TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue I March, 2025

AUTONOMOUS MOBILE SYSTEMS FOR PLANTATION MAINTENANCE: REVIEW AND ANALYSIS

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Abstract: *As demand for sustainable and efficient agriculture grows, autonomous mobile systems have become crucial for plantation maintenance. This paper reviews key commercial solutions, analyzing their capabilities and applications. It also examines locomotion models, highlighting their advantages and disadvantages in agricultural maintenance. Additionally, it summarizes the modular schematic framework for autonomous plantation maintenance systems, focusing on the task execution module, which automates essential operations. The analysis emphasizes sustainability and eco-friendly technologies that reduce environmental impact while improving efficiency and resource use.*
Key words: *autonomous mobile systems, plantation maintenance, precision agriculture, sustainable farming, smart agriculture, weed control automation.*

1. INTRODUCTION

For six decades, robots have played a fundamental role in increasing efficiency and reducing costs in industrial agricultural production. A comprehensive review of the historical evolution of robotic applications in agriculture is available in [1], while an in-depth analysis focusing on harvesting grippers can be found in [2]. Additionally, a broader discussion on the large-scale application of autonomous mobility in agricultural platforms is provided in [3], and an extensive review of mobile agricultural robotics for field operations, with a particular emphasis on cotton harvesting, is detailed in [4]. Many research activities in the field of agricultural robotics began more than 20 years ago, but most were interrupted or even halted due to high implementation costs and failed results.

However, recent advancements in smart farming solutions and the increasing demand for sustainable and efficient agricultural practices have renewed interest in autonomous mobile systems. These systems assist in plantation maintenance through tasks such as weeding, pruning, monitoring, and irrigation management, leveraging advanced robotics, artificial intelligence, and sensor technologies to optimize plantation care while reducing manual labor and environmental impact.

The increasing cost of labor, new workplace safety regulations, and stricter pesticide policies due to their negative effects [5], [6] make automation an appealing solution. Autonomous tractors equipped with GPS and advanced vision systems, enabling operation without a permanent operator [7], are already commercially available. Farmers are also adopting automated systems for tasks such as pruning, thinning, harvesting, mowing, spreading agricultural substances, and weed removal, with robotic platforms in orcharding doubling productivity compared to traditional methods. Advances in sensor technology and control systems improve resource optimization and the management of pesticides and diseases. The growing issue of herbicide-resistant weeds [8] and the lack of new herbicide action modes since the 1980s [9] further emphasize the need for automation. These aspects mark the beginning of a transformative shift in how agricultural products are grown, maintained, and harvested [7].

This paper explores the most relevant commercially available autonomous solutions

Received: 30.01.25; **Similarities**: 05.03.25: **Reviewed**: 24.02./25.02.25: **Accepted**:20.03.25.

for plantation maintenance, the main locomotion models used in agricultural applications and examines the modular schematic framework for autonomous plantation maintenance systems, with a particular focus on the task execution module. The analysis emphasizes sustainable and eco-friendly approaches, highlighting technologies that enhance efficiency while minimizing environmental impact.

2. COMMERCIAL SOLUTIONS FOR AUTONOMOUS MOBILE SYSTEMS IN PLANTATION MAINTENANCE

2.1 Introduction

Several commercial solutions have been developed to support plantation maintenance through autonomous mobile systems. These solutions vary in their design, capabilities, and target applications. Some of the prominent commercial solutions for autonomous mobile systems include:

- **BoniRob**: A four-wheeled autonomous platform for precise crop monitoring, fertilization, and weeding.
- **ecoRobotix**: A lightweight, solar-powered weeding robot capable of targeted herbicide application.
- **Vinobot & Vinoculer**: A combined robotic system for high-resolution plant monitoring and disease detection.
- **Tertill**: A small, solar-powered, consumer-grade weeding robot designed for home gardens, which autonomously trims small weeds without the use of herbicides.
- **FarmDroid FD20**: A solar-powered, fully autonomous field robot designed for seeding and weeding. It reduces labor costs and ensures precise, chemical-free weed control, making it an efficient and sustainable solution for agricultural operations.

Some of these solutions integrate advanced perception systems, navigation algorithms, and task-specific functionalities to improve efficiency and effectiveness in plantation management.

