic 9500CC)

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 realtime 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 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 4 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.

A close-up of a radio antenna

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***GPS RTK (Real-Time Kinematic):***

RTK (Real-Time Kinematic) GPS-based guidance systems are highly accurate positioning systems used in agricultural applications, including mechanized irrigation systems with corner arms. RTK GPS enhances the standard GPS accuracy, making it ideal for precision tasks like guiding corner arms in irrigation. Here's how RTK GPS-based guidance systems work:

**1. Understanding RTK GPS:**

* **RTK Enhancement**: RTK improves GPS accuracy to within 1-2 centimeters by using corrections transmitted from a fixed base station.

**2. Key Components of RTK GPS Systems:**

* **Base Station**: A fixed reference point that continuously receives signals from GPS satellites and calculates its exact position.
* **Rover Unit**: A mobile GPS receiver, usually mounted on the corner arm or pivot system, that moves through the field.
* **Communication Link**: Typically, a radio, cellular, or internet connection is used to transmit correction data from the base station to the rover.

**3. How RTK GPS Works:**

* **Base Station Setup**:
  + The base station is set up at a known, fixed location in or near the field.
  + It receives satellite signals and compares the calculated positions to its known position, determining the positional errors.
* **Correction Data Generation**:
  + The base station generates correction data based on the difference between the satellite-calculated position and its known true position.
  + This correction data is transmitted in real-time to the rover unit.
* **Rover Unit Operation**:
  + The rover unit on the corner arm receives the same GPS satellite signals as the base station.
  + It also receives the correction data from the base station via the communication link.
  + The rover adjusts its position calculations based on the correction data, achieving centimeter-level accuracy.

**4. Guiding the Corner Arm:**

* **Path Planning**: Before operation, a precise path or boundary is defined, typically using software that incorporates field boundaries and any obstacles.
* **Real-Time Position Adjustment**:
  + As the corner arm moves, the rover continuously calculates its exact position using the corrected GPS data.
  + The system adjusts the extension and retraction of the corner arm to follow the planned path precisely, ensuring complete and efficient field coverage, including irregular corners.
* **Feedback Loop**:
  + The RTK system provides constant feedback to the control system, allowing for real-time adjustments.
  + Any deviations from the planned path are quickly corrected to maintain accurate guidance.

**5. Advantages of RTK GPS-Based Guidance:**

* **High Accuracy**: Achieves centimeter-level precision, which is essential for tasks requiring exact positioning, like irrigation of field corners.
* **Reliability**: Provides consistent accuracy regardless of field conditions, day or night, and is less susceptible to environmental changes that could affect other guidance methods.
* **Efficiency**: Minimizes over-watering or missed areas, optimizing water usage and enhancing crop yields.
* **Flexibility**: Easily adaptable to different field shapes and sizes, and capable of accommodating changes in field layouts or boundaries.

**6. System Calibration and Maintenance:**

* **Initial Calibration**: RTK systems need to be calibrated initially to set up the base station correctly and align the system with the specific field layout.
* **Ongoing Maintenance**: Regular checks and software updates are necessary to ensure the system continues to operate at peak accuracy. Communication links must be monitored to avoid signal loss.

**7. Potential Challenges:**

* **Signal Interference**: RTK signals can be disrupted by physical obstructions like tall buildings, dense foliage, or even severe weather conditions.
* **Dependency on Base Station**: The system's accuracy is highly dependent on the quality and stability of the base station. If the base station experiences errors or signal loss, the rover's accuracy will be compromised.

In summary:

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.

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.

**Which is Better?**

* **Choose Cable Guidance** if you have a stable field layout with minimal changes, are concerned about GPS signal reliability, and prefer a system with no need for recalibration due to weather or environmental factors.
* **Choose GPS-Based Guidance (RTK)** if you need high precision, flexibility, and the ability to easily update or change field boundaries. It's also better if you have multiple fields or areas where cables would be impractical.

In general, GPS-Based Guidance Systems are more versatile and offer higher precision, making them the preferred choice in modern precision agriculture, especially where adaptability and high accuracy are critical.

**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.

\*-Sensors

In mechanized irrigation systems with corner arms, several sensors can be integrated to enhance performance, accuracy, and operational efficiency. Here’s a list of commonly used sensors and their purposes:

**1. GPS Sensors (RTK GPS Receivers):**

* **Purpose**: To provide precise positioning data for guiding the corner arm along the field boundaries.
* **Application**: Essential for GPS-based guidance systems, offering centimeter-level accuracy.

