

# Harnessing Robotics for Enhanced Precision in Agriculture

## ABSTRACT

In agriculture, Unmanned Aerial Vehicles (UAVs) are employed, falling under the within these vehicles consist of navigation sensors, computational techniques, path planning algorithms, and control strategies. Various smart sensors, such as optical sensors, are integrated into automated machines to detect early signs of pest infestation in standing crops. Additionally, UAVs are equipped with different types of sensors required for analyzing crop-related parameters category of agricultural robots. These robots, along with automated machines, are utilized to accomplish precision farming objectives. Autonomous navigation systems. Among the most common sensors are optical ones, including RGB, multispectral, and hyperspectral cameras.

**Key words:** *Agricultural Drone, Precision Farming, Smart Sensors, Unmanned Aerial Vehicles (UAVs).*

## 1. INTRODUCTION

Harnessing robotics for enhanced precision in agriculture represents a transformative approach to addressing contemporary challenges in the agricultural sector. Precision agriculture leverages automation and sensing technologies to reduce decision uncertainty and manage the unpredictable variations within agricultural fields. This method offers promising solutions to pressing issues such as water scarcity, agrochemical resistance, and environmental concerns. By integrating robotics, precision agriculture enhances efficiency, accuracy, and productivity in field operations. Automated machinery and robotic platforms equipped with sensory capabilities enable the collection of valuable data on soil conditions, crop health, seed quality, livestock management, water usage, and equipment performance. Moreover, emerging technologies like wireless sensor networks (WSNs) and the Internet of Things (IoT) provide advanced analytics and low-cost automation techniques. These innovations empower farmers to analyze essential data on weather, soil, temperature, and moisture, facilitating informed decision-making to optimize yields and enhance planning processes. Through the synergy of robotics and precision agriculture, farmers can navigate challenges effectively while maximizing agricultural output in a sustainable manner. This Special Issue highlights innovative robotics and AI approaches in agriculture and forestry, emphasizing dataset creation, edge AI benchmarking, perception challenges, and advancing solutions for real-world applications and autonomous systems [26]. Grounding DINO's has superior performance over YOLO-World in zero-shot detection for wild blueberry cropping systems, emphasizing its potential to enhance dataset annotation efficiency and guide future agricultural AI research advancements [10].

## 2. Materials and Methods

Materials for enhancing precision in agriculture through robotics include various sensors like LiDAR, GPS, machine vision cameras, and proximity sensors. Computational devices such as onboard computers and microcontrollers are essential for data processing and control algorithm execution. Additionally, robotic platforms equipped with actuators and communication modules facilitate interaction with the agricultural environment. Methods involve integrating sensors to perceive the agricultural field accurately. Computational algorithms, including machine learning and traditional control techniques, enable real-time decision-making and control. Path planning algorithms optimize robot trajectories to navigate efficiently while avoiding obstacles. Control strategies regulate robot movements for precise operations, incorporating techniques like fuzzy logic and proportional-integral-derivative (PID) controllers. Integration of these materials and methods results in autonomous systems capable of enhancing precision in various agricultural tasks, from planting and harvesting to monitoring crop health and managing resources efficiently.

## **2.1 Precision agriculture**

Precision agriculture is a systematic approach aimed at reducing decision uncertainty and understanding the unpredictable variations within agricultural fields [8]. In recent times, the agricultural sector has encountered various challenges, such as water scarcity, agrochemical resistance, and environmental concerns. However, the integration of automation and sensing technologies through precision agriculture holds promise for addressing these challenges in the future [34]. Precision agriculture technologies can be applied across various aspects of crop production systems, including cultural practices, equipment usage, weather forecasting, and farm management. The rapid advancements in agricultural science and technology have driven the adoption of robotics and automation within this sector [27, 28]. Automated machinery and agricultural robotics are increasingly recognized as essential solutions for conducting field operations with efficiency, precision, and productivity [38]. Furthermore, robotic platforms equipped with sensory capabilities enable the collection of valuable data pertaining to soil conditions, crop health, seed quality, livestock management, water usage, and equipment performance. Additionally, emerging technologies such as wireless sensor networks (WSNs) and the Internet of Things (IoT) offer advanced analytics and low-cost automation techniques, empowering farmers to analyze weather, soil, temperature, moisture data, and gain valuable insights to optimize yields and enhance planning processes [34]. Precision and smart agriculture leverage automation, IoT, AI, and data analytics to enhance productivity, efficiency, and sustainability. These technologies minimize environmental impact, optimize resource use, and revolutionize traditional practices, addressing global agricultural and environmental challenges effectively [3]. Advancements in precision agriculture and livestock farming, emphasizing technology-driven solutions for optimizing production and reducing environmental impact [19].

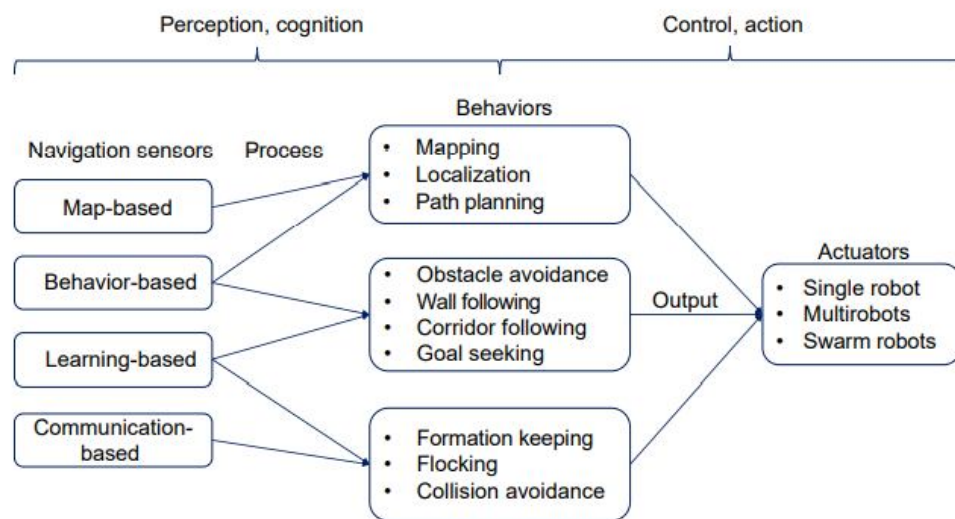
## **2.2 ROBOTICS AND INTELLIGENT MACHINES IN AGRICULTURE**

Currently, automation techniques, smart sensors, and agricultural robots (ag-robots) have made significant strides in farm applications, with ongoing research and development efforts focused on reducing equipment costs [15, 24]. The concept of Precision Autonomous Farming (PAF) involves the use of automatic agricultural machinery that operates safely and efficiently without human intervention [11]. In various farm operations, tasks traditionally performed by operators, such as steering vehicles and operating equipment, can now be executed simultaneously by Autonomous Mobile Robots (AMRs). This development aims to eliminate the need for continuous manual adjustments to steer vehicles, leading to the adoption of Autonomous Navigation Systems (ANSs) in agricultural machinery such as tractors, cultivators, planters, and harvesters [37]. To ensure the safe operation of autonomous vehicles in the field, real-time risk detection and obstacle avoidance strategies are essential [15, 24]. Agricultural robots support various technologies, with artificial intelligence (AI) and machine learning emerging as two major techniques among them [24]. An autonomous robot capable of precise plant identification and agro-chemical spraying using machine vision and RTK-GPS. Field experiments validate its potential to enhance agricultural efficiency, reduce resource use, and minimize labor demands.

### **2.3 AUTONOMOUS NAVIGATION SYSTEM (ANS<sub>s</sub>)**

In modern times, navigation tasks in agricultural Autonomous Mobile Robots (AMRs) are crucial for guiding robots autonomously and safely within agricultural environments. The navigation system determines the robot's position and identifies obstacles in the surrounding area [2, 15]. Depending on the target crops in a specific cultivation area, an autonomous navigation system is tailored accordingly. This system calculates and executes the required movements of an autonomous agricultural vehicle using task-specific actuation and sensing systems [9, 35]. Key components of the Autonomous Navigation System (ANS) include navigation sensors, computational algorithms, path planning, and control strategies. Figure 1 illustrates the navigational system, depicting the interactive communication between the robot's perception, which occurs during the sensing process, and the control process in the actuators. The global navigation system is the most commonly used sensor for automatic guidance in agriculture, followed by infrared sensors, machine vision, Light Detection and Ranging (LiDAR), and ultrasonic sensors. Implementing LiDAR and machine vision can assist in positioning vehicles near crops, particularly during harvesting activities [13, 33]. GPS navigation is widely employed in agriculture, especially in farm tractors and combines during harvesting. With the deployment of Real-Time Kinematic (RTK), GPS provides centimeter-level accuracy for automated positioning of large farm vehicles. However, in some cases, relative positioning and navigation accuracy are more critical than absolute positioning [4, 28]. Fully autonomous vehicle operation faces challenges in path planning, including optimal routing and obstacle avoidance. Optimal routing involves avoiding collisions with static and dynamic objects while minimizing traveled distance and environmental impact. Rotary encoders and proximity sensors are utilized to compute the position and orientation of steering angles, monitor clutch and brake positions, and can be integrated with Fiber Optic Gyro (FOG) sensors, Global Navigation

Satellite System (GNSS), and accelerometers for optimal routing. Data pertaining to the vehicle's environment is utilized for steering control and obstacle avoidance strategies [12, 16]. Various control strategies for steering include fuzzy logic (FL), neural networks (NNs), proportional-integral-derivative (PID) controllers, feed-forward PID (FPID) controllers, and genetic algorithms (GA) [15, 37]. A cost-effective, vision-based system for precision agriculture, combining autonomous weed detection, trajectory planning, and crop row navigation. The system significantly reduces herbicide usage, enhancing sustainability and efficiency in pest and weed management practices [7].



**Fig. 1: Schematic of the sensing and action process in navigation system**

Tractors and agricultural machinery are essential tools in modern farming practices. Over the past two decades, automatic guidance and steering control systems have become commonplace in the agricultural industry. Various tractor manufacturers have continuously updated their products with advanced features to meet the evolving needs of farmers. One notable advancement is John Deere's AutoTrac technology, which utilizes the NavComStarFire GNSS guidance system.

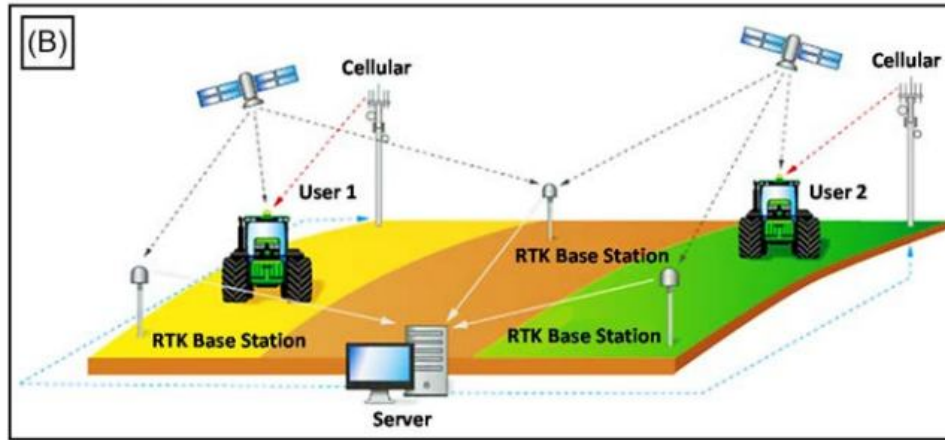
This system relies on satellite broadcast correction information or Real-Time Kinematic (RTK) positioning to accurately determine the position of agricultural machinery. The positioning accuracy of the StarFire guidance system can reach up to  $\pm 2.5$  cm when using satellite broadcast correction information or RTK positioning (Fig. 2A). This level of precision ensures that the machinery maintains a precise ground position, enhancing overall operational efficiency.

In addition to determining position, sensors integrated into the system also measure the roll, pitch, and yaw of the vehicle. These parameters are crucial for maintaining stability and accuracy, particularly when operating in diverse terrain conditions. To effectively measure and compensate for these parameters, a Terrain Compensation Module (TCM) is employed within the guidance systems.

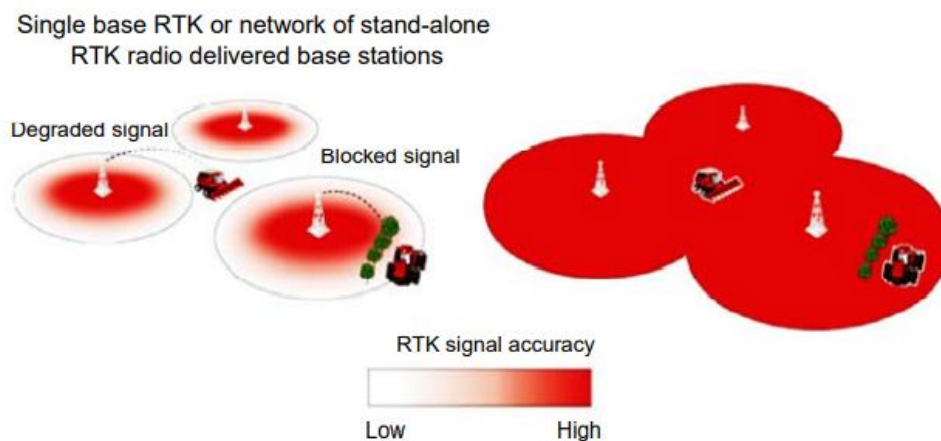
Furthermore, RTK differential corrections can be broadcast using a mobile RTK modem (Fig. 2B), allowing for real-time updates and adjustments to further improve positioning accuracy and operational performance [14, 17]. This integration of advanced technologies not only streamlines agricultural operations but also contributes to increased productivity and sustainability in farming practices.

Automated guidance systems have become essential components of farm machinery equipment. In the modern era, Case IH and Precision Land Management (PLM) of New Holland have developed an advanced farming system (AFS) that incorporates guidance systems such as AccuGuide, AutoPilot, and Intellisteer. These guidance systems utilize diverse GNSS technologies, including Trimble and Omnistar (Centerpoint RTX and Rangepoint RTX) [33]. Figure 3 illustrates the RTK-based station networks. Recently, Case IH introduced a proprietary RTK correction service (AFS RTK+) in the United States and Canada. This service implements an RTK base station network, allowing corrections to be broadcast through a mobile phone network. The AutoPilot system facilitates direct integration within the tractor's electrohydraulic system to control steering [20, 33].





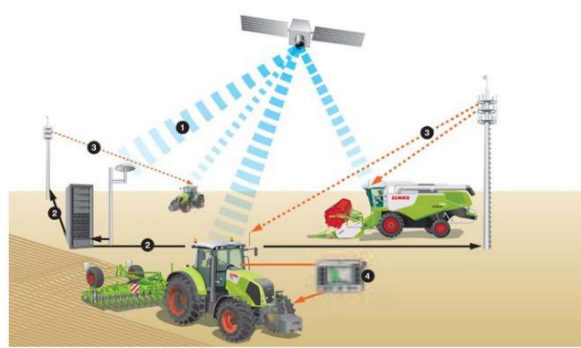
**Fig. 2: (A) Combine harvester equipped with an Auto Trac system using a GreenStar 2630 Display to run the guidance system and a host of other precision farming applications, developed by John Deere and (B) Mobile RTK corrections using 3G/4G communications [28].**



**Fig. 3: Case IH dealer network RTK correction service [2]**

Modern machinery often employs hydraulic steering systems, which offer operators effortless steering control. The GPS PILOT S3 developed by CLAAS exemplifies this, as its hydraulic steering system is adaptable to various types of machinery including tractors, combine harvesters, and forage harvesters. This system also supports automatic steering through the GPS PILOT FLEX, enhancing precision and control in farm operations. Overall, the hydraulic steering system plays a crucial role in enabling precision agriculture, providing precise steering performance and versatility. The GPS PILOT FLEX integrates with RTK correction, ensuring flexible and accurate operation [1]. Various differential GPS correction signal options are available with CLAAS systems, including satellite broadcast signals such as EGNOS, OMNISTAR HP/XP/G2, and BASELINE HD. These signals utilize mobile reference stations and RTK systems through RTK NET, which can deliver corrections via a mobile phone network [37]. Fig. 4

illustrates the process: (1) GPS satellite signals are received by the machine and the RTK network, (2) correction signals from networked reference stations are calculated by a central server, (3) the machine receives high-precision RTK correction signals via the mobile phone network, and (4) both signals are converted into steering signals by the GPS PILOT system.



**Fig. 4: Differential GNSS corrections associated with RTK NET, developed by CLAAS [32].**

Path planning is a critical aspect of guiding robots to achieve specific objectives, ranging from simple trajectory planning to selecting appropriate sequences of actions. In the context of machine operation, path planning systems are employed to enhance the coordination of implement and tractor operations, thereby reducing operator fatigue. Headland Management Systems (HMS) have been developed and implemented to facilitate this objective [1, 21].

Steering assistance features have also been integrated into farm machinery to enhance safety and control. These systems provide automated control assistance by supplying power to the steering wheel in emergency situations. Within the headland, steering assistance systems, such as iTEC by John Deere and TURN-IN by CLAAS, ensure precise alignment for the next maneuver, showcasing advanced path planning capabilities.

Another significant technology compatible with autonomous vehicle operation is implement guidance. This technology ensures that both the implement and tractor remain aligned along the same guidance line. Implement guidance is particularly favored in row crop farming for first-pass operations like planting or strip-tilling, as well as in vegetable operations where multiple passes are common and crop damage is costly. It effectively positions the implement with a proportional response to variations in loads, especially on slopes [11, 22].

TrueGuide and TrueTracker implement guidance systems, utilized in Case IH's PLM and New Holland's AFS developed by Trimble, are notable products in this domain. TrueGuide provides passive implement guidance in conjunction with the tractor guidance system, while TrueTracker serves as an active implement guidance system employing hydraulic mechanisms installed on the implement and terrain compensation to ensure independent implement guidance [25, 33].



## 2.4 AGRICULTURAL ROBOTS (ag-robot)

An agricultural robot refers to a robot specifically designed and deployed for agricultural tasks. These robots operate in challenging and dynamic agricultural environments to perform various field operations. They can be broadly categorized into manipulators and unmanned ground vehicles (AGVs). Ground robots are further classified into self-propelled mobile robots and robotic smart implements that are transported by a mobile machine [30, 31].

To achieve precise motion control and path following, particularly for non-destructive testing, self-propelled mobile robots are commonly utilized. These robots come in diverse sizes and designs. Traditional agricultural machinery such as tractors, combine harvesters, and sprayers have been equipped with robotic capabilities using Global Navigation Satellite Systems (GNSS) and autoguidance systems, as discussed in the preceding section (Fig. 2A).



(A)



(B)



(C)



(D)



(E)



(F)

**Fig. 5A Autosteered harvester developed by Kinze and a fully autonomous tractor operating as a grain cart puller for unloading [12], (B)Autonomous cab-less tractor, developed by Case IH [18], (C) Autonomous cab-less tractor, developed by John Deere [16], (D) BoniRob: a multipurpose weeding robotic platform for farm applications [16], (E) Lettuce- weeding robot, developed by Blue River [16]. And (F) Autonomous seed sower, developed by Small Robot Company [24].**

Figure 5A displays a harvester developed by Kinze alongside a fully autonomous tractor employed as a grain cart puller to unload the harvester. Case IH and John Deere have engineered autonomous cab-less tractor robots compatible with conventional cultivation implements (Figure 5B). The utilization of autosteer



combines offers significant advantages, including reduced operator stress and minimized crop loss. AutoSteer functionality enables operators to maintain consistent speed while the combine autonomously navigates along predetermined planting lines, ensuring uniform crop load distribution during threshing. This allows operators to focus on tasks such as crop unloading into grain carts. Bear Flag Robotics has developed a driverless automation kit for tractors and implements, enabling cost-effective retrofitting of existing vehicles with autonomous capabilities [23, 36].

These robots primarily target energy-intensive farm operations like plowing, planting, spraying, and harvesting. Conversely, smaller self-propelled robots are designed for low-power tasks such as scouting and weeding (Figure 5D). Autonomous tractors equipped with six pairs of cameras provide 360-degree imaging, enabling efficient operation without human intervention. Moreover, robotic smart implements have been commercialized for various applications, including transplanting and mechanical weeding. Blue River has integrated computer vision and machine learning technology to facilitate targeted herbicide application, optimizing input utilization in farming—a core tenet of precision agriculture (Figure 5E) [4]. Blue River's approach shifts farm management decisions from the field level to the plant level. Small Robot Company offers intelligent robots capable of seeding and monitoring individual plants in crops, enabling precise feeding and spraying based on each plant's condition to minimize waste (Figure 5F) [29].

Manipulator-type agricultural robots find primary application in food processing, dairy operations, horticulture, and orchard industries [32]. Parallel-type manipulators are specifically employed for handling heavy materials in agriculture. Each robot features an arm, necessitating the use of grippers to execute handling tasks. Soft grippers, for example, are utilized for selective harvesting of delicate produce such as mushrooms, sweet peppers, tomatoes, raspberries, and strawberries. These grippers typically comprise four legs that can be inflated to gently pick up objects. In both open fields and greenhouses, manipulators play a significant role in complementary harvesting tasks. Presently, researchers are integrating robotic arms with cameras to identify the three-dimensional (3D) location of fruits, aiding in automated harvesting processes [14]. Additionally, robotic arms are employed to automate the placement of goods or products onto pallets. Automating this process enhances accuracy, cost-effectiveness, and predictability in palletizing operations.

During harvesting operations, agricultural products exhibit heterogeneity, posing challenges for automated grasping and manipulation due to their varying nature, positions, and fragility. Abundant Robotics has developed an apple vacuum harvesting robot equipped with LiDAR for steering along tree rows and machine vision for detecting ripe apples. The robot gently suctions and picks apples from trees, with potential adaptation for harvesting other fruits (Figure 6A). Sweeper has introduced a sweet pepper harvesting robot tailored for use in commercial greenhouses [6]. This robot is optimized for single stem row cropping systems with non-clustered fruits and minimal leaf occlusion (Figure 6B) [6]. Robotic grippers are evolving to offer enhanced flexibility, plug-and-play functionality, and repeatability, rendering

them suitable for industrial applications (Figure 6C). The Soft Robotics System encompasses soft robotic grippers and a control unit capable of adjusting variables such as size, shape, and weight, all through a single device [30].



**Fig.6 (A) Apple vacuum-harvesting robot, developed by Abundant Robotics [6], (B) Sweet pepper harvesting robot, developed by Sweeper [5], and (C) Robotic grippers and the control unit, developed by Soft Robotics [25].**

In modern agricultural practices, robotics play a crucial role, encompassing both ground-based ag-robots and unmanned aerial vehicles (UAVs), commonly referred to as drones, which offer time and labor-saving functionalities. Agriculture drones operate semi-autonomously, following predetermined flight paths defined by waypoints and flight altitudes. Consequently, an onboard positioning measurement system is essential for precise navigation [5, 18].

UAVs utilize various types of optical sensors including RGB, multispectral, and hyperspectral cameras to capture data relevant to crop monitoring and analysis. These sensors are instrumental in studying crop-related parameters and identifying potential issues such as pest infestations at early stages through aerobiological sampling conducted above farm fields. UAVs are typically categorized into fixed-wing airplanes and rotary-motor helicopters [5, 12].

HoneyComb has developed an agricultural drone named AgDrone, equipped with an autopilot system called the AgDrone System, enabling autonomous flight operations (Figure 7).

### 3. RESULTS AND DISCUSSION

In contemporary agricultural practices, automated machinery and robotics have substantially transformed the agricultural landscape. Consequently, numerous companies are transitioning from traditional farming methods to a modernized, technologically advanced, and automated agricultural environment. However, despite notable advancements, the commercialization of many developed agricultural robots remains limited. This challenge often arises from the distinct technical and economic demands inherent in

agricultural tasks. Addressing these challenges necessitates the development of more adaptable and resilient robotic solutions.



**Fig. 7 The AgDrone developed by HoneyComb [17]**

#### **4. CONCLUSION**

In conclusion, agriculture drones play a pivotal role in precision farming, particularly during harvesting operations. While significant strides have been made in recent years, further theoretical studies and practical explorations are essential, considering both technical and economic aspects, to ensure the successful integration of agriculture drones into farming practices. Although agriculture robots offer promising alternatives for smart and precision farming activities, the high investment costs continue to hinder widespread deployment of automated and robotics technology in this sector.

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