INNOVATIVE MECHANICAL ENGINEERING **ISSN 2812-9229 (Online)**
University of Niš, Faculty of Mechanical Engineering
VOL. 4, NO 3, 2025, PP. 1-24

Original scientific paper *

AGAR: DESIGN AND CONTROL SYNTHESIS FOR A NEXT-GENERATION AGRICULTURAL GROUND ROBOT

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Abstract. *Unmanned ground vehicles (UGVs) emerge as practical enablers of automation for labor-intensive agricultural operations, but real deployment is still constrained by a persistent design tension: machines that are versatile enough to justify investment often become too heavy/rigid for uneven terrain, while lightweight robots typically sacrifice implement compatibility and slope stability. This paper first synthesizes recent advances in agricultural UGV mechanical architectures and autonomy stacks, with emphasis on drivetrain choices, suspension/levelling concepts, energy supply, perception, and hierarchical control. It then presents AgAR (Agriculture Autonomous Robot) as an integrated design-and-control solution that deliberately couples mechanical modularity with a layered autonomy framework. AgAR combines a lightweight modular chassis with four independently actuated wheel-leg modules forming a hybrid suspension/active levelling system, enabling dynamic ground-clearance control and improved stability on rough and sloped fields. A swappable battery concept supports long duty cycles, while optional modules-including a Category-I three-point hitch and an electric PTO-enable direct use of standard tractor implements and higher-power attachments. A multimodal sensor suite (RTK-GNSS, IMU, stereo vision, 3D LiDAR, ultrasonics) feeds a ROS-centered architecture that separates localization, perception, planning, and safety, supported by industrial control hardware for deterministic low-level actuation and fail-safe stops. Comparative analysis against representative contemporary platforms highlights AgAR's distinctive combination of terrain adaptability, interoperability with conventional implements, and extensible autonomy.*

Key words: *Unmanned Ground Vehicle (UGV), Agriculture robot, Mechanical design, Control design, Hybrid suspension, Design advantages.*

***Received: November 27, 2025 / Accepted December 16, 2025.**
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1. INTRODUCTION

Unmanned ground vehicles (UGVs) are gaining prominence in agriculture as enablers of automation for labor-intensive tasks, with the potential to raise productivity and lower operating costs. Freed from the need to accommodate a human driver, agricultural UGVs can adopt task-specific form factors and kinematics tailored to specific crops, implements, and terrains. Yet the agricultural domain is uniquely challenging: unstructured ground, variable traction and soil moisture, dense and deformable vegetation, and multi-hour duty cycles impose stringent requirements on both mechanical design and control. Modern platforms must simultaneously deliver mobility on rough and sloped fields, stability under changing payloads, sufficient tractive effort, and high energy efficiency due to accelerating electrification. Achieving low vehicle mass without compromising structural integrity is a key enabler for off-road maneuverability, endurance, and soil protection [1].

Despite rapid progress, solutions remain fragmented across mechanics (chassis, suspension, drives, materials) and autonomy (state estimation, path tracking, task execution, and safety). This motivates a consolidated view that treats design and control as a coupled problem rather than parallel efforts.

This paper provides a concise state-of-the-art review of agricultural UGV design and control over the past decade, synthesizing the core mechanical strategies, enabling technologies, and control architectures that underpin robust field performance. We then introduce AgAR (Agriculture Autonomous Robot) and detail its mechanical design and control stack as a representative, integrative solution. Finally, the AgAR is positioned against leading platforms through a comparative analysis of design choices and control capabilities, highlighting where it offers distinct advantages.

2. STATE OF THE ART UGV DESIGNS FOR AGRICULTURE

2.1. Drivetrain and Chassis Architectures in Agricultural Robots

Agricultural UGVs have adopted a variety of mobility architectures, primarily wheeled platforms (4-wheel and 6-wheel designs), with tracked or hybrid systems where soil or slope demands exceed tire traction. Noted mobility architecture approaches reflect a fundamental trade-off between energy efficiency, movement over harsh terrain, and soil and crop protection. Four-wheel designs with skid-steer or Ackermann steering dominate because they are mechanically simple and cost-effective. However, skid-steer waste energy and disturbs soil in tight turns, while Ackermann reduces soil/turf damage but imposes larger turning radius and kinematic constraints in narrow head rows. Commercial example such as Naïo's Orio [2], a steered 4-wheel electric platform for weeding row crops, show that electric drivetrains can sustain full-day operations with fast charging, yet their substantial mass requires compromises between endurance, payload, and soil compaction [3]. Tracked platforms like Vinerobot [4] or Hammerhead by Field Robotics [5], trade speed and efficiency for low ground pressure and capability to move on high slopes terrains, but incur higher maintenance and drivetrain losses, making them niche rather than universal solutions. High-power "tractor replacement" robots like AgXEED [6] preserve compatibility with conventional implements and PTOs, yet their weight and cost profile favor large farms and risk counterproductive compaction on wet soils. Articulated or multi-module chassis, like Robotti [7] by AgroIntelli, improve maneuverability and load distribution for heavy tools, but add mechanical complexity and thus more possible failure points. At the other extreme, ultra-light solar or low-power rovers like FarmDroid FD20 [8] excel at seeding/weeding on flat fields with minimal soil impact, but lack the payload, traction, and robustness required for rough terrain or high-throughput tasks. Between these poles, agricultural robots commonly adopt in-wheel or per-axle electric drives and open chassis "tool-carrier" concepts to balance adaptability and cost, yet their real-world utility is often curtailed by vendor-specific implements and proprietary electro-hydraulic interfaces. Critically, the absence of truly interoperable mechanical (standard hitches), power (DC bus/PTO equivalents), and communication interfaces across small/medium UGVs entrench vendor lock-in and slows adoption among small and mid-sized farms. A credible path forward is to co-design mobility and implements around lightweight frames, low-compaction tires or tracks, and energy-aware steering, combined with open, standardised tool interfaces so that a single robot base can perform diverse tasks without compromising agronomic outcomes.