**2. Ultrasonic Sensors:**

* **Purpose**: To detect obstacles such as trees, fences, or other equipment in the path of the corner arm.
* **Application**: Helps in real-time adjustments to prevent collisions and ensure smooth operation.

**3. Proximity Sensors:**

* **Purpose**: To sense the presence of nearby objects and avoid contact.
* **Application**: Commonly used near end guns or corner arms to avoid obstacles in proximity.

**4. Soil Moisture Sensors:**

* **Purpose**: To measure the moisture levels in the soil, ensuring optimal water application.
* **Application**: Helps in adjusting irrigation rates based on real-time soil moisture data, enhancing water efficiency.

**5. Pressure Sensors:**

* **Purpose**: To monitor water pressure within the irrigation system.
* **Application**: Ensures that the system is operating within the correct pressure range, avoiding over- or under-pressurization that could affect water distribution.

**6. Flow Sensors:**

* **Purpose**: To measure the flow rate of water through the irrigation system.
* **Application**: Assists in detecting blockages or leaks, ensuring uniform water distribution across the field.

**7. Tilt and Angle Sensors:**

* **Purpose**: To monitor the angle and tilt of the corner arm or pivot structure.
* **Application**: Helps in maintaining proper alignment and positioning, especially on uneven terrain.

**8. Speed Sensors:**

* **Purpose**: To measure the speed of the corner arm or pivot as it moves through the field.
* **Application**: Ensures consistent movement speed, which is crucial for uniform water application.

**9. Weather Sensors (Wind, Rain, Temperature):**

* **Purpose**: To monitor environmental conditions that can impact irrigation, such as wind speed, rainfall, and temperature.
* **Application**: Allows the system to adjust irrigation schedules and operations based on current weather conditions, optimizing water usage.

**10. Position Sensors:**

* **Purpose**: To track the position of the corner arm or pivot relative to the field layout.
* **Application**: Ensures the system follows the programmed path accurately, especially in complex field shapes.

**11. Infrared Sensors:**

* **Purpose**: To detect heat signatures, which can be used for identifying stressed or dry areas in the field.
* **Application**: Enhances precision irrigation by targeting specific areas that need more water.

**12. Light Sensors (LIDAR):**

* **Purpose**: To map field topography and detect objects with high precision using light detection and ranging.
* **Application**: Useful in creating detailed field maps and guiding the corner arm around obstacles.

These sensors can be integrated individually or as part of a comprehensive control system to improve the accuracy, efficiency, and reliability of mechanized irrigation systems. The choice of sensors depends on the specific requirements of the field, the level of precision needed, and the type of guidance system being used.

\*-Data

To effectively implements a mechanized irrigation system with a corner arm, especially when using advanced guidance systems like RTK GPS or cable guidance, collecting and analyzing the right data is crucial. Here's a breakdown of the key data points needed for planning, implementing, and optimizing the system:

**1. Field Data:**

* **Field Boundaries and Layout**: Accurate GPS coordinates or map data of the field's perimeter, including any irregular shapes or corners.
* **Topography**: Elevation data to understand field slopes and contours, which can impact water flow and system movement.
* **Obstacles**: Locations of obstacles such as trees, buildings, fences, and utility lines that the system must navigate around or avoid.

**2. Soil Data:**

* **Soil Type and Composition**: Understanding the soil types (e.g., sandy, loamy, clay) to tailor irrigation schedules and water amounts.
* **Soil Moisture Levels**: Baseline moisture levels and real-time measurements to adjust watering dynamically.
* **Infiltration Rates**: Data on how quickly water infiltrates into the soil, affecting how much water should be applied and how often.

**3. Crop Data:**

* **Crop Type**: Specific water requirements for the crop(s) being grown, which influence irrigation scheduling.
* **Growth Stage**: Different stages of crop growth have varying water needs; data on the current growth stage helps fine-tune irrigation.

**4. Irrigation System Data:**

* **System Specifications**: Information on the pivot length, corner arm length, sprinkler types, and nozzle spacing.
* **Water Pressure and Flow Rates**: Data on the system’s water pressure and flow rates to ensure consistent and adequate water delivery.
* **Operational Speeds**: Speed settings of the pivot and corner arm to maintain uniform coverage.

**5. Weather Data:**

* **Current Weather Conditions**: Real-time data on temperature, humidity, wind speed, and rainfall.
* **Forecast Data**: Weather forecasts to adjust irrigation schedules, reducing water usage during expected rain or high wind conditions.

**6. Guidance System Data:**

* **RTK GPS Coordinates**: Precise location data from GPS for accurate guidance of the corner arm.
* **Correction Signals**: Data from RTK base stations to correct GPS inaccuracies.
* **System Calibration Data**: Initial setup and calibration data to ensure that the guidance system aligns correctly with the field boundaries.

