Connectivity and Navigation Bottlenecks in IoT-Controlled Agricultural Robots: A Systematic Review

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Abstract — The integration of Internet of Things (IoT) technologies with agricultural robots has transformed modern farming by enabling autonomous monitoring, precision agriculture, intelligent harvesting, and real-time decision-making. Communication technologies such as 5G and LoRaWAN facilitate data exchange between robots, cloud platforms, and sensor networks, while navigation technologies including Global Positioning System (GPS), Real-Time Kinematic GPS (RTK-GPS), LiDAR, computer vision, and sensor fusion enable autonomous mobility in complex agricultural environments. Despite significant advancements, connectivity and navigation remain major bottlenecks limiting the large-scale deployment of agricultural robots. This systematic review examines the challenges associated with wireless communication and autonomous navigation in IoT-controlled agricultural robots. The study analyzes recent literature on 5G, LoRaWAN, GPS, LiDAR, and sensor-fusion technologies and identifies critical limitations including communication latency, network coverage gaps, signal interference, GPS dependency, sensor inaccuracies, and environmental constraints. The review further discusses emerging solutions such as hybrid communication architectures, edge computing, multi-sensor fusion, and AI-driven navigation systems. Findings indicate that reliable robot operation in agricultural environments requires integrated communication and navigation frameworks capable of maintaining connectivity and localization accuracy under dynamic field conditions.

Keywords: Agricultural Robots, IoT, 5G, LoRaWAN, GPS, RTK-GPS, LiDAR, Precision Agriculture, Autonomous Navigation, Wireless Communication

I. Introduction

The increasing demand for food production, labor shortages and the need for sustainable agricultural practices have accelerated the adoption of agricultural robotics and IoT technologies. Autonomous agricultural robots are now used for crop monitoring, precision spraying, weeding, harvesting, and soil analysis. These robots rely heavily on wireless communication networks and navigation systems to perform operations with minimal human intervention.

IoT-controlled agricultural robots operate through continuous communication among sensors, actuators, cloud platforms, and robotic controllers. Networking technologies such as LoRaWAN, ZigBee, Wi-Fi, and 5G support this connectivity, while navigation technologies including GPS, LiDAR, cameras, inertial measurement units (IMUs), and simultaneous localization and mapping (SLAM) systems enable autonomous movement within agricultural fields. Recent reviews identify networking technologies such as LoRaWAN and 5G as foundational components for robot coordination and real-time data management in agriculture. [2,4,5,6,11,14,23]

However, agricultural environments present unique challenges. Large field sizes, uneven terrain, vegetation occlusion, weather conditions, and limited network infrastructure can degrade communication performance and localization accuracy. Consequently, connectivity and navigation bottlenecks remain major obstacles to achieving reliable autonomous agricultural operations.

This review investigates these challenges with a specific focus on the technical communication and navigation infrastructures of IoT-controlled agricultural robots.

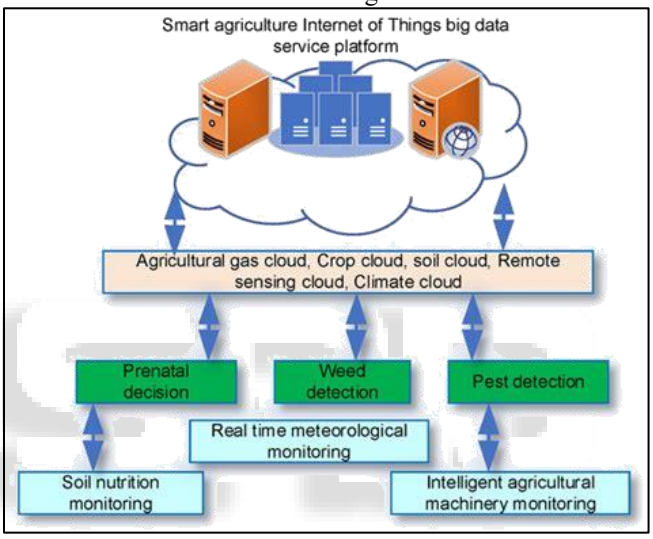


Fig. 1: Overall IoT-Controlled Agricultural Robot Architecture

This figure shows the complete communication chain:

- Agricultural Robot, LiDAR Sensor, GPS/RTK-GPS, IMU, Edge Computing Node, 5G Base Station, LoRaWAN Gateway, Cloud Platform, Farm Management Dashboard
- The diagrams illustrate 5G-enabled agricultural IoT architectures integrating cloud, edge computing, sensors, and robotic systems. [2,4,6,11,14,23]

II. Methodology

This systematic review follows a literature-based approach focusing on peer-reviewed journal articles, conference papers, and technical reports published between 2022 and 2026. Sources were selected based on relevance to:

- Agricultural robotics
- IoT communication technologies
- 5G networking
- LoRaWAN applications
- GPS and RTK-GPS navigation
- LiDAR-based localization
- Autonomous field navigation

The reviewed studies were categorized into two primary domains:

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- Connectivity Technologies
- Navigation Technologies
- Bottlenecks and proposed solutions were extracted and synthesized to identify research trends and future directions.

III. Connectivity Technologies in Agricultural Robots

A. LoRaWAN for Agricultural Robotics

LoRaWAN (Long Range Wide Area Network) is one of the most widely adopted communication technologies in agricultural IoT systems due to its long-range communication capability and low-power operation. Studies show that LoRa-based agricultural networks support large-scale field monitoring while maintaining energy efficiency. [1,7,10,19]

1) Advantages

- Long communication range (several kilometers)
- Low power consumption
- Low deployment cost
- Suitable for remote agricultural fields

2) Bottlenecks

a) Limited Data Rate

LoRaWAN was designed for low-bandwidth sensor communication and is unsuitable for transmitting:

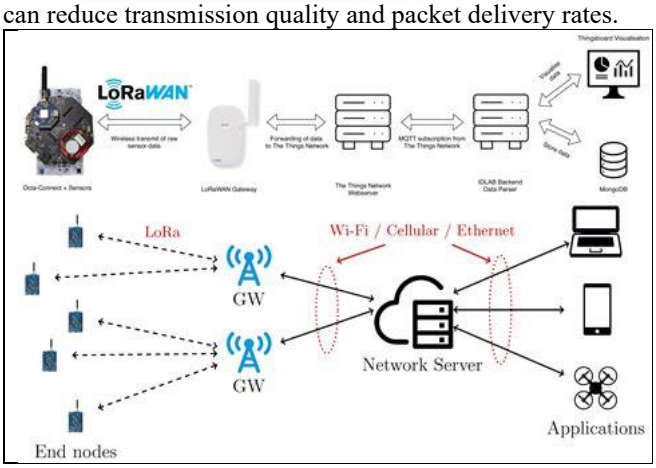
- High-resolution images
- LiDAR point clouds
- Real-time video streams

b) Network Scalability Issues

Performance can degrade when numerous sensors and robots simultaneously access network resources. Research highlights challenges related to routing, relay design, and network congestion in large agricultural deployments. [1,7,10,19]

c) Signal Attenuation

Vegetation density, crop growth stages, and field topology can reduce transmission quality and packet delivery rates.



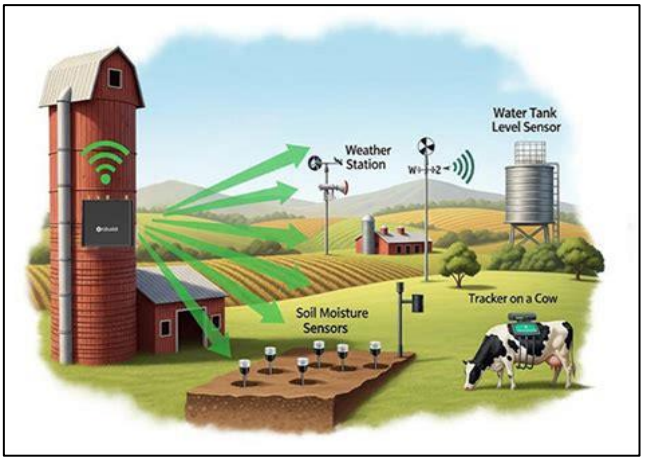


Fig. 2: LoRaWAN-Based Smart Agriculture Communication Architecture

Useful in the "Connectivity Technologies" section.

These figures demonstrate how LoRaWAN nodes, gateways, cloud servers, and agricultural sensors exchange data across large farms. [2,4,6,11,14,23]

B. 5G Networks for Agricultural Robotics

5G provides ultra-reliable low-latency communication (URLLC), high bandwidth, and massive machine-type communication capabilities, making it highly suitable for agricultural robotics. Studies indicate that private 5G networks significantly outperform 4G in agricultural robotic applications requiring high throughput and reliable communication. [2,4,6,7,11,14,19,23].

1) Advantages

Low latency, High bandwidth, Real-time communication, Support for AI and cloud robotics, Multi-robot coordination

2) Bottlenecks

a) Infrastructure Availability

Many farming regions lack sufficient 5G infrastructure, especially in rural and remote areas.

b) High Deployment Cost

- Private 5G networks require:
- Base stations, Edge servers
- Maintenance infrastructure
- This increases implementation costs for farmers.

c) Coverage Limitations

Large agricultural fields may exceed the effective coverage of a single 5G installation.

d) Dependence on Hybrid Networks

Evidence suggests that no single wireless technology currently satisfies all agricultural communication requirements, requiring multiple communication solutions to coexist. [2,4,6,7,11,14,19,23]

C. Comparison of LoRaWAN and 5G

Parameter	LoRaWAN	5G
Range	Very High	Medium
Power Consumption	Very Low	High
Data Rate	Low	Very High
Latency	High	Very Low
Cost	Low	High
Video Support	No	Yes
Real-Time Control	Limited	Excellent

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A hybrid architecture combining LoRaWAN for sensor networks and 5G for robotic operations is increasingly viewed as the optimal solution. [1,10]

IV. NAVIGATION TECHNOLOGIES IN AGRICULTURAL ROBOTS

A. GPS and RTK-GPS Navigation

GPS remains the primary localization technology for agricultural robots.

RTK-GPS improves positioning accuracy from several meters to centimeter-level precision, enabling precise path planning and field operations. Improvements in RTK-GPS have significantly enhanced autonomous mowing, spraying, and harvesting tasks. [8,22]

1) Advantages

- High positioning accuracy
- Scalable deployment
- Established infrastructure
- Navigation Bottlenecks

2) Signal Loss

- GPS accuracy degrades when:
- Trees obstruct satellites
- Farms are located in valleys
- Weather conditions interfere with signal reception

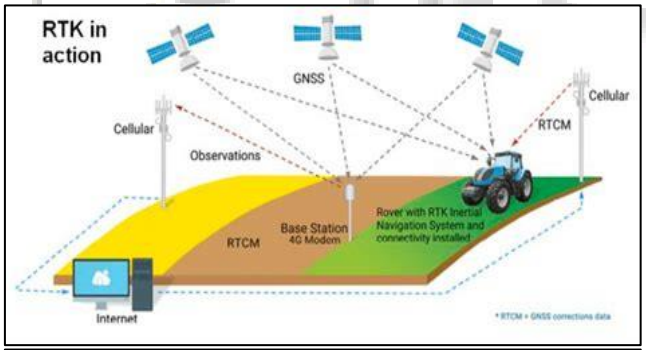
Researchers report that RTK correction signals can be interrupted due to poor network coverage or communication failures. [7,19]

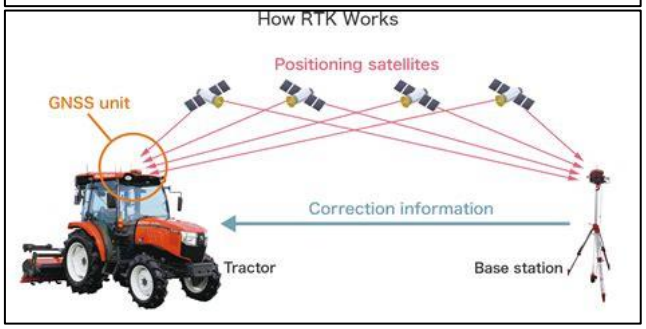
3) Dependence on Internet Access

RTK systems often require continuous correction data from base stations or cloud services.

4) Multi-Path Errors

Signal reflections from structures and machinery can generate localization inaccuracies.





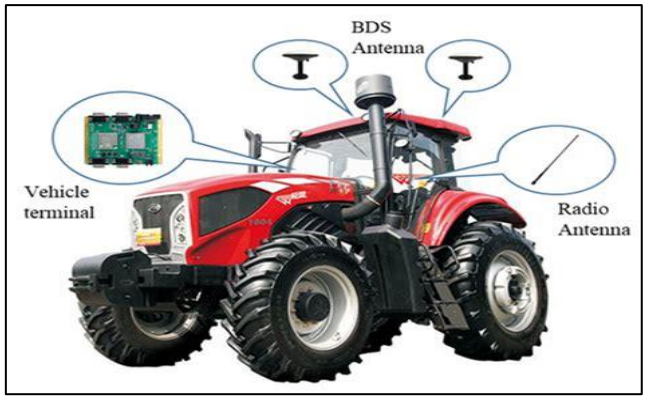


Fig. 3: "RTK-GPS based localization architecture for precision field navigation."

Useful in the Navigation section.

These images illustrate RTK correction mechanisms, satellite communication, and navigation workflows used in autonomous agricultural machinery. [2,4,6,11,14,23]

B. LiDAR-Based Navigation

LiDAR (Light Detection and Ranging) sensors generate three-dimensional representations of agricultural environments.

They enable:

Obstacle detection, Crop row detection, Terrain mapping, Autonomous navigation

Agricultural robots increasingly employ LiDAR to create detailed 3D field maps and improve navigation precision. [2,4,6,8,11,14,22,23]

1) Advantages

- High environmental awareness
- Accurate obstacle detection
- Independence from lighting conditions

2) Bottlenecks

a) High Cost

LiDAR sensors remain expensive compared with conventional GPS systems.

b) Computational Complexity

Real-time processing of LiDAR point clouds requires substantial computational resources.

c) Environmental Sensitivity

Dust, rain, fog, and dense vegetation can affect point cloud quality and mapping accuracy.

d) Data Transmission Challenges

LiDAR generates large datasets that require high-bandwidth communication channels, creating connectivity demands beyond the capabilities of LoRaWAN.

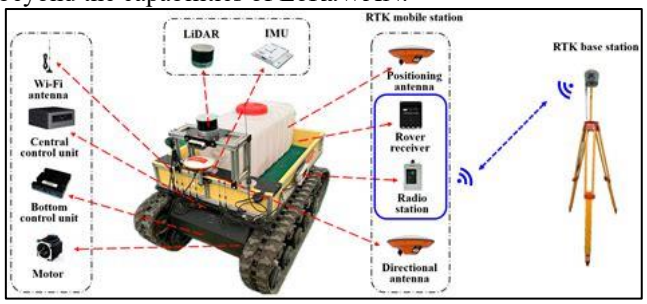


Fig. 4: "Sensor-fusion architecture for LiDAR-based agricultural robot navigation."

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These figures show how LiDAR, IMU, and GNSS sensors are integrated to achieve autonomous navigation and obstacle avoidance. [2,4,6,11,14,23]

C. LiDAR-Based Crop Row Navigation

Recent studies demonstrate LiDAR-based crop-row navigation systems capable of operating without GPS. Such approaches allow robots to navigate through fully occluded crop rows while maintaining high positional accuracy and achieving average cross-track errors of only a few centimeters. [7,19]

Similarly, LiDAR-only navigation methods have successfully guided robots between crop rows using line extraction and fuzzy-control techniques. [3]

However, deployment challenges remain due to computational burden and environmental variability.

D. Sensor Fusion Approaches

To overcome limitations of individual sensors, researchers increasingly employ sensor fusion strategies involving:
GPS, LiDAR, Cameras, IMUs, Wheel odometry

Recent reviews highlight that reliable field autonomy requires localization pipelines combining GNSS, IMU, LiDAR, cameras, odometry, and SLAM techniques. [2,4,6,11,14,23]

Benefits include:

- Increased localization accuracy
- Reduced dependence on GPS
- Better obstacle avoidance
- Enhanced robustness under dynamic conditions

V. Major Connectivity and Navigation Bottlenecks

The literature consistently identifies several recurring challenges.

- Connectivity Bottlenecks
- Limited rural network infrastructure
- LoRaWAN bandwidth constraints
- 5G deployment costs
- Network congestion
- Communication latency
- Coverage gaps across large farms
- Navigation Bottlenecks
- GPS signal degradation
- RTK correction dependency
- LiDAR computational demands
- Environmental interference
- Dynamic field conditions
- Sensor calibration errors

These challenges collectively reduce operational reliability and hinder widespread adoption of autonomous agricultural robots.

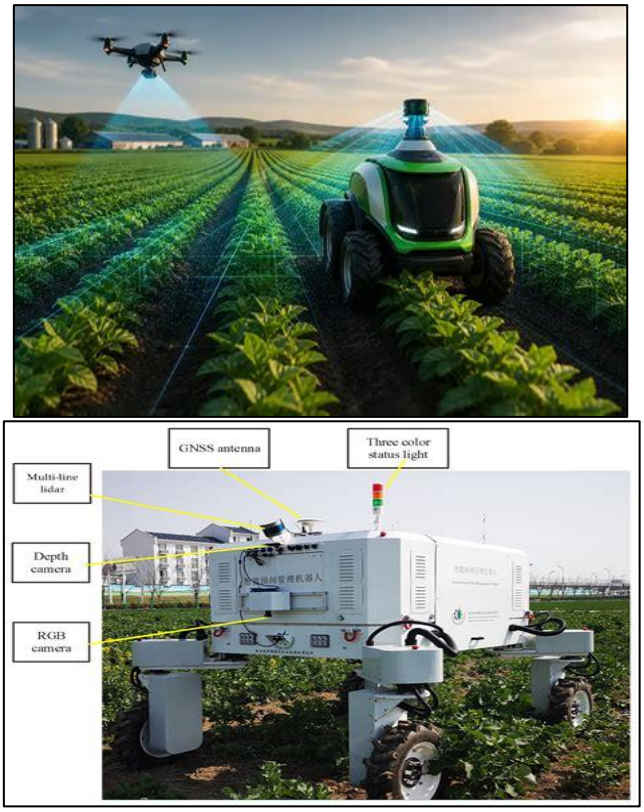


Fig. 5: Autonomous Agricultural Robot Equipped with LiDAR

These images show field robots carrying LiDAR scanners, cameras, GPS antennas, and other sensors used in precision farming. [2,4,6,11,14,23]

VI. Emerging Solutions

Recent research proposes several approaches to overcome existing limitations.

A. Hybrid Communication Architectures

- Combining:
- LoRaWAN for low-power sensing
- 5G for robotic control
- Edge computing for local processing
- can improve scalability and reliability. [2,4,6,11,14,23]

B. Multi-Sensor Fusion

Integrating GPS, LiDAR, cameras, and IMUs enhances localization robustness. [2,4,6,11,14,23]

C. AI-Assisted Navigation

- Machine learning techniques improve:
- Path planning
- Obstacle avoidance
- Crop row detection
- Localization accuracy

D. Edge Computing

Processing data closer to robots reduces network delays and improves real-time response.

E. Future 6G-Enabled Agriculture

- Emerging research anticipates 6G networks supporting:

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- Massive robotic deployments
- Digital twins
- Ultra-reliable autonomy
- AI-native networking architectures. [5]
- Additional Discussion Section

F. Connectivity Bottlenecks and Research Gaps

From recent studies, major communication challenges include:

- Limited 5G coverage in rural areas.
- High deployment cost of private 5G networks.
- Low throughput of LoRaWAN.
- Packet loss caused by crop canopies.
- Energy constraints in long-term deployments.
- Network congestion in multi-robot systems.

Research indicates that hybrid 5G-LoRaWAN architectures can combine the high-speed capabilities of 5G with the long-range, low-power benefits of LoRaWAN. [2,4,6,11,14,23]

G. Navigation Bottlenecks and Research Gaps

Studies report that navigation failures are frequently associated with:

- GPS signal blockage.
- RTK correction interruptions.
- Dense canopy occlusion.
- LiDAR degradation under fog and dust.
- Difficulty detecting crop rows in mature crops.
- Dynamic terrain conditions.

Recent LiDAR-based systems achieve centimeter-level navigation even without GPS, highlighting the potential of vision-LiDAR sensor fusion. [3,7,19]

VII. Conclusion

Agricultural robots are becoming essential components of modern precision agriculture. However, their effectiveness depends heavily on reliable communication and accurate navigation systems. This review demonstrates that LoRaWAN and 5G each provide distinct advantages and limitations for agricultural robotic communication. Likewise, GPS and LiDAR remain core navigation technologies, yet both suffer from environmental and operational constraints.

Current evidence suggests that the most promising solution lies in hybrid communication architectures combined with multi-sensor navigation frameworks. Future research should prioritize integrated 5G-LoRaWAN infrastructures, sensor-fusion algorithms, edge intelligence, and AI-assisted field navigation to enable resilient, scalable, and autonomous agricultural robotic systems.

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