Harnessing Robotics for Enhanced Precision in Agriculture

ABSTRACT

The inner workings of the Unmanned Aerial Vehicles (UAVs) employed in agricultureconsist of navigation sensors, computationaltechniques, path planning algorithms, and control strategies. Various smart sensors, such as optical sensors, are integrated into automated machines to detect early signsofpestinfestationin standingcrops.Additionally,UAVsareequippedwithdifferenttypesofsensors 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.

***Keywords**:AgriculturalDrone,PrecisionFarming,SmartSensors,UnmannedAerialVehicles(UAVs).*

1. INTRODUCTION

Harnessing robotics for enhanced precision in agriculture represents a transformative approach toaddressingcontemporarychallengesintheagriculturalsector [9]. 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)provideadvancedanalyticsandlow-costautomationtechniques.Theseinnovationsempower farmers to analyze essential dataonweather,soil,temperature, and moisture,facilitating informed decision-makingtooptimizeyieldsandenhanceplanningprocesses.Throughthesynergyofroboticsandprecision agriculture, farmers can navigate challenges effectively while maximizing agricultural output in a sustainablemanner.ThisSpecialIssuehighlightsinnovativeroboticsandAIapproachesinagricultureand forestry, emphasizing dataset creation, edge AI benchmarking, perception challenges, and advancing solutions for real-world applications and autonomous systems [29,42]. Grounding DINO's has superior performanceoverYOLO-Worldinzero-shotdetectionforwildblueberrycroppingsystems,emphasizingits potentialtoenhancedatasetannotationefficiencyandguidefutureagriculturalAIresearchadvancements [13].

2. MaterialsandMethods

Materials forenhancingprecisioninagriculturethroughroboticsincludevarious sensorslikeLiDAR,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 whileavoidingobstacles.Controlstrategiesregulaterobotmovementsforpreciseoperations,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 Precisionagriculture

Precision agriculture is a systematic approach aimed at reducing decision uncertainty and understanding the unpredictable variations within agricultural fields [11]. 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 holdspromiseforaddressingthesechallengesinthefuture[37].Precisionagriculturetechnologiescanbe appliedacrossvariousaspectsofcropproductionsystems,includingculturalpractices,equipmentusage, weather forecasting, and farm management. The rapid advancements in agricultural science and technology have driven the adoption of robotics and automation within this sector [30, 31]. Automated machinery and agricultural robotics are increasingly recognized as essential solutions for conducting field operations with efficiency, precision, and productivity [41]. 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 analyticsandlow-costautomationtechniques,empoweringfarmerstoanalyzeweather,soil,temperature, moisturedata,andgainvaluableinsightstooptimizeyieldsandenhanceplanningprocesses[37].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].Advancementsinprecisionagricultureandlivestockfarming,emphasizingtechnology-drivensolutions for optimizing production and reducing environmental impact [22].

2.2 ROBOTICSANDINTELLIGENTMACHINESINAGRICULTURE

Currently,automationtechniques,smartsensors,andagriculturalrobots(ag-robots)havemadesignificant stridesinfarmapplications,withongoingresearchanddevelopmenteffortsfocusedonreducingequipment costs [18, 27]. The concept of Precision Autonomous Farming (PAF) involves the use of automatic agricultural machinery that operates safely and efficiently without human intervention [14]. In various farm operations,taskstraditionallyperformedbyoperators,suchassteeringvehiclesandoperatingequipment, 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 [40]. To ensure the safe operation of autonomous vehicles in the field, real-time risk detection and obstacle avoidance strategies are essential [18, 27]. Agricultural robots support various technologies,withartificialintelligence(AI)andmachinelearningemergingastwomajortechniquesamong them [27]. 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 AUTONOMOUSNAVIGATIONSYSTEM(ANS$_{s}$)

Inmoderntimes,navigationtasksinagriculturalAutonomousMobileRobots(AMRs)arecrucialforguiding robots autonomously and safely within agricultural environments. The navigation system determines the robot'spositionandidentifiesobstaclesinthesurroundingarea[2,18].Dependingonthetargetcropsina specific cultivationarea,an autonomous navigationsystemis tailoredaccordingly. This systemcalculates and executestherequired movementsofanautonomousagricultural vehicle usingtask-specificactuation and sensing systems [12, 38]. Key components of the Autonomous Navigation System (ANS) include navigationsensors,computationalalgorithms,pathplanning,andcontrolstrategies.Figure1illustratesthe navigationalsystem,depictingtheinteractivecommunicationbetweentherobot'sperception,whichoccurs 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, followedbyinfraredsensors,machinevision,LightDetectionandRanging(LiDAR),andultrasonicsensors.

Implementing LiDAR and machine vision can assist in positioning vehicles near crops, particularly during harvesting activities [16, 36]. 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, 31]. 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 traveleddistanceandenvironmentalimpact.Rotaryencodersandproximitysensorsareutilizedtocompute the position and orientation of steering angles, monitor clutch and brake positions, and can be integrated withFiberOpticGyro(FOG)sensors,GlobalNavigationSatellite System(GNSS),andaccelerometers for optimal routing. Data pertaining to the vehicle's environment is utilized for steering control and obstacle avoidance strategies [15, 19]. Various control strategies for steering include fuzzy logic (FL), neural networks(NNs),proportional-integral-derivative(PID)controllers,feed-forwardPID(FPID)controllers,and geneticalgorithms(GA)[18,40].Acost-effective,vision-basedsystemforprecisionagriculture,combining autonomousweeddetection,trajectoryplanning,andcroprownavigation.Thesystemsignificantlyreduces herbicide usage, enhancing sustainability and efficiency in pest and weed management practices [7].

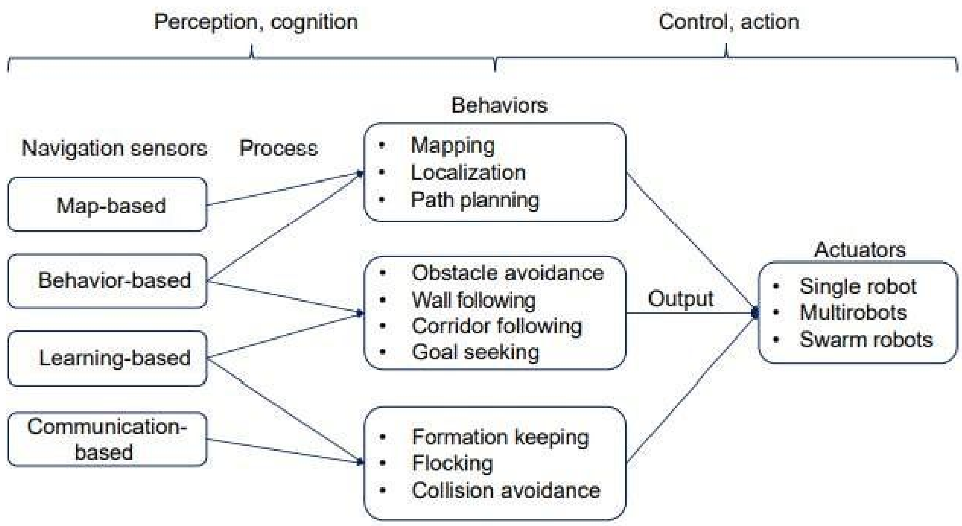

Fig.1:Schematicofthesensingandactionprocessinnavigationsystem

Tractors and agricultural machinery are essential tools in modern farming practices. Over the past two decades,automaticguidanceandsteeringcontrolsystemshavebecomecommonplaceintheagricultural 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 NavCom StarFire 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 ±2.5 cm when using satellite broadcast correction information or RTK positioning(Fig.2A).Thislevelofprecisionensuresthatthemachinerymaintainsaprecisegroundposition, enhancing overall operational efficiency.

Inadditiontodeterminingposition,sensorsintegratedintothesystemalsomeasuretheroll,pitch,andyaw 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,RTKdifferentialcorrectionscanbebroadcastusingamobileRTKmodem(Fig.2B),allowing forreal-timeupdatesandadjustmentstofurtherimprovepositioningaccuracyandoperationalperformance

[17, 20]. 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 modernera,CaseIHandPrecisionLandManagement(PLM)ofNewHollandhavedevelopedanadvanced 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) [36]. Figure 3 illustrates the RTK-based station networks. Recently, Case IH introducedaproprietaryRTKcorrectionservice(AFSRTK+)intheUnitedStatesandCanada.Thisservice 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 [23, 36].

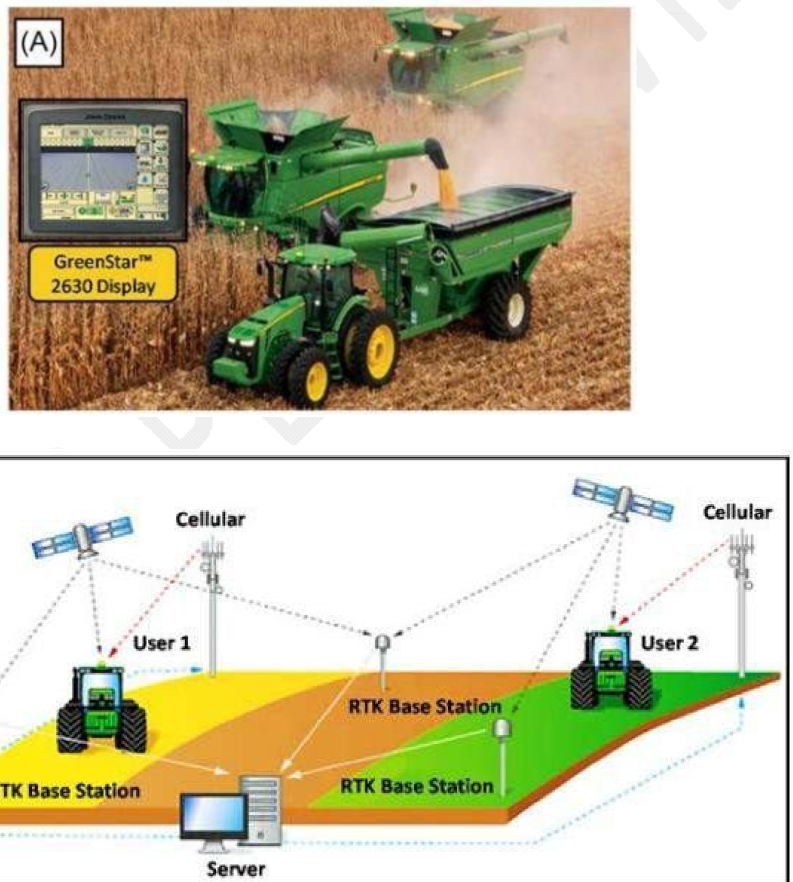

Fig. 2: (A) Combine harvester equipped with an Auto Trac system using a GreenStar 2630 Display toruntheguidancesystemandahostofotherprecisionfarmingapplications,developedbyJohn Deere and (B) Mobile RTK corrections using 3G/4G communications [31].

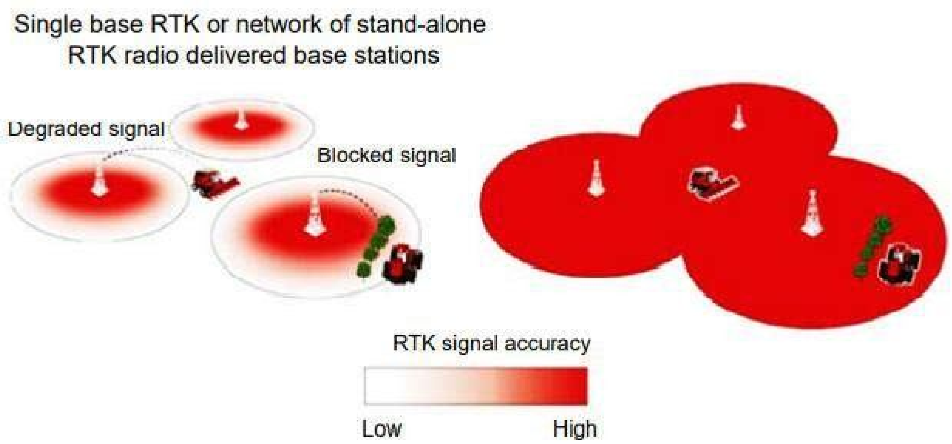

Fig.3:CaseIHdealernetworkRTKcorrectionservice[2]

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 adaptabletovarioustypesofmachineryincludingtractors,combineharvesters,andforageharvesters.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 systemsthroughRTKNET,whichcandelivercorrectionsviaamobilephonenetwork[40].Fig.4illustrates the process: (1) GPS satellite signals are received by the machine and the RTK network, (2) correction signalsfromnetworkedreferencestationsarecalculatedbyacentralserver,(3)themachinereceiveshigh-precision RTK correction signals via the mobile phone network, and (4) both signals are converted into steering signals by the GPS PILOT system.

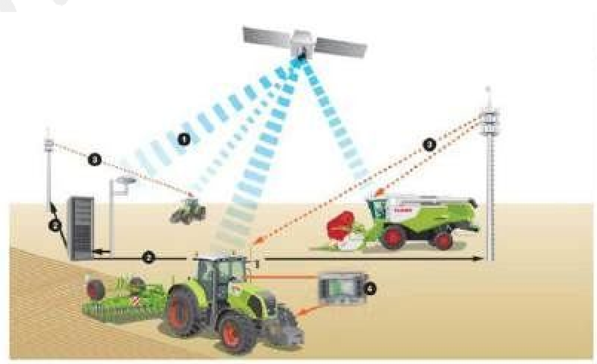

Fig.4:DifferentialGNSScorrectionsassociatedwithRTKNET,developedbyCLAAS[35].

Path planning is a critical aspect of guiding robots to achieve specific objectives, ranging from simple trajectoryplanningtoselectingappropriatesequencesofactions.Inthecontextofmachineoperation,path planning systemsare employedto enhance the coordination of implement andtractoroperations, thereby reducingoperatorfatigue.HeadlandManagementSystems(HMS)havebeendevelopedandimplemented to facilitate this objective [1, 24].

Steeringassistancefeatureshavealsobeenintegratedintofarmmachinerytoenhancesafetyandcontrol. These systems provide automated control assistance by supplying power to the steering wheel in emergencysituations.Withintheheadland,steeringassistancesystems,suchasiTECbyJohnDeereand TURN-INbyCLAAS,ensureprecisealignmentforthenextmaneuver,showcasingadvancedpathplanning capabilities.

Anothersignificanttechnologycompatiblewithautonomousvehicleoperationisimplementguidance.This technology ensures that both the implement and tractor remain aligned along the same guidance line. Implementguidanceisparticularlyfavoredinrowcropfarmingforfirst-passoperationslikeplantingorstrip-tilling,aswellasinvegetableoperationswheremultiplepassesarecommonandcropdamageiscostly.It effectivelypositionstheimplementwithaproportionalresponsetovariationsinloads, especiallyonslopes [14, 25].

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 guidanceinconjunctionwiththetractorguidancesystem,whileTrueTrackerservesasanactiveimplement guidancesystememployinghydraulicmechanismsinstalledontheimplementandterraincompensationto ensure independent implement guidance [28, 36].

2.4 AGRICULTURALROBOTS(ag-robot)

Anagriculturalrobotreferstoarobotspecificallydesignedanddeployedforagriculturaltasks.Agriculturalrobotcan be broadly categorized into manipulators and unmanned ground vehicles (AGVs)[8, 10]. Ground robots are further classified into self-propelled mobile robots and robotic smart implements that are transported by a mobile machine [33, 34].

Toachieveprecisemotioncontrolandpathfollowing,particularlyfornon-destructivetesting,self-propelled mobile robots are commonly utilized. These robots come in diverse sizes and designs. Traditional agriculturalmachinerysuchastractors,combineharvesters,andsprayershavebeenequippedwithrobotic capabilitiesusingGlobalNavigationSatelliteSystems(GNSS)andautoguidancesystems,asdiscussedin 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 graincartpullerforunloading[15],(B)Autonomouscab-lesstractor,developedbyCaseIH[21],(C) Autonomouscab-lesstractor,developedbyJohnDeere[19],(D)BoniRob:amultipurposeweeding roboticplatformforfarmapplications[19],(E)Lettuce-weedingrobot,developedbyBlueRiver[19]. And (F) Autonomous seed sower, developed by Small Robot Company [27].

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 tractorrobotscompatible withconventionalcultivation implements(Figure 5B).Theutilization 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 navigatesalongpredeterminedplantinglines,ensuringuniformcroploaddistributionduringthreshing.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 [26, 39].

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,enablingefficientoperationwithouthumanintervention.Moreover,roboticsmartimplementshave beencommercializedforvariousapplications,includingtransplantingandmechanicalweeding.BlueRiver hasintegratedcomputervisionandmachinelearningtechnologytofacilitatetargetedherbicideapplication, 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) [32].

Manipulator-type agricultural robots find primary application in food processing, dairy operations, horticulture, and orchard industries [35]. Parallel-type manipulators are specifically employed for handling heavy materials in agriculture. Each robot features an arm, necessitating the use of grippers to execute handlingtasks.Softgrippers,forexample,areutilizedforselectiveharvesting ofdelicateproducesuchas mushrooms, sweet peppers, tomatoes, raspberries, and strawberries. These grippers typically comprise four legs that can be inflatedto gently pick up objects. Inboth open fields andgreenhouses,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 [17]. 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.

Duringharvestingoperations,agriculturalproductsexhibitheterogeneity,posingchallengesforautomated 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 harvestingrobottailoredforuseincommercialgreenhouses[9].Thisrobotisoptimizedforsinglestemrow croppingsystemswithnon-clusteredfruitsandminimalleafocclusion(Figure6B)[9].Roboticgrippersare evolvingtoofferenhancedflexibility,plug-and-playfunctionality,andrepeatability,renderingthemsuitable forindustrialapplications(Figure6C).TheSoftRoboticsSystemencompassessoftroboticgrippersanda controlunitcapableofadjustingvariablessuchassize,shape,andweight,allthroughasingledevice[33].

(A) (B) (C)

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 [28].

Agriculture drones operate semi-autonomously, following predetermined flight paths defined by waypoints and flight altitudes. Consequently, anonboard positioning measurement system is essential for precise navigation [5, 21].

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, 15].

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

3. RESULTSANDDISCUSSION

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.7TheAgDronedevelopedbyHoneyComb[20]

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.Althoughagriculturerobotsofferpromisingalternativesforsmartandprecisionfarming activities,thehighinvestmentcostscontinuetohinderwidespreaddeploymentofautomatedand robotics technology in this sector.

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