**7. Performance and Efficiency Data:**

* **Water Application Rates**: Data on the amount of water applied per unit area to ensure optimal irrigation.
* **Coverage Uniformity**: Measurements of water distribution across the field to identify and correct uneven coverage.
* **Energy Usage**: Data on the power consumption of the system to optimize energy use and reduce costs.

**8. Sensor Data:**

* **Proximity and Obstacle Detection**: Data from sensors that help navigate and avoid obstacles.
* **Pressure and Flow Monitoring**: Real-time monitoring of system pressure and flow rates to ensure the system operates within desired parameters.

**9. Historical Data:**

* **Past Irrigation Schedules**: Historical data on irrigation timings, amounts, and methods used.
* **Crop Yield Data**: Historical crop yield data to correlate with irrigation practices and optimize future strategies.

**10. Economic Data:**

* **Cost of Implementation**: Data on the costs associated with setting up the guidance and irrigation systems, including sensors and equipment.
* **Maintenance Costs**: Ongoing maintenance and operational costs to evaluate the cost-effectiveness of the system.
* **ROI Analysis**: Return on investment data considering increased yields, water savings, and operational efficiencies.

**Implementation Steps:**

1. **Data Collection and Analysis**: Gather all necessary data points using GPS surveys, soil testing, weather monitoring, and existing field records.
2. **System Design**: Use the collected data to design the irrigation system layout, configure guidance paths, and set irrigation schedules.
3. **Calibration and Testing**: Calibrate the guidance system and sensors according to the collected data, and perform test runs to ensure accurate operation.
4. **Real-Time Monitoring**: Continuously collect data during operation to monitor performance, adjust settings, and refine irrigation strategies.
5. **Feedback Loop**: Implement a feedback system using real-time sensor data to make dynamic adjustments to irrigation schedules and guidance paths.

By collecting and utilizing this comprehensive data, you can implement a highly efficient and effective mechanized irrigation system that maximizes water use, enhances crop yields, and adapts to changing field conditions.

\*-Corner movement (problems and solutions)

The movement of the corner arm in mechanized irrigation systems can encounter several problems that impact its efficiency and effectiveness. Here are some common issues and potential challenges associated with the movement of corner arms:

**1. Alignment and Tracking Errors:**

* **Misalignment with Field Boundaries**: The corner arm may deviate from the intended path, leading to areas of under- or over-watering.
* **Guidance System Failures**: Problems with GPS or cable guidance systems, such as signal loss, interference, or calibration errors, can cause the corner arm to drift off course.

**2. Obstacle Detection and Avoidance Issues:**

* **Failure to Detect Obstacles**: Sensors may fail to detect obstacles like rocks, poles, or sudden changes in terrain, causing collisions or damage to the corner arm.
* **Delayed Response**: Even if an obstacle is detected, delayed or incorrect responses from the control system can lead to the arm hitting the object.

**3. Terrain Challenges:**

* **Rough or Uneven Ground**: Uneven terrain, soft soil, or areas with significant slopes can cause the wheels or tracks of the corner arm to lose traction or become stuck.
* **Wheel Slippage**: On wet or muddy ground, wheel slippage can occur, disrupting the movement and leading to misalignment.

**4. Mechanical Failures:**

* **Joint and Articulation Issues**: Hinges, joints, or pivot points on the corner arm can wear out or fail, leading to improper extension and retraction.
* **Motor and Hydraulic Failures**: Electric motors or hydraulic systems that control the arm’s movement can fail, causing it to stop or move incorrectly.

**5. Speed Synchronization Problems:**

* **Inconsistent Speeds**: If the speed of the corner arm is not properly synchronized with the main pivot, it can result in uneven water application, causing areas to be over-watered or missed.
* **Speed Fluctuations**: Variations in speed due to mechanical issues or control errors can affect the uniformity of irrigation.

**6. Sensor Malfunctions:**

* **Faulty Sensors**: Malfunctioning sensors can provide incorrect data to the control system, leading to inappropriate adjustments in the arm's movement.
* **Sensor Interference**: Environmental factors like heavy rain, dust, or strong sunlight can interfere with sensors, reducing their accuracy and reliability.

**7. Environmental Interferences:**

* **Wind Effects**: Strong winds can physically push the corner arm off course, especially if it has a large surface area or is fully extended.
* **Electrical Interference**: Nearby power lines or other electrical equipment can interfere with the guidance system’s signals, leading to movement errors.