2.2. Stability and Suspension of Agricultural Robots

Navigating realistic, uneven farmland with UGVs demands careful suspension design and deliberate management of the centre of gravity. Existing work typically groups UGV suspension solutions into four main types: rigid, passive, active and hybrid [3]. With a rigid suspension, the wheels are mounted directly to the chassis, so ground irregularities are transmitted straight to the vehicle body. Such robots are mechanically simpler and can work acceptably on relatively flat fields at low speeds. Representative platforms include early systems like AgTracker [9] and Fendt's Xaver seeding robots [10], as well as more recent machines such as VitiBOT BAKUS [11]. However, rigid layouts are susceptible to wheel lift-off and loss of traction on rough terrain, which limits mobility, accurate path following, repeatability, slope capability and achievable speed.

Passive suspensions introduce compliant elements or articulated joints that allow relative motion between wheels and chassis, smoothing out surface roughness without the need for active control. Examples include Wageningen's weeding robot [12] and the TerraSentia robot developed at the University of Illinois [13]. Compared with rigid systems, passive suspensions enhance ride stability and traction, but they are unable to actively correct large roll or pitch angles. Some designs adopt "semi-passive" ideas such as adjustable dampers or variable-stiffness shock absorbers, which offer only limited, indirect control over stiffness and damping.

Active suspensions, in contrast, employ actuators (electric, hydraulic or pneumatic) to continuously adjust wheel positions or chassis attitude based on sensor feedback and control algorithms [3]. Although this significantly increases system complexity, it enables substantial improvements in stability on irregular terrain by maintaining a more level chassis or a more favorable load distribution. In agricultural applications, fully active suspensions are still rare. They are more often combined with passive elements, forming hybrid suspensions. These hybrid solutions have not yet reached commercial deployment, but they are the focus of intense research, as illustrated by the Agri.Q concept [14]. Agri.Q is an eight-wheeled rover with four rocker-arm pairs driven by electric linear actuators that actively control the platform. By combining articulated mechanics with actuators, Agri.Q-type hybrids can negotiate unstructured terrain while avoiding many of the drawbacks associated with purely rigid or purely passive suspensions. Both active and hybrid systems rely on robust control schemes and sensors such as tilt sensors, IMUs and wheel odometry to react in real time to terrain-induced disturbances. Their main advantage is markedly improved stability, which has long been a critical challenge in agricultural machinery. In addition, because hybrid suspensions retain some passive shock absorption, they can filter high-frequency vibrations, reducing both the load on the actuators and the required actuation speed.

In general, the last decade has seen growing emphasis on stability control. Fernandes et al. highlight that, in the absence of a human driver, agricultural robots must autonomously cope with unpredictable terrain conditions, making stability a key design concern [3]. Consequently, modern UGVs are expected to incorporate at least basic stability monitoring, even if they do not employ active or hybrid suspensions. Recent autonomous tractor retrofit solutions, for instance, often implement automatic stability cut-off systems instead of full active levelling.

2.3. Stability and Suspension of Agricultural Robots

Power for agricultural UGVs is typically supplied either by internal combustion engines or by battery driven electric motors. The general move toward electrification in ground vehicles has also influenced UGV design, but this transition is progressing more slowly in agriculture. Electric motors are attractive because they are easier to control for automation and generate less noise and local emissions; however, relatively few commercial platforms have fully adopted electric drivetrains, and these are mostly in the small to medium size range. Well known examples include several Naïo platforms (Ted, Oz, Jo, Orio) [2], as well as Bosch's Bonirob [15], which uses a 15 kW electric drive supported by an onboard gasoline generator acting as a range extender.

For larger machines, hybrid architectures are increasingly used to combine all day operating capability with electrically actuated drives or implements. Purely battery powered systems are more common in smaller robots, where many research demonstrators achieve between roughly 2 and 10 hours of operation per charge. Recent designs add features such as rapid battery exchange or, in some cases, solar panels to extend autonomy. In contrast, high power autonomous tractors still rely predominantly on diesel engines because of their substantial energy requirements. For instance, the AgroIntelli Robotti employs two Kubota diesel engines that feed hydrostatic transmissions and can also provide power to a PTO. The recently launched Monarch MK V electric tractor [16] delivers about 40 hp continuous power (70 hp peak) and can operate for up to 14 hours on a single large battery pack, but its mass exceeds 2300 kg due to the battery, which raises concerns about soil compaction. Scaling this approach to even higher power levels would further increase weight and exacerbate compaction problems.

These constraints have motivated alternative strategies, such as deploying multiple smaller robots in coordinated fleets or using hybrid powertrains to cover peak loads. Overall, experience from the last decade indicates that battery electric UGVs are technically feasible for many agricultural applications, particularly when combined with improved energy management concepts like swappable battery packs, onboard generators or solar assisted charging. In current practice, powertrain choice is strongly linked to vehicle size and intended task: lighter robots (approximately below 500 kg) are most often fully electric, whereas heavier platforms that must carry or drive implements generally adopt diesel or hybrid solutions to meet power and endurance requirements.

A further emerging option is the use of hydrogen as an energy carrier for agricultural robots. Most current concepts rely on proton exchange membrane (PEM) fuel cells that convert hydrogen into electricity to drive electric motors, combining the controllability and efficiency of electric drivetrains with fast refuelling and higher energy density than batteries. This makes hydrogen-powered UGVs particularly attractive for high-duty applications or larger platforms where battery mass and charging time become limiting. However, their adoption in agriculture is still at an early stage, constrained by the cost and durability of fuel cell systems, the lack of refuelling infrastructure in rural areas, and challenges related to safe on-farm storage and handling of hydrogen. As demonstrator projects, like AgiOne field robot from AGICU [17], mature and broader hydrogen ecosystems develop, such platforms may become a viable low-emission alternative to diesel, especially for regions investing in green hydrogen production.

2.4. Payload and Implement Integration

Agricultural robots are often grouped into two broad families: those built for a single, well-defined task and those conceived as general-purpose platforms. In the first case, the implement or payload is structurally integrated from the outset, so a machine designed exclusively for weeding, for instance, will typically carry fixed weeding tools and cannot be repurposed easily for other operations. In contrast, multipurpose robots are intended to work more like compact tractors or tool carriers, with the ability to accept different implements over time.