2.2 BoniRob

Weeds are the primary cause of agricultural yield losses [10], which is why extensive research has been dedicated to this field. It has been found that crop spraying is one of the most expensive operations for agricultural farms. The application of pesticides exposes workers to high levels of hazardous chemicals; however, implementing robots for this task will not only reduce the volume of pesticides used but also ensure the protection of operators, animals, and ecosystems. In the future, robots will be able to provide crop care and later contribute to harvesting autonomously and independently.

One example of a mobile platform for plantation maintenance is BoniRob. This is a flexible four-wheeled platform where each wheel can be steered separately via four electric motors mounted on each wheel (fig. 1). Depending on the plantation and the width of cultivated rows, BoniRob can adjust its working width from 0.75 m to 2 m, with a safety space between 0.4 m and 0.8 m. The BoniRob system is equipped with several dedicated control units: four motor controllers, an interface for the motor and hydraulic system, a navigation system control unit, and an application control unit. The various control units are connected via Ethernet and TCP/IP [7].

BoniRob is a commercially available autonomous agricultural platform designed to assist farmers by optimizing field management through advanced automation. This robotic system is equipped with state-of-the-art sensors and artificial intelligence to conduct precise monitoring of crops, ensuring efficient plant care while reducing manual labor. It continuously inspects the plantation, utilizing high-resolution image acquisition sensors to analyze individual plants in detail. By assessing plant health, recording growth levels, and evaluating the mineral content in leaves, BoniRob helps farmers make data-driven decisions to optimize crop performance.

Additionally, the robot determines the precise amount of fertilizer required for each plant, ensuring targeted nutrient application that enhances soil health and productivity. It also integrates an advanced weed detection and removal system, allowing it to identify weed coverage and autonomously eliminate unwanted vegetation. This reduces reliance on chemical herbicides, promoting more sustainable agricultural practices. By automating critical farming operations such as plant monitoring, fertilization, and weed control, BoniRob significantly improves efficiency, conserves resources, and contributes to higher crop yields [7], [11].

Fig. 1. BoniRob [7]

In addition to its herbicide spraying system, BoniRob can also use a mechanical device to crush weeds, with the primary requirement being that cultivated plants should not be too tall, as this could hinder field mobility [11].

2.3 ecoRobotix

Given the increasing need for high-yield crops and the reduction of pesticide and herbicide usage, a similar commercial solution is offered by ecoRobotix. They have developed an intelligent and independent mobile robotic platform that can target weeds individually, applying a significantly reduced amount of herbicide only where necessary (fig. 2). Compared to BoniRob, this mobile platform is much lighter and operates solely on solar energy [12], [13].

A high-resolution camera positioned at a strategic height on the platform analyzes the plantation area ahead of the mobile platform, transmitting the exact weed positions to two robotic arms equipped with precise pesticide spraying devices.

This platform is capable of maintaining approximately 3 hectares per day, provided the weeds are still small (fig. 3). The main requirement is that the mobile platform must be deployed shortly after planting [12], [13].

Fig. 2. The ecoRobotix solution for mobile plantation maintenance [12]

Fig. 3. Weed detection for ecoRobotix [13]

2.4 Vinobot and Vinoculer

A simpler and more accessible solution is Vinobot, which performs detailed inspections of individual plants or plant groups to prevent specific diseases for each plantation type. This platform is assisted by another system called Vinoculer, which can scan the entire crop and, upon identifying problematic areas, send the coordinates to Vinobot (fig. 4).

The advantages of this architecture are:

- It enables scanning of a large crop area at any time of day or night while identifying affected zones.
- It allows rigorous in-field phenotyping, either on individual plants or plant groups.
- It eliminates the need for costly aerial vehicles or similar platforms in open-field conditions.

This type of platform is most commonly utilized when the plantation has reached an advanced stage of maturity, when frequent weed control interventions are no longer essential. Instead, the focus shifts toward comprehensive plant health monitoring and targeted disease management, ensuring optimal crop growth and productivity. By this stage, the primary concerns are detecting and mitigating potential diseases, nutrient deficiencies, and environmental stress factors that could impact yield quality. The ability of such platforms to conduct regular, high-resolution inspections allows for early intervention and precise treatment, reducing reliance on broad-spectrum chemical applications while enhancing overall plantation sustainability [14].