**8. Guidance System Limitations:**

* **RTK GPS Signal Loss**: RTK GPS systems rely on continuous communication with base stations. Signal loss due to obstructions or weak connections can cause positioning errors.
* **Cable Breaks in Cable Guidance Systems**: In cable-guided systems, buried cables can be damaged by soil movement, rodents, or farm equipment, leading to guidance failures.

**9. End Gun Activation Issues:**

* **Incorrect Activation**: End guns may activate at the wrong times or fail to turn on when needed, leading to uneven water distribution in the corners.
* **Pressure Drops**: The activation of end guns can cause pressure drops in the system, affecting the overall performance and movement of the corner arm.

**10. Weather-Related Challenges:**

* **Mud and Soft Ground**: Heavy rains can create muddy conditions that impede the movement of the corner arm, causing it to sink or get stuck.
* **Freezing Conditions**: In cold weather, ice buildup can restrict movement, particularly in the joints and hinges of the arm.

**11. Control System Failures:**

* **Software Glitches**: Bugs or errors in the control software can lead to incorrect movement commands or system crashes.
* **Loss of Power**: Electrical failures or power loss can cause the corner arm to stop moving, potentially leaving parts of the field unwatered.

**12. Operational Errors:**

* **Incorrect Calibration**: Poor initial calibration of the system can lead to persistent errors in movement and coverage.
* **Operator Mistakes**: Manual overrides or incorrect settings input by operators can disrupt the automated movement of the corner arm.

To address the common problems associated with the movement of corner arms in mechanized irrigation systems, several solutions and strategies can be employed. Here’s a detailed list of solutions for each issue:

**1. Alignment and Tracking Errors:**

* **Regular Calibration**: Ensure that the guidance system (GPS or cable-based) is regularly calibrated to maintain accuracy.
* **High-Quality Sensors**: Use high-quality sensors and ensure they are properly installed to minimize tracking errors.
* **Redundant Systems**: Implement redundant guidance systems to cross-check and correct deviations in real-time.

**2. Obstacle Detection and Avoidance Issues:**

* **Enhanced Sensor Technology**: Upgrade to more reliable ultrasonic, radar, or LIDAR sensors for better obstacle detection.
* **Regular Sensor Maintenance**: Clean and test sensors regularly to ensure they function correctly.
* **Automated Responses**: Implement advanced control algorithms that provide quicker and more precise responses to detected obstacles.

**3. Terrain Challenges:**

* **Terrain Preparation**: Level or improve the field’s terrain where possible to reduce the impact of uneven ground on the corner arm’s movement.
* **Adaptive Suspension Systems**: Use adaptive suspension systems or adjustable wheels that can handle varying terrain conditions more effectively.
* **Soil Stabilization**: Apply soil stabilization techniques or use soil conditioners to improve traction and reduce mud accumulation.

**4. Mechanical Failures:**

* **Routine Maintenance**: Schedule regular maintenance checks for joints, hinges, motors, and hydraulic systems to prevent wear and tear.
* **Quality Parts**: Use high-quality, durable parts that can withstand the operational stresses and environmental conditions.
* **Spare Parts Inventory**: Maintain an inventory of critical spare parts to quickly address any mechanical failures.

**5. Speed Synchronization Problems:**

* **Automated Speed Control**: Implement automated systems that adjust the speed of the corner arm in real-time based on the speed of the main pivot.
* **Speed Monitoring**: Continuously monitor the movement speed and make adjustments as needed to ensure synchronization.

**6. Sensor Malfunctions:**

* **Regular Testing and Calibration**: Frequently test and calibrate sensors to ensure they are functioning correctly.
* **Redundant Sensors**: Use multiple sensors or backup systems to provide accurate data even if one sensor fails.
* **Shielding and Protection**: Protect sensors from environmental factors that could cause interference, such as dust or extreme temperatures.

**7. Environmental Interferences:**

* **Weather-Resistant Equipment**: Use weather-resistant and sealed components to protect against environmental factors like rain, dust, or extreme temperatures.
* **Shielding and Grounding**: Implement shielding and grounding techniques to reduce electrical interference from nearby power lines or equipment.

**8. Guidance System Limitations:**

* **Signal Boosters**: Use signal boosters or repeaters to enhance RTK GPS signal reliability and reduce the impact of obstructions.
* **Alternative Guidance Methods**: Consider integrating alternative or complementary guidance methods (e.g., visual markers or inertial measurement units) to reduce reliance on a single system.

**9. End Gun Activation Issues:**

* **End Gun Controls**: Regularly check and calibrate end gun controls to ensure proper activation and deactivation.
* **Pressure Regulation**: Monitor and adjust water pressure to prevent drops that could affect end gun performance.