Despite the clear appeal of spreading investment across multiple jobs, progress toward truly multipurpose systems over the last decade has been relatively modest. Many contemporary UGVs do provide mounting points, proprietary hitches or docking frames, yet they still depend on bespoke implements, as seen with platforms such as Slopehelper [18]. Smaller robots sometimes offer a flat deck or modular rails where tools, tanks or sensor masts can be bolted on, but this typically requires that the implement itself be redesigned or adapted. In practice, this means that standard farm implements usually cannot be attached directly without custom modifications. Only a small number of more advanced concepts, such as AgXEED, have adopted attachment geometries that mimic conventional tractor interfaces.

Adding such implement interfaces is not only a geometric challenge but also a structural one: the robot must withstand substantial static and dynamic loads transmitted from the tool. It needs adequate drawbar capability and hitch lifting force to, for example, tow a light plough, haul a cultivator or carry a fertiliser tank without compromising stability or durability.

2.5. Perception

Perception for agricultural UGVs builds on a combination of global positioning and local environment sensing. High-precision GNSS, typically with RTK corrections, remains the backbone for absolute positioning in open fields, but signal dropouts near tree canopies, buildings or steep terrain make GNSS alone insufficient for reliable autonomy [19]. To increase robustness, most recent systems fuse GNSS with inertial sensors (IMU/INS) and sometimes wheel odometry, using Kalman-filter or related schemes to maintain centimeter-level pose estimates during brief outages [20, 21]. On top of this global pose layer, local perception is handled by cameras, LiDAR and, in specific tasks, radar or ultrasonic sensors, providing the detailed scene understanding required for row following, obstacle avoidance and implement guidance [22].

Machine vision is currently the dominant approach for crop-row detection and in-row navigation, especially in row crops such as maize, rice or vegetables [23]. Early systems relied on handcrafted image processing (color thresholding, edge detection, Hough transforms) to extract navigation lines, but these methods are sensitive to weeds, shadows and variable illumination. More recent work adopts deep learning, using convolutional networks or encoder–decoder architectures (e.g. U-Net variants, lightweight semantic segmentation networks, YOLO-style detectors) to infer crop rows, boundaries and regions of interest directly from RGB or RGB-D images [24–26]. These approaches improve robustness under occlusion, weed pressure and heterogeneous canopies, but require large, annotated datasets and careful domain adaptation when moving between crops, varieties or regions. Depth cameras are also increasingly used under canopies and in orchards, where GNSS is degraded, to reconstruct 3D structure and support navigation between trunks or trellises [27].

LiDAR-based perception provides complementary geometric information that is less affected by lighting and can operate in dust, twilight or partial fog. 2D and 3D LiDAR sensors are used to detect crop walls, furrows, tree rows and static or dynamic obstacles, often by clustering, template matching or model fitting (e.g. RANSAC-based line extraction) on point clouds [28, 29]. LiDAR is particularly attractive for vineyard and orchard robots, where accurate distance and height information enable safe navigation in narrow alleys and around irregular vegetation structures. However, its relatively high cost and processing demands have so far limited adoption in low-cost platforms, and perception quality can still degrade in dense foliage or highly reflective environments. Consequently, there is a clear trend toward multi-modal perception stacks that combine cameras, LiDAR, GNSS/INS and sometimes radar, with sensor-fusion and AI-based perception pipelines designed to exploit the strengths of each modality and compensate for their individual weaknesses [20, 22, 30]. Despite significant progress, many agricultural UGVs still face challenges in reliably perceiving highly unstructured, dynamic field environments, highlighting the need for better datasets, more generalizable models and tighter integration between perception, planning and control.

2.6. Control and Autonomous Functions

Control and autonomous functions in agricultural UGVs are typically organized in a hierarchical fashion, with mission planning at the top, path planning and behavior selection in the middle, and low-level motion control at the bottom. At the mission level, the robot must decompose a field into work zones, schedule coverage paths that respect headlands, turning radii and no-go areas, and decide when to interrupt work for refilling or battery exchange [31, 32]. Coverage path planning methods that originated in field machinery, such as boustrophedon and lane-based patterns, remain standard but are increasingly combined with optimization techniques that account for minimising non-productive travel, soil compaction and time windows for specific operations [31, 33]. For multi-robot systems, mission planners allocate sub-fields or swaths to each unit and coordinate rendezvous with logistics vehicles, which require balancing travel distance, energy use and task deadlines [34]. Such mission-level decision making is often implemented as a separate planning module that interacts with farm management software, enabling semi-automatic generation of robot missions from prescription maps or GIS data [33].

Below the mission layer, path planning and path tracking form the core of autonomous motion. Global planners generate collision-free trajectories that respect vehicle kinematics and terrain constraints, while local planners refine these paths in real time to handle obstacles, slip and implement dynamics [31, 32]. Traditional guidance laws such as pure pursuit and Stanley controllers are still widely used, but recent work increasingly adopts model predictive control to handle speed-dependent dynamics, actuator limits and strong disturbances like wheel slip on soft soils [35–37]. For articulated or four-wheel-steered platforms, MPC schemes that explicitly model vehicle geometry and load transfer can significantly improve tracking accuracy on tight headland turns and side slopes [35, 36]. In many commercial systems, these advanced controllers operate alongside simpler PID loops for engine speed, PTO torque or implement height, with supervisory logic switching between modes for straight-line work, headland turning and maneuvering near obstacles [32, 37].

Higher-level autonomy is typically implemented using finite state machines or behavior trees that sequence operations such as route following, row changing, obstacle avoidance, refilling and safe stopping [33, 38]. Reactive behaviors rely on perception inputs to trigger slowdown, replanning or emergency braking if obstacles or humans enter the safety zone [22, 28]. At the same time, most fielded robots remain under some form of human supervision, for example through remote monitoring, teleoperation modes for docking or loading, and manual confirmation of mission start and end [18, 32]. Recent frameworks integrate perception, planning and control in unified software stacks tailored to agriculture, allowing reusable components for navigation, coverage planning and task execution across different crops and implements [18, 38]. Despite this progress, achieving reliable, fully unattended operation over long days and across seasons remains challenging because control systems must cope with changing soil conditions, varying payloads, mixed traffic with human-operated machines and strict agricultural safety regulations.

3. MECHANICAL DESIGN OF THE AGAR PLATFORM

The AgAR robotic platform is conceived as a modular machine composed of a set of mechanical subassemblies that together provide high versatility and adaptability in agricultural use. The principal mechanical modules, illustrated in Figure 1, are:

1. a central load-bearing body frame (chassis) with an external protective shell,
2. four wheel-leg units, each comprising a drive wheel, electric motor and an actively suspended leg,
3. the drivetrain and power unit, including traction motors, gearboxes and the main battery pack,
4. safety components responsible for emergency stopping and system shutdown,
5. an optional three-point hitch with integrated counterweight, allowing attachment of standard farm implements,
6. an optional PTO drive module with dedicated motor, gearbox and battery,
7. an additional protective enclosure for the PTO electronics and auxiliary battery,
8. housing for environment perception, localisation and communication sensors.

The main body of AgAR acts as the central load-bearing structure to which all other modules are attached. It is designed to combine high stiffness with low mass, relying on a mix of standard aluminum profiles and custom steel components. The base frame is formed from extruded aluminum beams arranged in a rectangular layout, creating a modular skeleton that can be assembled, reconfigured or extended with relative ease. Aluminum was selected for its favorable strength-to-weight characteristics and inherent corrosion resistance, which are important for outdoor operation and exposure to fertilizers, humidity and dirt. Additional aluminum sheet-metal elements are fixed to this frame; these serve both as structural reinforcements and as exterior body panels. The outer shell shields internal components from impacts and contamination, while also providing convenient mounting surfaces for sensors, lighting and other auxiliaries. The structure is joined predominantly with bolted connections so that subassemblies can be removed for service, repair or future upgrades. Overall, the body is a compromise between modularity and mass efficiency: the design supports flexible configurations while keeping weight as low as practical. At the front, the chassis is fitted with a safety bumper offering approximately 10 cm of travel; when it is deflected by an obstacle in the robot's path, it triggers an immediate stop of the vehicle.

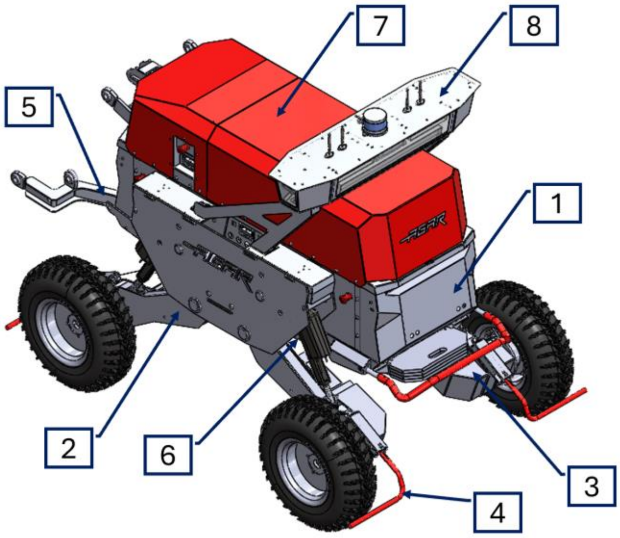

Fig. 1 3D model of the AgAR robotic platform

Each of the four-wheel units' functions as a powered leg (4, Figure 2). A single module includes an off-road wheel and tyre suitable for skid-steer operation, a gearmotor, a leg linkage driven by an electric linear actuator for vertical adjustment, and an interface with a damped, adjustable shock absorber that connects the actuator to the chassis. Different wheel diameters (approximately 480–735 mm) and widths (175–300 mm) can be installed to tune travel speed, tractive capability and ground pressure for specific crops or soil conditions. Traction on each wheel is provided by a 3 kW brushless DC motor (1, Figure 2) coupled to a planetary gearbox with a reduction ratio of 64:1 (3), enclosed by a protective shell (2), transforming the motor's high-speed, low-torque output into the high torque required at the wheel. The motors are equipped with electromagnetic brakes that engage during an emergency stop, limiting the stopping distance of the robot to less than 10 cm. In addition, each wheel hub (5) carries a 203 mm disc brake (6), which supplements regenerative electric brake, particularly when operating on slopes. These mechanical brakes are actuated by electric linear actuators mounted to the lower part of the chassis. Similar to the main body, each leg incorporates its own safety bumper (8, Figure 2); contact with an obstacle in the wheel's path activates this bumper and commands the robot to stop. Each leg is attached to the main chassis via cylindrical supports (7). Furthermore, the wheels can be repositioned laterally with extenders. This effectively allows adjusting track width from a maximum to a narrower stance.

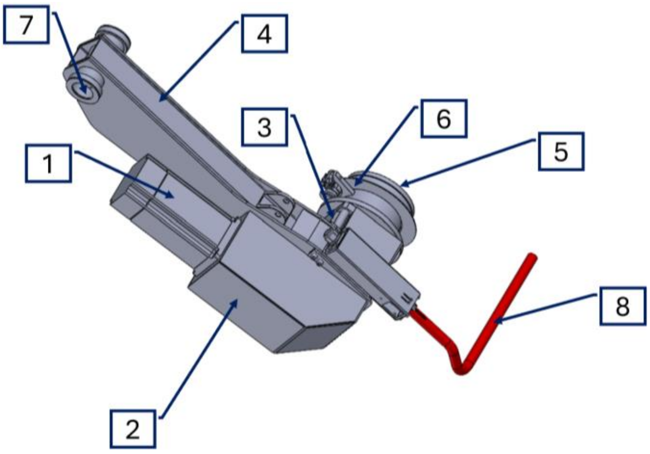

Fig. 2 3D model of the AgAR drive train

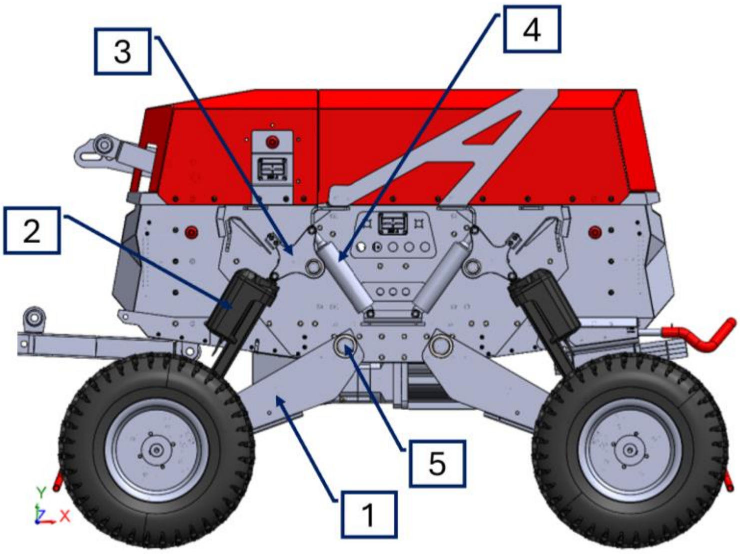

Fig. 3 AgAR hybrid suspension system

The wheel modules (1, Figure 3) are connected to the chassis, through vertical pivot pins (5) so that each unit behaves as a swing arm capable of moving up and down. Vertical motion is provided by a heavy-duty electric linear actuator (2) on each leg, which extends or retracts to change the wheel position with respect to the main body. The actuator is linked to the chassis via a motion amplification mechanism (3) and an air-damped, adjustable shock absorber (4), pinned to the frame. Together, these elements form the basis of the robot's dynamic levelling system.

By coordinating the four actuators, the control system can maintain a nearly horizontal platform attitude over uneven ground or deliberately vary the ground clearance when required. Because they must carry not only the vehicle itself but also any attached implements or payloads, the actuators are dimensioned for high static loads, with each unit rated for approximately 11 kN. In operation, the legs are subjected to impacts from bumps and ruts, as well as continuous small-scale irregularities. These disturbances are partly absorbed by the damped shock absorbers, which smooth out the motion and help keep the chassis level. The result is a hybrid suspension system, combining active height control with passive damping.

Fig. 4 Change of clearance from the ground

In practical use, the levelling system on AgAR also functions as a continuously adjustable height control. The operator can command all four legs to extend or retract together, so that the chassis rises or lowers uniformly while remaining level. This mode, illustrated in Figure 4, is useful when lifting attached implements off the ground, clearing tall obstacles or positioning a mounted robotic arm at canopy level. With the legs fully extended and a robot arm installed, AgAR can reach working heights of more than 3.5 m, enabling operations on higher fruit tree branches. At the opposite extreme, the platform can be brought down to a very low stance, just above the ground, which is suitable for tasks such as strawberry harvesting or travelling under low-hanging foliage. The broad vertical adjustment range is therefore a direct consequence of the actively controlled leg architecture.

The drivetrain is complemented by a distributed power electronics and control system. Each traction motor is paired with its own motor driver that provides closed-loop control of torque and speed. A central computer running ROS2 (Robot Operating System) coordinates these units by sending velocity commands to the four-wheel motors and position commands to the leg actuators, based on feedback from onboard sensors. The wheel motors incorporate Hall sensors for speed and position measurement, which enables accurate skid-steer motion and supports odometry estimation for navigation. Likewise, the leg actuators are equipped with position feedback, allowing precise control of ground clearance and body attitude. In effect, each corner of the vehicle behaves as an independently controlled suspension module that can be adjusted in software.

All actuators and controllers are supplied by a battery system housed within the main body. The primary energy source is an 11 kWh lithium iron phosphate pack, dimensioned to support approximately 8 to 12 hours of typical operation. The pack is mounted in a front-accessible drawer: by removing the front panel, the depleted battery can be pulled out and replaced, a process designed to take no more than about three minutes, as indicated in Figure 5. For long-duration missions, several packs can be used in rotation so that one is charging while another is in service. The chassis roof includes mounting rails for an auxiliary top battery, for example an additional 27 kWh pack, which can be installed when higher energy capacity is required. This extra pack not only extends operational time beyond 24 hours in low-power tasks such as monitoring or tilling but also acts as an energy reservoir for the PTO drive. The modular battery concept thus supports the multipurpose character of AgAR by adapting energy capacity to the demands of each application.

Fig. 5 AgAR battery swap

In operation, the traction drivetrain allows AgAR to reach a maximum speed of approximately 6 km/h on level ground. Longitudinal dynamics are actively limited by the controller, which caps acceleration and braking rates to avoid oscillations or loss of stability, particularly when the platform carries heavy implements or payloads. The skid-steer layout enables on-the-spot rotation around the robot's centre (zero turning radius), verified on both concrete and bare soil. Because such spot turns on high-friction surfaces generate the highest motor currents – and thus peak torque and mechanical loading – the motion planner restricts aggressive pivoting on asphalt and similar surfaces to preserve drivetrain components. Motor currents are continuously monitored and, when necessary, the controller derates the available torque to protect the drives.

The PTO drivetrain is mounted underneath the main body (Figure 6) and powered from the auxiliary battery pack. It comprises a 48 V, 10 kW brushless DC motor (1) coupled to a planetary gearbox (2), delivering up to 350 Nm at the PTO shaft. The external PTO shaft and joints are guarded (3) in line with ISO 5673-2 safety requirements.

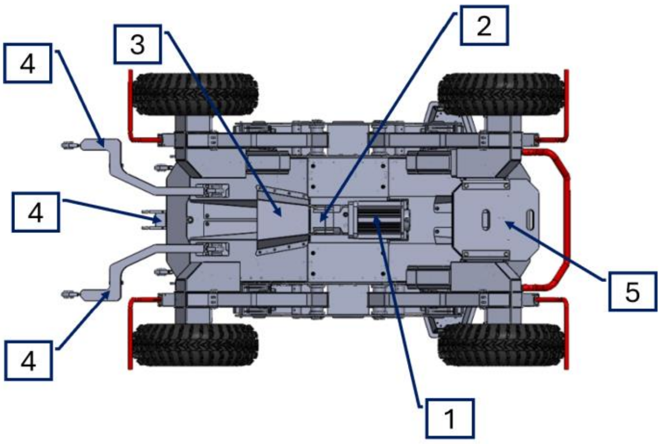

Fig. 6 AgAR PTO drivetrain

The AgAR platform can be fitted with a three-point hitch of Category I, compliant with ISO 11001-1:2016 (4, Figure 6). In this configuration the robot can work with standard Category I tractor implements. The same interface can be reconfigured with a drawbar hook so that AgAR can tow trailers or pulled machines such as trailed sprayers, atomizers or balers. To increase stability while working with heavy implements, the counterweights (5) can be added to the opposite platform side. Because the base vehicle is designed to operate independently of its nominal "forward" direction, the hitch assembly may be mounted so that implements are positioned either behind or in front of the platform. This bidirectional use is supported by the sensor bridge design, which can be relocated to the opposite side of the robot when needed. In addition, the bridge is mounted on a hinge, allowing it to swing out of the way for rapid access to the auxiliary battery cover and enabling quick battery replacement.

The AgAR platform is equipped with a comprehensive sensor suite that supports precise navigation, rich perception of the environment and continuous monitoring of the robot's health, as shown on Figure 7. At the core of the positioning system is the RTK GNSS rover with two antennas that provide UTC-stamped three dimensional coordinates, altitude, solution status, velocity and the number of satellites used, which together form a high-accuracy global pose estimate for autonomous operation in the field. This information is complemented by an AHRS-class IMU that delivers tri-axial accelerations, angular rates, magnetic field, roll, pitch, yaw, delta angle, delta velocity and ambient pressure, together with fused attitude and reference vectors in a complementary filter frame (attitude, north and up vectors).

For visual perception, AgAR uses a pair of ZED X stereo cameras that supply synchronised RGB images and depth information. These data streams enable visual navigation, row and path following, as well as AI-based object recognition and plant-level inspection tasks. A compact 3D LiDAR generates a dense 3D point cloud of the surroundings, which is used for SLAM, map building and obstacle detection, particularly in structured environments such as orchards and vineyards. Short range coverage around the chassis is provided by four ultrasonic sensors that measure distance to nearby obstacles and crop structures, forming an additional safety and proximity layer.

Fig. 7 AgAR sensor stack

In parallel with navigation and perception, the platform continuously monitors its own powertrain and energy system. The battery management system records battery voltage, current, temperature and state of charge, while each BLDC motor controller reports motor speed (RPM), motor voltage and current, motor and controller temperatures, battery voltage at the controller input and the commanded forward or reverse direction and throttle value. These internal measurements are integrated into the control and logging framework of AgAR and are used for traction control, thermal protection, diagnostics and post-mission analysis. Together, these sensors provide a detailed, multi-modal view of both the environment and the robot itself, which is essential for safe, reliable and data-rich autonomous operation.

The AgAR control architecture, schematically depicted in Figure 8, is designed as a hierarchical architecture in which localisation, perception, safety and mission-level decision making are clearly separated yet tightly interconnected. At the base of this hierarchy lies the navigation layer, which maintains a continuous estimate of platform pose and motion state. This layer blends high-accuracy satellite-based localisation with motion feedback from the drivetrain and leg mechanisms and forwards a filtered pose to the upper layers. In this way, the robot keeps a coherent representation of its position within the field and along crop rows, which the path-planning and path-tracking modules use to generate and execute smooth, kinematically feasible trajectories over heterogeneous terrain.

Encapsulating this navigation core is the perception layer, which turns raw visual and ranging data into a geometric and semantic description of the surroundings. Rather than being tied to individual hardware devices, this layer operates on fused depth, point-cloud and proximity information to detect obstacles, delineate rows and headlands, and characterise crop structures. The resulting maps, cost grids and obstacle lists are published within the ROS ecosystem and consumed by local planners and behavior modules as shown in Figure 9. This allows the platform to adapt speed, negotiate obstacles and support precision-agronomy tasks such as targeted treatment or inspection, without replicating sensor-specific logic in each node.

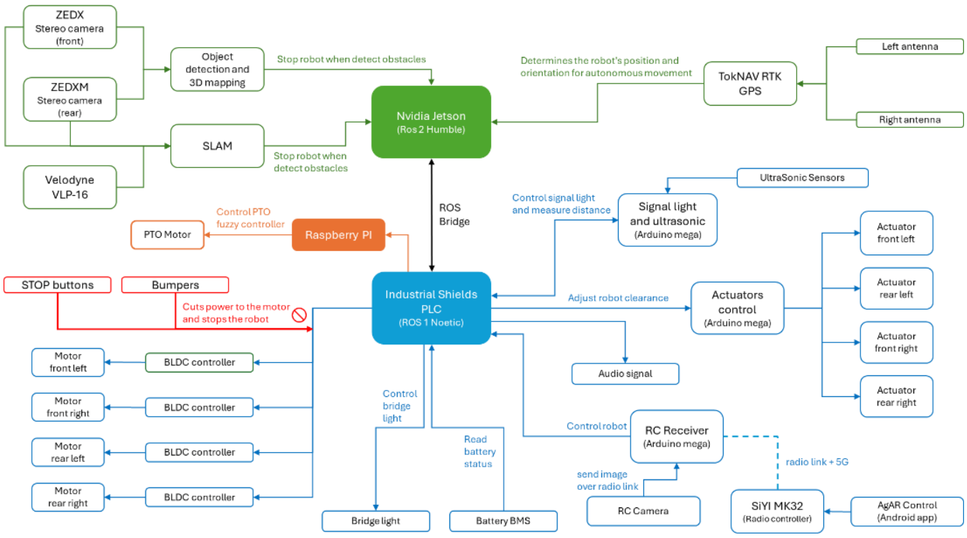

Fig. 8 AgAR control architecture

Fig. 9 Detection of obstacle on the robot path

Operating independently of these functional layers, AgAR incorporates a dedicated safety backbone that supervises the entire machine. Mechanical bumpers, emergency-stop devices and other safety inputs are hard-wired to the motor controller and brake systems, ensuring that any unsafe condition drives the platform directly into a safe state, regardless of the status of higher-level software. This includes immediate power cut-off to the traction drive and activation of braking systems, which limits stopping distance and provides a robust protective envelope when the robot is working near operators, animals or sensitive crops. The safety layer thus acts as an autonomous guardian that overrides all other commands whenever required.

Above the safety and navigation layers, a distributed control system implements the high-level behaviour of the platform. It is built around two main compute nodes: an Industrial Shields PLC running ROS 1 Noetic and an NVIDIA Jetson module running ROS 2 Humble, connected via a ROS bridge. The PLC provides industrial-grade I/O and executes deterministic low-level routines for motor control, actuator handling and safety supervision, while the Jetson hosts ROS-based nodes for localisation, perception pipelines, planning and mission management. Ancillary controllers, including a Raspberry Pi, take care of specialised tasks such as interfacing with the battery management system, driving signal lights and audio alarms, and supervising the fuzzy controller of the PTO motor, thereby decoupling implement-level control from the main autonomy stack and simplifying integration of new tools.

User interaction is provided through a combination of direct radio control and networked interfaces. A SiYI MK32 radio controller with an RC camera enables teleoperation with live video, while the AgAR Control Android application allows configuration of missions, status monitoring and execution of predefined routes. Communication between the control hardware and these user interfaces is realised over a radio, WiFi and 5G connectivity, supporting both local line-of-sight operation and remote supervision.

Taking together, these layers form an integrated perception-and-control stack in which sensing, decision making and actuation are tightly coupled yet cleanly modularised. The architecture supports a continuum of operating modes, from manual driving through supervised autonomy to fully autonomous missions, while remaining compatible with standard agricultural implements and practices. Its modular, ROS-centered organisation also facilitates future extensions, such as new perception algorithms, decision modules or implements, without disrupting the core navigation and safety functions of the AgAR platform.

4. DESIGN ADVANTAGES OF AGAR VS. CONTEMPORARY PLATFORMS

AgAR was conceived to address several gaps observed in existing UGVs. A comparison of key specifications is given in Table 1.

Table 1. Comparison of AgAR with selected agricultural UGVs. Key: AWD – All-wheel drive; PTO – Power Take-Off; Levelling indicates if active chassis leveling is present; runtime assumes one refuel or full battery charge.

Platform	Drive & Power	Weight (kg)	Payload / Hitch	Terrain & Slope	Notable Features
AgAR (Coming, 2024)	4×4 electric (4×3 kW motors); Battery 8 - 12 h, swap in 3 min	~900	750 kg payload; Cat-I 3-pt hitch	GPS based leveling, 30° max slope	Dynamic height adjustment (0.7 m); standard Category I implement; Multi-robotic attachment support;

	PTO 5- 10 kW				Autonomous & teleopation modes
Robotti (AgroIntelli, 2018)	4×4 diesel (2×25 kW engines); 60 - 80 h per refuel	~1500	1500 kg implement; Cat-II hitch, optional PTO	Rigid chassis; 15° max slope	High endurance; Full tractor implements; RTK-GPS navigation; No active suspension
Dino (Naïo, 2017)	4×4 electric (hub motors); Battery 8 - 10 h	~600	Approx. 100 kg tool load (weeding tools)	Passive suspension, flat fields (vegetable rows)	Autonomous weeding robot; Vision guided row following; Task-specific (cultivator)
Agri.Q (Polito, 2020)	8×8 electric (hub motors); Battery ~6 h	~800	200 kg sensors & arm (no hitch)	Hybrid suspension, active leveling (rocker-arms)	
AgBot 2.055W4 (AgXeed, ~2020)	Diesel-electric 4×4; 2.9 L Deutz diesel 55 kW / 75 hp, electric drive, 0–13.5 km/h; optional electric PTO up to ~50–55 kW	~2800	Front Cat-II 3-pt hitch 1.5 t; rear Cat-II 3-pt hitch up to 4 t lift	Broad-acre arable fields, rolling terrain; rigid chassis (no active levelling)	High-capacity autonomous tractor; up to ~24 h runtime on one tank; RTK-GNSS navigation and ISOBUS support; optional high-voltage connectors for electric implements
Orio (Naïo, 2021)	4×4 electric (4×3 kW, 48 V motors); swappable battery packs 21.5–32.3 kWh; 8–12 h operation	~1450 - 1550	Rear 3-pt hitch, ~600 kg lift; designed for standard vegetable implements (seeders, harrows, weeders)	Flat to moderately sloping vegetable beds; high ground clearance gantry	Autonomous gantry-type implement carrier; RTK-GPS + camera-guided side-shift for precise row tracking; compatible with standard 3-pt tools for sowing, weeding and cultivation; 100% electric, low soil compaction

Bakus (Vitibot, ~2019)	100% electric vineyard robot; ~48 kW electric power; Li-ion battery, autonomy up to ~14 h	≈2050–2400	Straddle-type tool carrier with integrated hydraulic/electric tool lift; pulling force ≈1800 kg; no standard rear 3-pt hitch	Narrow and standard vineyards; handles difficult terrain and slopes up to about 45°	Fully electric autonomous straddle carrier for vineyards; RTK-GPS with dual antennas; low-pressure tyres for reduced soil compaction; supports mechanical soil work, mowing, trimming and spraying with modular tools
Slopehelper (PeK Automotive, ~2021)	Fully electric tracked carrier; Li-ion battery; up to ~14 h autonomy, max speed ~10 km/h	~2800 (grapepicker configuration)	Modular front/rear implement frames and self-levelling cargo platform; tow-bar for sprayers, mowers, harvest bins (no standard Cat-I/II hitch)	Orchards & vineyards; tracked undercarriage and self-stabilising platform allow work on slopes up to ≈42–45° in any direction	Multi-purpose autonomous agrosystem replacing several tractor tasks (spraying, mulching, mowing, harvesting support); low-voltage electric system; TeroAir connectivity for mission planning and fleet monitoring
SwarmBot 5 (SwarmFarm, 2018)	Diesel engine (≈62 kW / 86 hp) with hydrostatic 4×4 drive; diesel tank sized for ~30 h operation on one fill	~2500	Cat-II 3-pt linkage with ≈1500 kg lift; 5 hydraulic remotes (100 L/min); supports 3-pt tools, drawbar implements and custom sprayers/mowers via SwarmConnect interface	Field crops, orchards and vineyards on flat to rolling terrain (CTF compatible track widths; no active levelling)	Mature commercial platform (100+ units in service); 2 cm RTK-GPS + LiDAR + ToF cameras for obstacle detection; designed as an open carrier for 3rd-party implements (spraying, mowing, spreading, etc.); up to ~30 h

					runtime and ~18 ha/h with 18 m spray boom

Terrain adaptability: In the past decade many commercial UGVs have been built with either rigid frames or simple passive suspension. As a result, they are restricted to relatively smooth fields or must move very slowly when the surface becomes uneven. AgAR uses a four point hybrid active leveling system that continuously adjusts the leg modules to keep the chassis close to horizontal on sloping ground. The platform has been trialed on inclines up to 40° in loose sand, without loss of stability. Under implement load, it was tested on a 25° with a 1.5-ton atomizer where it was proved that machines have the traction of power and stability to perform maneuvering and entrance into rows even in terraced vineyards as shown in Figure 10. This capability opens up applications in steep vineyards and terraced plots where, until now, work has been performed almost exclusively with tracked machines or manually operated equipment.

Fig. 10 AgAR on a 25° slope with a 1.5 t atomizer

Multipurpose attachment support: AgAR is conceived as a generic robotic carrier rather than a single purpose machine. The frame integrates standardized agricultural interfaces, most notably a Category I three point hitch and several electrical power outlets. Farmers can therefore couple existing small tractor implements for typical tasks such as tillage, seeding, mowing or spraying, as presented in Figure 10. Many competing platforms cannot do this. For example, Dino transports dedicated weeding tools and does not offer a standard hitch, whereas Robotti and similar systems accept implements but often require dedicated solutions. AgAR brings full implement compatibility to a compact, fully electric robot and further provides high power electric outputs for driven tools or inverters, along with space for an auxiliary battery or a robotic arm on the upper deck (Figure 11). The underlying concept is not to optimize for a single job, but to deliver a versatile “generalist” machine whose investment can be justified across numerous operations.

Fig.10 AgAR performing various applications with existing implements

Fig.11 AgAR platform equipped with a robotic system for grape harvesting

Adjustable geometry: Through its articulated leg mechanisms AgAR can modify both ground clearance and track width. The vertical travel is close to 0.9 m and is used for both leveling and adapting the underbody's height to the task at hand. The robot can squat to lower its center of gravity for heavy work or operations near the ground, or it can raise the chassis to straddle higher crops or bring tools in line with tree canopies. In addition, the wheels can be shifted laterally so that the running width can be matched to different row spacings and tire configurations. Only a few existing robots offer more than a fixed width or slow manual adjustment. AgAR's rapid reconfiguration makes it suitable for a broad range of crop geometries without structural modification.

High torque drivetrain in a compact package: AgAR is powered by four 3 kW electric motors, resulting in 12 kW of continuous drive power, which is modest compared with large diesel robots. However, each motor is coupled to a high ratio planetary gearbox so the available torque at the wheels is substantial. The drivetrain is therefore optimized for tractive effort at low travel speeds. Combined with the active leveling system, this allows the robot to tow implements or trailers on gradients where similarly sized electric platforms would either stall or become unstable. Although the maximum speed is relatively low, it matches the 5–8 km/h range commonly used for agricultural work, so there is no practical penalty for field operations. All four wheels are driven and can be counter-rotated for skid steering, which allows zero radius turns in confined spaces. The drawback is increased contact forces on the soil and higher stresses in the structure and drivetrain during such maneuvers, which have been taken into account in the mechanical design.

Safety and reliability features: Working in proximity to people and crops requires robust safety measures. AgAR incorporates several layers of protection. Emergency stop buttons are located on all corners and mechanical bumpers are fitted to arrest the vehicle and absorb minor impacts. External panels and guards shield users from moving parts such as wheels and actuators and help to prevent entanglement. As with many current UGVs, environmental perception is based on a combination of LiDAR and vision sensors that feed obstacle detection and emergency stop logic, providing 360° coverage around the platform.

A particular design choice is that all electromechanical components are housed inside the main body or inside the moving leg structures, which protects them against dust, moisture and accidental impacts while also giving the robot a clean outer shape.

5. CONCLUSION

In this paper, we reviewed recent developments in agricultural unmanned ground vehicles and examined how the AgAR platform extends and reshapes the current state of the art. Over roughly the last decade, agricultural robots have been moving from single-purpose demonstrators toward more durable, multi-role platforms. Common trends include modular frames that accept different tools, a gradual transition to electric drivetrains for better controllability and lower emissions, and more advanced suspension concepts to cope with irregular field conditions. Despite this progress, most existing designs still involve compromises between versatility, terrain accessibility, and system complexity.

AgAR can be seen as a point where several of these threads come together. It is a fully electric, general-purpose field robot that maintains good stability on uneven ground. The four-point hybrid leveling mechanism directly targets one of the main weaknesses of many UGVs, namely limited stability on slopes. The capability to keep the chassis within a safe orientation on gradients up to 25° while adjusting ground clearance during operation represents a clear step beyond typical rigid or passively sprung platforms. The comparison with other robots shows that AgAR is unusual in combining the use of standard tractor implements with an adaptable chassis that also supports multiple robotic payloads. Structurally, it attains high stiffness and load capacity at moderate mass through careful layout of the frame and digital-twin-supported topology optimization, without sacrificing robustness. Such data-driven iterative design workflows are likely to become increasingly common in agricultural robotics, as they allow designers to jointly optimize performance, efficiency, and manufacturability.

The AgAR project also underlines the value of an integrated, interdisciplinary design approach. Mechanical architecture, electrical systems, and software were developed together with autonomous field deployment in mind. For example, the frame and bodywork are prepared for sensor installation and routing, while safety elements such as bumpers and emergency stop hardware are built in from the outset to meet practical operating requirements. The outcome is not only a technically capable robot, but a platform that can realistically be introduced into farm practice, with attention paid to usability, maintenance, and scalability.

Looking ahead, the design choices made in AgAR and comparable platforms indicate several likely directions for future UGVs. Adaptive geometries, including variable track widths and active suspension or leveling, can be expected to become standard features, particularly for work in complex environments such as orchards, vineyards, and steep or terraced fields. At the same time, emphasis on mass reduction through advanced materials and structural optimization will continue, since robots must combine sufficient strength with low ground pressure and high energy efficiency. AgAR's combination of aluminum alloys and high strength steels, together with systematic removal of non-critical material, illustrates how achieving an appropriate mass–stiffness balance is emerging as a central design objective beyond the logic of conventional tractor construction.

Acknowledgement: *The AGAR development was partially financed by the Innovation Fund in Serbia from the Pre-Accession Funds of the European Union and the budget of the Republic of Serbia from the Ministry of Science, Technological Development and Innovation of the Republic of Serbia and supported by the StarTech support program implemented by NALED and funded by Philip Morris International.*

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