(a) Vinobot (b) Vinoculer

Fig. 4. Proposed field inspection platforms: (a) terrestrial vehicle, Vinobot; (b) observation tower, Vinoculer, with a height of 4.5 m [14]

2.5 Tertill

Tertill is a small, fully autonomous weeding robot designed for home gardens (fig. 5). Unlike large-scale agricultural robots, Tertill operates in small, controlled environments, using built-in sensors to navigate and trim small weeds effectively. It is powered by solar energy, eliminating the need for battery replacements or manual charging.

Equipped with a trimmer, Tertill can distinguish between mature plants and weeds, allowing it to eliminate unwanted vegetation without harming crops. Its rugged, waterproof design enables it to function in various weather conditions, making it a low-maintenance solution for gardeners seeking automated weed control. While its application is limited to small-scale gardening, its approach to autonomous weeding without the use of herbicides aligns with broader agricultural trends toward sustainability and reduced chemical dependence.

Fig. 5. Tertill robot [15]

2.5 FarmDroid FD20

FarmDroid FD20 provides a unique solution by combining seeding and weeding functionalities in a fully autonomous platform. Unlike traditional agricultural robots, this solar-powered field robot is designed to precisely sow seeds while simultaneously performing chemical-free weed control, reducing the need for herbicides (fig. 6). By operating autonomously, it significantly lowers labor costs and enhances productivity in large-scale farming operations.

Fig. 6. FarmDroid FD20 autonomous platform for seeding and weeding [A16]

The FarmDroid FD20 utilizes GPS-based precision guidance to ensure accurate seed placement and weed removal. As the robot remembers the exact location of each planted seed, it can later perform mechanical weeding with high precision, eliminating the need for harmful chemical treatments. Its lightweight design minimizes soil compaction, preserving soil health and ensuring long-term agricultural sustainability.

This platform is capable of autonomously maintaining several hectares per day, depending on the crop type and field conditions by offering inter- and intra-row high precision weeding (fig. 7). Due to its reliance on solar energy, the

FarmDroid FD20 provides a cost-effective and environmentally friendly alternative to conventional mechanized farming methods, making it an attractive option for modern agricultural enterprises.

Fig. 7. Precision inter- and intra-row weeding using the FarmDroid FD20[16]

3. ANALYSIS OF LOCOMOTION MODELS

Locomotion is a critical aspect of autonomous mobile systems, determining their adaptability to different plantation environments. The primary locomotion models employed in these systems include:

- **Wheeled Robots**: Common in structured agricultural environments, providing high-speed navigation and energy efficiency.
- **Tracked Robots**: Offer enhanced stability and traction, suitable for rough and uneven terrains.
- **Legged Robots**: Emerging in agricultural robotics for navigating complex environments, though still in research phases.
- **Hybrid Locomotion Models**: Combine multiple locomotion mechanisms to achieve improved adaptability and maneuverability.

Each locomotion model presents advantages and limitations based on terrain conditions, energy efficiency, and maneuverability. The selection of an appropriate model is crucial for ensuring optimal system performance in plantation maintenance.

The most commonly used in agriculture are wheel-based and track-based systems (fig. 6). Both have advantages and disadvantages, making it important to understand their operation, benefits, and suitability for specific plantations to determine the best solution. In some cases, a hybrid system may provide the optimal outcome.

Several studies have analyzed the impact of heavy agricultural machinery, tire inflation pressure, and field traffic on soil properties, crop growth, and yields. While machinery enhances farming efficiency and food production, it also degrades soil structure, reducing productivity and environmental quality. Soil compaction increases density and resistance while decreasing porosity and hydraulic properties, limiting root growth, water infiltration, and oxygen availability. In severe cases, these factors can lead to yield losses of up to 50% or more [17].

Fig. 6. Proposed compaction - wheels vs. tracks [18]

Research comparing rubber tracks and pneumatic wheels in large harvesting equipment analyzed soil displacement and density changes using tracers, dry bulk density, and penetrometer resistance. Tracks with 10.5 and 12-ton loads compacted the soil less than wheels at the same load (10.5 t), both in uniform weak soils and stratified soils. Towed equipment wheels (4.5 tons) caused soil displacement similar to tracks at 12 tons. Tire inflation pressure significantly influenced soil parameters, with larger tire diameters being more effective than width in reducing compaction. Thus, pressure distribution is more important than total axle load [19].

Other studies focused on soil compaction have considered both tire pressure and field traffic effects on different soil depths. For instance, study [20] used two tire types (narrow and standard) on an ITM70 tractor with three pressure levels and one, three, and five passes at depths of 10, 20, 30, and 40 cm. An adaptive neuro-fuzzy inference system (ANFIS) was employed to predict soil density. Results showed that tire size, pressure, traffic, and depth significantly affected soil compaction, with narrow tires increasing surface and deep soil density.

Firestone Ag studied soil contact pressures in two-track, four-track, and wheeled tractors, publishing findings with the American Society of Agricultural and Biological Engineers [21]. Soil compaction from agricultural machinery remains a key research focus in both developed and developing countries [22]. Research in Uzbekistan [22] suggests reducing compaction by using higher speeds within agricultural limits and the lowest recommended tire pressure. Another study [23] in Switzerland examined pressure distribution under moving agricultural tires, comparing experimental data with finite element modeling (PLAXIS), showing strong correlation and highlighting the impact on crop growth and soil health.

Tracked systems generally provide greater resistance, which can result in higher fuel consumption. However, when comparing a tracked tractor to a properly inflated wheeled tractor, fuel consumption tends to be similar when performing the same agricultural tasks. If the tires of a wheeled tractor are overinflated, the vehicle loses traction, leading to inefficiencies and making the tracked system a more fuel-efficient option. Furthermore, tracked systems excel in challenging terrain, offering superior traction in extremely wet, muddy, or marshy conditions, where wheeled tractors may struggle with stability and maneuverability [21].

4. MODULAR SCHEMATIC FRAMEWORK FOR AUTONOMOUS PLANTATION MAINTENANCE SYSTEMS

A modular approach in designing autonomous systems enhances flexibility, scalability, and adaptability. A typical modular system for plantation maintenance consists of the following core components:

- **Perception Module:** Incorporates cameras, LiDAR, and multispectral sensors for environment monitoring and obstacle detection.
- **Navigation Module:** Implements SLAM (Simultaneous Localization and Mapping) and GPS-based path planning for autonomous mobility.
- **Task Execution Module:** Includes robotic arms, sprayers, or mechanical tools for performing maintenance tasks.
- **Communication Module:** Facilitates data exchange between the autonomous system and farm management platforms.
- **Locomotion System:** Ensures movement and adaptability to different terrains, whether using wheels, tracks, or hybrid solutions.
- **Central Control Unit:** Processes sensory inputs, optimizes decision-making, and coordinates all system components for efficient operation.

Developing a standardized modular framework will enable more efficient and cost-effective deployment of autonomous systems in various plantation environments.

When aiming to manage and maintain crops with minimal human intervention while optimizing agricultural processes, reducing costs, and improving yield with a positive impact on agricultural sustainability, the use of autonomous platforms for plantation maintenance is recommended.

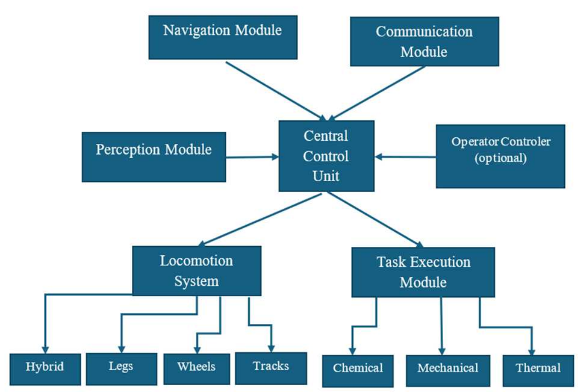

Fig. 7. Modular schematic of the basic structure of an autonomous plantation maintenance system

An analysis of the studies published in the open literature reveals a series of common components found in most of these autonomous systems/platforms. A modular schematic of the basic structure of such an autonomous system is presented in fig. 7.

Using an image acquisition system, the surroundings and obstacles are detected, and the signal is transmitted to the control unit, which processes the information and forwards it to the locomotion system for platform movement. The robot's position and orientation are also determined using a GPS module that ensures real-time platform localization and plant identification for efficient weeding without harming crops.

Once identified, weeds are eliminated through a spraying system that receives commands from the central control unit based on acquired data. There are multiple methods for weed removal and crop protection, including chemical, mechanical, or thermal approaches, or a combination of these methods.

The chemical method eliminates weeds by applying herbicides to the soil, but it leads to pollution and reduced fertility. Herbicides disrupt microbial respiration and enzymatic activity, threatening soil health and crop production [24]. They also impact consumers, the environment [25], [26], and may contribute to climate change [27]. Recent research focuses on reducing herbicide use. ecoRobotix achieves this with an autonomous platform using advanced imaging to minimize chemical inputs [12], [13]. Other solutions combine chemical and mechanical methods, such as crushing weeds before herbicide application [28] or selectively using mechanical or chemical control based on weed species [29].

The mechanical method can be implemented using different techniques, such as a rotating disk or wire trimmer to remove weeds without herbicides. Tertill, one of the first commercial weeding robots [30], is a suitable example because it effectively removes newly sprouted weeds using a wire trimmer. Another method is mechanical crushing, as employed by BoniRob, which uses a cylinder to crush weeds instead of applying herbicides [7], [11]. However, mechanical weed crushing can impact beneficial organisms on the soil surface and within the soil [31, 32].

A more environmentally friendly approach is the thermal method, which uses steam, lasers, or flames to eliminate weeds. An analysis of laser technology applications in plantation maintenance is provided in [33]. The emergence of the first agricultural equipment equipped with such technologies on the market demonstrates practical interest in integrating these systems [34]. Laser beams allow energy to be directed at the stems of unwanted plants, causing their destruction through intense heating [35], [36].

However, this method has several limitations: the large size and weight of laser modules and auxiliary components contribute to soil compaction, and performance is affected by unfavorable environmental conditions such as high humidity. Additionally, the high energy consumption and the need for extremely precise weed identification require the integration of advanced AI-based recognition systems [37], [38], along with high-resolution cameras and high-precision laser scanners, significantly increasing implementation costs.

Most existing steam-based systems do not directly maintain plantations but rather prepare the soil for planting by sterilizing it before seeding [39], [40], and [41]. This approach may negatively impact soil microbiota, eradicating microorganisms or altering bacterial community composition if the steam is not chemically enhanced. The main disadvantage is that disrupting soil microbiota can affect crops and yields.

Given these challenges, there still remains a clear need for the development of alternative, more sustainable, and environmentally friendly methods to complement or replace existing weed control solutions.

7. CONCLUSIONS

Autonomous mobile systems play a crucial role in modern plantation maintenance, offering sustainable solutions that reduce labor dependency, optimize resource use, and minimize environmental impact. This review has explored the most relevant commercially available solutions, analyzed the advantages and disadvantages of different locomotion models, and examined the modular schematic framework with a focus on the task execution module. These technologies enhance efficiency and precision in plantation management while promoting eco-friendly agricultural practices. However, challenges remain in terms of adaptability, cost, and the integration of advanced sensing and decision-making systems. Future research should focus on improving AI-driven perception, refining energy-efficient power solutions, and advancing hybrid locomotion systems to enhance flexibility. Despite significant progress, there is still room for improvement and further research to make these autonomous solutions more accessible, adaptable, and efficient for large-scale agricultural operations.

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Sisteme mobile autonome pentru întreținerea plantațiilor: Sinteză și Analiză

Rezumat: Pe măsură ce cererea pentru o agricultură sustenabilă și eficientă crește, sistemele mobile autonome au devenit esențiale pentru întreținerea plantațiilor. Această lucrare examinează principalele soluții comerciale, analizând capacitățile și aplicațiile acestora. De asemenea, evaluează modelele de locomoție, evidențiind avantajele și dezavantajele utilizării lor în întreținerea agricolă. În plus, rezumă cadrul schematic modular pentru sistemele autonome de întreținere a plantațiilor, cu un accent deosebit pe modulul de execuție a sarcinilor, care automatizează operațiunile esențiale. Analiza pune accent pe sustenabilitate și tehnologii ecologice, menite să reducă impactul asupra mediului, îmbunătățind în același timp eficiența și utilizarea resurselor.

Cuvinte cheie: *sisteme mobile autonome, întreținerea plantației, agricultură de precizie, agricultură durabilă, agricultură inteligentă, automatizarea controlului buruienilor.*

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