**10. Weather-Related Challenges:**

* **Weather Monitoring Systems**: Install weather monitoring systems to provide real-time data and adjust irrigation schedules accordingly.
* **Weather Adaptation**: Design the system to adapt to changing weather conditions, such as implementing automatic adjustments for rain or wind.

**11. Control System Failures:**

* **Robust Software**: Use reliable and well-tested software for controlling the system, and keep it updated to address potential bugs.
* **Power Backup**: Implement backup power solutions (e.g., generators or UPS systems) to ensure continuous operation during power outages.
* **Manual Overrides**: Ensure manual override options are available and functioning correctly for emergency situations.

**12. Operational Errors:**

* **Training and Procedures**: Provide thorough training for operators on system use, calibration, and troubleshooting procedures.
* **Clear Instructions**: Ensure that operators have clear, up-to-date instructions and guidelines for setting up and maintaining the system.
* **System Documentation**: Maintain detailed documentation of system settings, calibration data, and operational procedures for reference.

**Additional Solutions:**

* **Data Analytics**: Utilize data analytics to monitor system performance and identify potential issues before they become critical problems.
* **Remote Monitoring**: Implement remote monitoring and diagnostic tools to keep track of system health and performance from a distance.
* **Continuous Improvement**: Regularly review system performance and incorporate feedback to make continuous improvements and address emerging challenges.

***-\*Geometrically :***

**Key Geometrical Terms:**

* **Circle**: The initial path of the main pivot (without the corner arm) forms a circle with a fixed radius.
* **Radius**: The distance from the center of the pivot to the end of the pivot arm (without the corner).
* **Variable Radius Curve**: As the corner arm extends, the radius varies, creating a non-circular path that extends beyond the main pivot’s circle.
* **Polygonal Area**: The corner arm irrigates an irregular, polygonal area outside the main pivot’s perfect circle.
* **Arc Length**: The path traced by any point on the pivot or corner arm. The arc length increases as the corner arm extends.

**Steering and Corner Angle:**

* **Steering Geometry**: The corner arm has additional wheels or tracks that adjust based on its extension. The wheels move at different angles from the main pivot to steer the corner arm.
* **Turning Angle**: When the corner arm extends outward, the **angle of the corner arm relative to the pivot arm** changes, typically becoming more acute. This angle decreases as the arm retracts.
* **Angular Velocity**: The angular velocity of the corner arm is not constant. The arm slows down as it moves outward (to cover a larger radius), and it speeds up when retracting (as the radius shortens).

**Corner Arm Movement – Extension Beyond the Circle:**

* **Non-circular Path**: The corner arm moves outside the main pivot’s circular path, creating a complex, **non-circular curve** (typically a **variable-radius curve** or **irregular shape**).
* **Variable Radius**: As the corner arm extends, the system’s effective radius increases. At maximum extension, the corner arm creates the largest possible radius for the system. When the arm retracts, the system follows the original circular path.
* **Geometric Shape**: The area irrigated by the corner arm follows an irregular boundary, typically described as a **quadrilateral** or **polygonal** shape, depending on the field’s geometry and obstacles.

***Angle 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. 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

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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∘180∘). 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 quadrants and ensures numerical stability, even when one of the components is zero. In realtime 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 αraw Using atan2



• Step 2: Adjust the Raw Angle αraw Since atan2 provides angles in the range −180 to 180∘, convert the angle to a positive range [0∘,360∘]



• Step 3: Restrict the Angle to 90∘≤α≤180∘



Actuators and motors

The motor drive 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 motor drive, 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 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.

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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).

• Direction Detection: The motor can indirectly detect the direction of wheel movement by monitoring its own rotational state, which is linked to the wheel’s 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.

Steering 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 missing 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.

Diagram of a machine with text

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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.

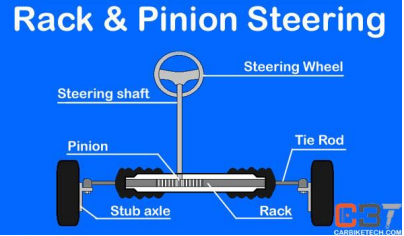
4. Wheel Adjustment:

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

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.



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 13 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. 14 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.

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2. Area of the Pivot (Apivot): The area covered by the center pivot is given by the area of a circle



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

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

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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

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

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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. Inputs Requireds 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. To determine the direction of the wheel angle: • 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). 16 • If θcurrent > θtarget, you need to retract the arm (towards90). The steering angle δsteering could be computed using a proportional control approach: