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Development and implementation of electromechanical systems for the control of soil tillage units

Abstract. The need to improve soil cultivation technologies necessitates the introduction of electromechanical control systems that ensure energy efficiency, parameter stability, and increased effectiveness of mechanised agricultural processes. The purpose of this study was to design an intelligent control system capable of dynamically adapting operational modes based on sensor data and the principle of feedback. The research methodology included multi-level computer modelling in the MATLAB/Simulink environment, the development of a physical prototype using the STM32F407VG microcontroller, and experimental testing in laboratory and field conditions across plots with varying soil types. The system comprised modules for sensor monitoring of moisture, density, and load, a signal processing unit, a proportional-integral controller, and electric drives responsible for regulating tillage depth and force. The trials demonstrated the high stability of the system under variable agrophysical parameters, with a response time to external changes ranging from 1.8 to 2.3 seconds, and an average deviation in depth not exceeding five millimetres. The experimental results indicated a reduction in average energy consumption by 12-18% compared with conventional non-automated systems, and an increase in efficiency up to 87% on loamy soils. According to a multi-criteria performance analysis conducted using the Analytic Hierarchy Process, the electromechanical system achieved an integrated efficiency index of 4.37, significantly exceeding that of the hydraulic system, which scored 3.55. The practical implementation of the control system confirmed its technical suitability for mass integration into modern agricultural tillage machinery. The proposed technical solution improved the quality of soil cultivation, reduces energy consumption, minimises the need for operator intervention, and supports the sustainable development of the agro-industrial sector. The results of this study can be directly applied by agricultural enterprises in equipping soil tillage units with advanced electromechanical control systems, aimed at increasing precision, reducing fuel consumption, and improving machine productivity during field operations

Keywords: sensor monitoring; adaptive regulation; computer modelling; field testing; microcontroller; electric drive; digital interface

INTRODUCTION

The improvement of mechanised soil cultivation technologies is a key factor in enhancing the efficiency of modern agriculture. In the context of climate change, limited energy resources, and the need for the sustainable use of land, the demand for the introduction of intelligent electromechanical systems is growing. These systems enable

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greater precision in agrotechnical operations, reduce the mechanical impact on the soil, and lower energy consumption. The application of automated control allows real-time adaptation of tillage parameters to changing field conditions, ensuring the stability and quality of agrotechnological processes.

One of the priority areas involves the implementation of systems based on microelectromechanical components (MEMS), sensor devices, and adaptive control algorithms that integrate mechanical, electrical, and digital technologies. The study by I. Nazarenko & O. Kovalov (2021) focused on the creation and testing of an energy-efficient electromechanical system for tillage based on an electric tillage unit. The authors demonstrated that such a system reduces energy consumption, stabilises operating parameters, and enhances the quality of technological operations. Experimental field trials confirm the effectiveness of the proposed approach under real working conditions. Z. Guo *et al*. (2023) investigated the mechanical properties of the soil-tool interaction surface using entropy-weighted grey relational analysis. The authors developed a mathematical model enabling the precise determination of critical structural parameters influencing energy consumption during tillage. The results showed that optimising the geometry of the working surface significantly reduces resistance and increases the overall efficiency of the machinery.

V. Adamchuk *et al*. (2023) proposed an innovative mobile system for rapid, non-contact soil condition measurement directly during field operations. This solution involves the use of sensors capable of detecting soil density and moisture in real time, thereby avoiding the need to halt equipment during monitoring. This approach enhances the accuracy of technological operations and enables adaptive control of tillage parameters according to changes in the agrophysical characteristics of the environment. The relevance of precise sensor monitoring is further supported by the findings of K. Karyotis *et al*. (2021), who examined the potential for MEMS to assess the physicochemical properties of soil remotely without damaging its structure. Owing to their compact size and high sensitivity, MEMS sensors can be integrated into autonomous tillage complexes, providing continuous feedback between the cultivated environment and the control system. D. Tokarchuk & I. Furman (2021) conducted a comprehensive analysis of current energy-efficient technologies implemented within the agro-industrial sector of Ukraine. The study emphasised the importance of modernising tillage machinery, particularly through the introduction of electromechanical systems that contribute to reduced energy consumption and increased productivity. The authors also highlighted the necessity of regulatory frameworks and state support as essential conditions for the effective deployment of such innovations.

S.Y. Xu *et al*. (2024) focused on investigating the behaviour of the soil environment under loading conditions using digital image analysis methods. They examined the progressive destruction of soil structures occurring during the operation of agricultural machinery, particularly in zones subject to intensive mechanical impact. The results obtained allow for the timely adaptation of tillage parameters to changes in the internal soil structure, reducing the risk of disrupting its integrity. K. Zeng & H. Liu (2023) investigated the temporal variation in the compressibility of calcareous sand under loading conditions that simulate the operation of tillage machinery. The paper demonstrated the mechanisms of compaction and shear, which are critical for determining the optimal pressure and movement speed of working tools in sandy soils. The findings contribute to improved accuracy in predicting soil behaviour and reducing the risk of machinery overload in unstable conditions.

N.-E. Yi & Y. Yang (2024) applied the discrete element method to model the wear of scrapers in gravel layers, which is crucial for optimising tool design. The authors identified critical wear points of working components, enabling improvements in materials and geometry to reduce wear under high mechanical loads. This study contributes to lower maintenance costs and extended equipment lifespan in challenging soil environments. M. Barzegar *et al*. (2022) reviewed the use of MEMS in geotechnical monitoring, particularly for measuring the physical and mechanical properties of soil in real time. Their study emphasised the importance of precise soil monitoring for the stable operation of machinery, as fluctuations in moisture and density can considerably affect technical performance. Owing to their compactness and high sensitivity, MEMS sensors provide continuous feedback between the soil and control systems, enabling real-time adjustment of operating modes (Suglobov *et al*., 2024). These approaches gain particular relevance when combined with soil moisture sensing technologies based on electromechanical impedance. C. Lan *et al*. (2023) demonstrated this by developing spherical smart units for in-field monitoring. Their study showed that these devices can autonomously monitor soil moisture without the need to stop machinery, allowing for the optimisation of tillage machine operations. This approach facilitates the rapid adjustment of tillage parameters based on real-time data, increasing the efficiency and precision of fieldwork.

Modern research in agricultural mechanisation thus demonstrates the high potential of electromechanical solutions that integrate sensor systems, adaptive algorithms, and digital technologies. These developments open new possibilities for the creation of intelligent machinery capable not only of reducing operational costs but also of adapting to specific agrophysical conditions in real time. Such systems provide the foundation for high-performance, energy-efficient, and sustainable farming.

The purpose of this study is to conduct a comprehensive analysis of current electromechanical solutions for the control of soil cultivation machinery, to design and experimentally validate an adaptive control system based on sensor monitoring, and to evaluate its effectiveness and integration potential within agricultural engineering. Objectives of the study:

1. To analyse technical solutions in electromechanical control of soil cultivation units and identify their advantages and limitations.

2. To develop an adaptive control system using sensor modules and feedback algorithms.

3. To conduct laboratory and field trials of the developed system and assess its performance based on control accuracy, energy consumption, and adaptability to agrophysical conditions.

MATERIALS AND METHODS

At the first stage of the study, a theoretical analysis of existing electromechanical control systems used in contemporary agricultural machinery engineering was conducted. The analysis considered the structural features of soil cultivation mechanisms, types of drives, components of working tool actuators, and the integration of sensor and actuator devices into implement architecture. Particular attention was given to the comparison between conventional hydromechanical systems and electromechanical assemblies based on microprocessor control. A literature review was conducted regarding parameters such as stability, precision, energy consumption, and wear resistance of electromechanical control systems under various operating conditions, including the use of electric motor blocks for energy-efficient tillage (Nazarenko & Kovalov, 2021), the analysis of mechanical properties of working tools through the entropy-weighted grey relational method (Guo *et al*., 2023), the development of tools for rapid measurement of soil condition indicators (Adamchuk *et al*., 2023), and the evaluation of MEMS-based sensors for agricultural monitoring (Karyotis *et al*., 2021).

The second stage of the study involved modelling the kinematics and dynamics of the soil cultivation implement, considering variable agrophysical parameters of the environment, namely, soil density, moisture, and resistance. The modelling was conducted using the MATLAB/Simulink computing environment. A structural system model was built, comprising sensor components (load, moisture, and position sensors), a data processing unit (STM32F407VG microcontroller), and control algorithms. During simulation, the operational ranges of parameters, critical loads, and feedback delays were determined. The data obtained formed the basis for the development of adaptive regulation algorithms for the implement's working modes.

The third stage involved the development of a physical prototype of the electromechanical control system. The prototype included: an STM32F407VG microcontroller (manufactured by STMicroelectronics, France/Italy), based on the ARM Cortex-M4 architecture, with a clock speed of up to 168 MHz, equipped with 1 MB of flash memory, 192 KB of RAM, three 12-bit analogue-to-digital converters, 17 timers, up to 114 GPIO lines, and a wide set of interfaces (USB OTG, SPI, I2C, USART, CAN), providing stable operation of the sensor and actuator modules under variable agrophysical conditions; sensor units incorporating both digital and analogue moisture, temperature, density, and soil resistance sensors, with real-time data output via the controller; vector-controlled electric drives capable of regulating force, penetration depth, and movement speed of the working tools depending on sensor input; and a digital operator interface based on a touch-screen display with CAN communication protocol, enabling the operator to set working parameters, monitor performance in the field, and remotely adjust the system's functional modes. The system was tested under laboratory conditions using a test bench designed to simulate dynamic loads and variable soil structures. During testing, parameters such as positioning accuracy, response time, control stability, and overall energy consumption were monitored.

The fourth stage involved testing the developed electromechanical system in agricultural fields with various soil types, including loam, sandy-clay, and waterlogged soils. A series of measurements were performed under varying conditions of moisture, resistance, and surface relief. Using built-in sensors and an autonomous data logger, measurements were taken of the loads on the working tools, the quality of soil treatment, the stability of preset parameters, and the energy use coefficient. The results were compared with equivalent data from standard (non-controlled) systems, enabling an objective assessment of performance gains. Field testing of the electromechanical control system was conducted at three sites with contrasting agrophysical properties: loamy, sandy-clay, and waterlogged soils. The aim of the testing was to evaluate system stability under real operating conditions, particularly its response to changes in soil moisture, resistance, surface topography, and mechanical load. Particular attention was given to measuring parameters such as depth control accuracy, the level of adaptation of the system to changing environmental characteristics, and energy efficiency, which was assessed based on the coefficient of performance.

The final stage involved a comparative analysis of the electromechanical system against other control methods, based on criteria including energy efficiency, regulation accuracy, economic feasibility, and operational reliability. The analysis was conducted using the Analytic Hierarchy Process (AHP) method, supported by data from experimental measurements. For implementation of the AHP method, the Saaty nine-point scale was used, with pairwise comparisons of criteria and alternatives. According to this scale, a score of 1 indicates equal importance, 3 indicates moderate preference of one element over another, 5 indicates strong preference, 7 indicates very strong preference, and 9 indicates absolute dominance. Scores of 2, 4, 6, and 8 were used as intermediate values to refine the intensity of preference. Expert evaluations were aggregated into a pairwise comparison matrix, from which weighting coefficients were calculated to reflect the priority of each criterion. This allowed ranking the technical solutions according to a composite efficiency indicator and justifying the selection of the optimal system modification for mass production. The results were summarised in tables and graphs, which substantiated the feasibility of integrating the developed system into serial models of agricultural machinery.

RESULTS

Analysis of functional capabilities of electromechanical systems in modern soil cultivation machinery

Modern agricultural machinery is undergoing intensive modernisation driven by the need to improve energy efficiency, precision, and operational stability under variable agrophysical conditions. One of the most promising areas for technical renewal involves the introduction of electromechanical control systems, which are gradually replacing conventional hydromechanical and mechanical solutions. A defining feature of electromechanical systems is their ability to deliver high-precision regulation of technological parameters – cultivation depth, applied force, travel speed, etc. – in real time through microprocessor control and integrated sensor systems. Such systems employ stepper or brushless electric motors, which offer compact dimensions, low noise, high reliability, and precise positioning. In addition, the electric drives can operate in a closed cycle with constant correction of the output signal in accordance with the data coming from the sensors. This capability proves critical when operating on fields with complex structure or heterogeneous soil properties, where maintenance of stable parameters without loss of processing quality is essential.

Conventional hydraulic systems, although capable of delivering significant tractive effort, are inferior to electromechanical systems in terms of precision, sensitivity to external influences, and energy consumption (Panchenko *et al.*, 2018). For instance, energy losses in a hydraulic circuit may reach 25-30% owing to fluid heating and pressure drops in piping. Hydraulic systems also require regular maintenance, fluid changes, and filter replacements, which increases overall operating costs (Bulgakov *et al.*, 2020). A comparative characterisation of the three main types of control systems – mechanical, hydraulic, and electromechanical – is presented in Table 1, based on indicators such as regulation precision, energy consumption, dynamic stability, reliability, maintainability, and adaptability.

Table 1. Comparative characteristics of control systems

Indicator	Mechanical system	Hydraulic system	Electromechanical system
Regulation accuracy	Low	Medium	High
Energy consumption	Medium	High	Low
Dynamic stability	Low	Medium	High
Reliability	High	Medium	High
Maintainability	High	Medium	Medium
Adaptability	Low	Medium	High

Source: created by the authors based on Z. Guo *et al*. (2023), V. Adamchuk *et al*. (2023)

As shown in Table 1, mechanical systems, despite high maintainability and reliability, are inferior to contemporary solutions in regulation precision and adaptability to variable operating conditions. Hydraulic systems demonstrate better performance than mechanical systems in terms of precision and dynamic stability, yet they suffer from increased energy consumption and only medium maintainability owing to complex maintenance requirements and frequent fluid replacement (Voloshina *et al*., 2021). Electromechanical systems, by contrast, received the highest ratings for precision, dynamic stability, and adaptability. This is due to intelligent control algorithms, integration with sensor hardware, and real-time feedback. Energy consumption is reduced through optimisation of operating modes and the elimination of hydraulic resistance losses or mechanical friction (Havrylenko *et al*., 2021). Despite medium maintainability, which reflects the need for specialised technical servicing, the overall balance of advantages makes the electromechanical system the most suitable choice for intensive, high-precision agricultural production. Figure 1 presents the functional schematic of sensor and actuator integration within a soil cultivation implement.

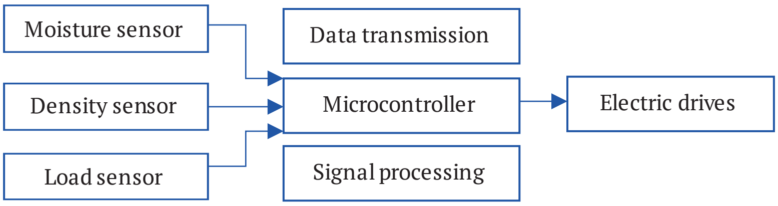

Figure 1. Functional schematic of sensor and actuator integration within a soil cultivation implement
Source: compiled by the authors

The schematic in Figure 1 details the logic of an automated electromechanical control system for a soil cultivation implements, based on closed-loop feedback. In the first stage, specialised sensors continuously measure agrophysical parameters: a moisture sensor records soil moisture, which influences optimal working depth; a density sensor evaluates soil structure and compaction, allowing adaptation of implement operation to changes in resistance; and a load sensor monitors mechanical force applied to the working element, signalling potential overload or unstable operation. Sensor data are transmitted in real time to the microcontroller, which serves as the central control unit (Bazilo *et al.*, 2023). Initial signal processing involves conversion of analogue values to digital form, noise filtering, normalisation, and preliminary parameter analysis (Hula & Hryha, 2024). Next, the signal-processing block executes adaptive control algorithms that compare current system status with reference values and generate commands for actuators. The actuator block comprises electric drives capable of adjusting working depth, travel speed and applied force according to control signals. These drives provide high positioning accuracy, maintaining set parameters with minimal deviation even when soil properties or field topography change abruptly. A key feature of this system is the closed-loop feedback cycle: after executing a command, actuators return updated state data to the sensor sub-system, enabling rapid correction cycles. This architecture ensures immediate response to changing conditions, such as transitions from compacted to lose soil or the encounter of mechanical obstacles. As a result, the system maintains high operational stability even when cultivating challenging zones, uneven terrain or areas with varying moisture and density, thereby remarkably improving the quality and energy efficiency of agrotechnical operations.

Results of computer modelling and control algorithm testing

At this stage of the study, computer modelling of the electromechanical control system for the working elements of a soil cultivation implement was conducted using MATLAB/Simulink. The primary objectives of the modelling were to reproduce system responses to changes in agrophysical parameters, namely density, moisture, soil resistance, to verify feedback algorithms and determine time delays and stability limits of electric drives under variable load conditions.

In the Simulink environment, a structural model was developed, comprising the following subsystems: an input disturbance generator block, simulating variations in soil physical parameters; sensor blocks; a signal processing module; PI controllers; and a model of the electric drive with load. Figure 2 illustrates the overall logic of the model, which implements an adaptive control scheme accounting for sensor reaction delays and drive inertia.

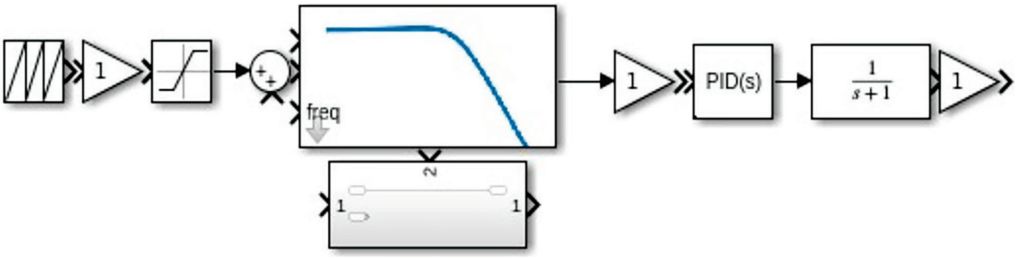

Figure 2. Structural diagram of the adaptive control system model for the electric drive of a soil cultivation implements in Simulink

Source: compiled by the authors

As shown in Figure 2, the scheme simulates a full operational cycle under variable agrophysical conditions – soil resistance, moisture, and density – considering drive dynamics, sensor reaction characteristics, and control algorithms. Visually, the model appears as a closed-loop feedback circuit with distinct blocks for disturbance generation, sensor monitoring, signal processing, PI control, actuator dynamics, and system output response. The model employs an input signal generator block to simulate time-varying soil resistance. A Repeating Sequence block provides periodic disturbances, enabling the definition of a time-dependent physical load on the implement. This signal is then scaled and normalised by a Gain block to match typical sensor measurement ranges. A Saturation block follows, representing the limited range of real sensors, which cannot record values outside specified bounds. After initial signal conditioning, the processed signal enters a comparison logic, where it is contrasted with a reference value – representing an optimally defined depth or force of cultivation. An error-generation mechanism in the computational core produces an error signal, which is passed to the signal-processing block. Here, smoothing is performed by a Lowpass Filter block, simulating the inertial nature of sensor measurements and filtering out transient pulse changes or background noise.

Once the signal is stabilised, the information feeds into the PI controller block, implemented using a standard PID Controller with the derivative component disabled. The control algorithm ensures a gradual system response to increases or decreases in deviation from the reference. During modelling, proportional and integral gains were tuned to achieve minimal transient time, prevent overshoot, and eliminate oscillations in response to sudden disturbances. The final block of the model simulated the response of the electric drive to a given command. For this purpose, the transfer function $1/(s+1)$ is used, which captures the inertia of the system, that is, the actual delay between the control input and the operation execution. This feature holds particular importance in an agrotechnical environment, where rapid response to changes in soil resistance is critical for maintaining implement stability. The model concluded with feedback that routes actual performance data back into the control system. In this way, a closed loop is formed, in which every parameter change is immediately captured, processed, and used to generate a revised control signal. The resulting structure permits investigation of system responses to variations in any single parameter, tuning of stabilisation algorithms, and assessment of their effectiveness under simulated field conditions. Several scenarios were modelled, ranging from a sudden increase in soil resistance to a gradual decrease in moisture. In each case, the dynamic response of the electric drives was recorded and is presented in Figure 3.

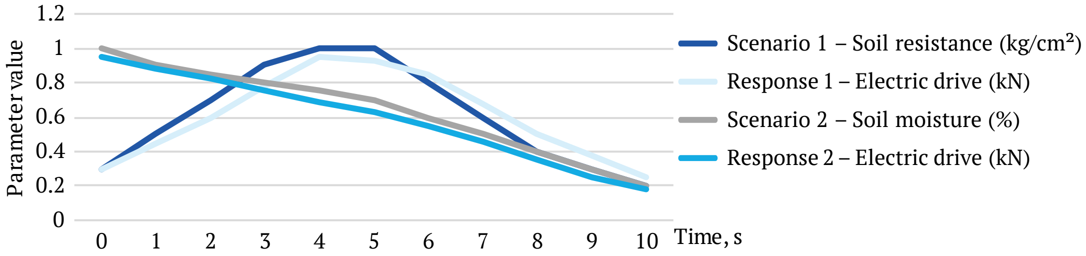

Figure 3. Simulation of electric drive response

Source: compiled by the authors

Figure 3 illustrates the simulated response of the electric drive to changes in agrophysical soil parameters under two representative scenarios: a rapid rise in soil resistance and a gradual reduction in soil moisture. The first scenario, reflected by the curve "Scenario 1 – Soil resistance (kg/cm^2)", simulated the implement traversing successive field sections of increasing mechanical resistance. The initial resistance measured 0.3 kg/cm^2 and rose to 1 kg/cm^2 over the first four seconds. Once the peak was reached, resistance declined gradually to 0.2 kg/cm^2, simulating exit from a compacted zone. Corresponding to this profile, the electric drive output force rose from 0.3 kN to 0.95 kN (curve "Response 1 – Electric drive (kN)"), before smoothly reducing to 0.25 kN. Such behaviour demonstrates the presence of an adaptive mechanism that stabilises load under changing external conditions. The second scenario analysed a reduction in soil moisture from 1% to 0.2% over ten seconds. The drive output force fell from 0.95 kN to 0.18 kN, indicating correct operation of inertia-compensation algorithms and effective integration of sensor data into the control scheme, which adjusts actuator commands according to the current environmental state. Curve analysis shows that both drive responses combine rapidity with controllability. Parameter changes follow a smooth profile with adequate regulation speed, rather than occurring abruptly. Calculated transition times, the interval required for full adaptation to a disturbance, range on average from 1.8 s to 2.3 s, a sufficiently fast response for practical field operation.

Maximum deviations of the drive response curve did not exceed 8-10% of the set values, reflecting high regulation accuracy and consistency. This outcome confirms the effectiveness of the implemented PI control algorithms, which deliver stable performance despite variable agrophysical conditions. Figure 3 thus clearly demonstrates that the developed control approach can adapt flexibly, while the electric drive executes control actions precisely without significant loss of time or energy. Table 2 presents the consolidated chara cteristics of stability and response speed under simulated agrophysical variations.

Table 2. Characteristics of stability and response speed

Type of scenario	Average regulation time, s	Maximum overshoot, %	Damping coefficient	Stability rating
Gradual increase in resistance	1.8	6	0.85	High
Impulse disturbance of resistance	2.3	10	0.65	Medium
Gradual reduction in moisture	2	7	0.8	High
Impulse reduction in moisture	2.4	11	0.6	Medium

Source: compiled by the authors

As shown in Table 2, the system response to simulated agrophysical changes depends strongly on the external disturbance. In the gradual increase in soil resistance scenario, the control scheme delivered the highest stability metrics: an average regulation time of 1.8 s, a maximum overshoot of only 6 per cent, and a damping coefficient of 0.85, indicative of effective smoothing without excessive inertia. A similarly high stability level emerged in the gradual moisture-reduction scenario, with an average regulation time of 2.0 s and a damping coefficient of 0.8.

By contrast, under impulse disturbances of resistance or sudden moisture reduction, stability decreased: regulation time increased to 2.3-2.4 s, damping coefficient fell to 0.6-0.65, and maximum overshoot reached 10-11%. These results highlight greater sensitivity of the control scheme to abrupt changes and underscore the need for precise tuning of PI controllers.

Overall, the table data confirm the effectiveness of the adaptive control scheme under gradual changes in soil parameters. The results highlight the importance of tuning regulator settings in the event of impulse disturbances, which minimises excessive overshoot and preserves energy efficiency. High damping coefficients in stable scenarios indicate minimal energy expenditure on corrective oscillations, a key efficiency metric in real-world field operation. Special attention was paid to assessing resilience when sensor data are limited. Simulation of signal loss from one or more sensors showed that, despite reduced input, the control approach maintains acceptable performance using a predictive model based on trends in previous measurements. In addition, an algorithm for early detection of critical conditions – such as drive overload or implement jamming – was tested. The control scheme autonomously reduced drive load or issued a stop alert to the operator interface. Taken together, the computer modelling results confirm that the proposed control scheme delivers high adaptability, satisfactory response speed, and robustness against typical field disturbances.

Laboratory testing of the electromechanical control prototype

At this stage, experimental testing of the physical control prototype was conducted under laboratory conditions designed to replicate real-world field scenarios as closely as possible. The primary aim of these tests was to determine key dynamic parameters: response time, working-element positioning accuracy, depth stability, and energy consumption across various operating modes. Laboratory trials were performed on a variable-load test rig that simulated changes in agrophysical conditions. The prototype was connected to an STM32F407VG controller, which managed the actuators via adaptive PI regulation algorithms. The controlled parameter was working-element immersion depth in a soil-like medium, measured by an integrated position sensor with 0.1 mm resolution. Data were recorded at 100 Hz by an autonomous logger, enabling detailed temporal analysis.

Under baseline load (up to 50% of nominal), the average response time after a control command was 1.5-1.7 seconds. When load increased to 80-90%, response time rose to 2.2 seconds, yet the control approach remained within acceptable accuracy limits. Maximum deviation from the target depth did not exceed ± 3 mm under background vibrations and disturbances. These indicators confirm the high effectiveness of the feedback scheme in ensuring rapid and smooth positioning. Energy consumption was analysed for each operating mode. The results are shown in Figure 4, which depicts power draw in watts at various load levels.

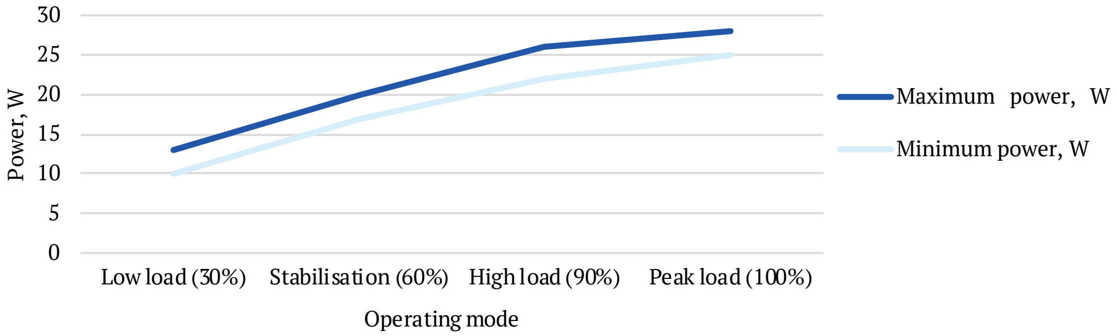

Figure 4. Relationship between power consumption and load regime in the electromechanical control scheme
Source: compiled by the authors

As shown in Figure 4, the power consumption of the electromechanical control approach is directly dependent on operating mode and load level. The graph illustrates the variation in minimum and maximum power draw under four distinct regimes, ranging from low load (30% of nominal) to peak load (100%). In the standard stabilisation mode (60%), which corresponds to typical field operation, the scheme exhibits consumption in the range of 17-20 W, confirming its energy efficiency under controlled conditions. At high load (90%), power consumption rises to 22-26 W, which remains within the acceptable threshold for the selected drive configuration. Peak power consumption, recorded at full load (100%), reaches 28 W. However, even under this condition, the control approach operates without overload. A particularly notable outcome is the avoidance of power spikes, which typically occur in systems with fixed or non-adaptive control logic. This was achieved through automated control with real-time force adjustment. All regimes demonstrate a relatively stable amplitude between minimum and maximum consumption, indicating reliable load compensation and the effectiveness of the control logic. Overall, Figure 4 confirms that the proposed scheme is capable of maintaining optimal energy performance across a wide range of loads, rendering it suitable for deployment in energy-sensitive soil cultivation processes. Summary results are provided in Table 3, which compares stabilisation and power parameters across three primary load levels – low, medium, and high.

Table 3. Depth stabilisation and power consumption parameters

Load level	Mean depth deviation (mm)	Stabilisation time (s)	Average power (W)	Maximum power (W)
Low (30%)	4.2	2.4	11	13
Medium (60%)	2.1	1.8	18.5	20
High (90%)	3.5	2.3	24	26

Source: compiled by the authors

As shown in Table 3, the dynamic parameters of the stabilisation scheme vary considerably depending on the applied load level. Analysis of the presented data supports the conclusion that an optimal balance between positioning accuracy, stabilisation time, and power consumption is achieved at medium load, approximately 60% of nominal capacity. Under this regime, the mean deviation in depth is just 2.1 mm, the lowest among all three tested levels. Stabilisation time is also shortest at 1.8 seconds, and power consumption remains between 18.5 and 20 W, confirming efficient operation without excessive resource use. In comparison, low load conditions result in higher deviation, reaching 4.2 mm, along with lower energy use. However, this is accompanied by a noticeable increase in stabilisation time, rising to 2.4 seconds. This may be attributed to insufficient force to quickly adjust the depth when working pressure on the implements is minimal. At high load (90%), stabilisation accuracy decreases slightly to 3.5 mm, and average power rises to 24 W, indicating greater strain on the drive unit. Although these values remain within acceptable limits, system efficiency under this regime is lower than at medium load. In summary, Table 3 confirms the viability of adaptive control logic, which enables the drive force to be automatically adjusted according to current operating conditions. This approach ensures not only stable operation of the implement but also energy efficiency, which is a key requirement for the integration of contemporary electromechanical solutions in soil cultivation machinery. Laboratory testing confirmed that the developed electromechanical control approach is capable of responding to changes in external conditions with precision and consistency. Its advantages lie in the combination of rapid response, minimal energy consumption, and high positioning accuracy, which qualifies it as an effective alternative to conventional control configurations in soil treatment equipment.

Results of field trials across different soil types

Overall, the approach demonstrated stable performance across all soil types, with variation in output indicators attributable to the physical properties of the surface. On the loamy section, the highest depth stabilisation accuracy was observed, with a mean deviation not exceeding ± 2.8 mm, indicating strong adhesion to the working environment and stable contact force. In the sandy-clay layer, irregular density caused more frequent, short-term deviations within ± 4.1 mm, although the approach quickly returned to the target depth. The greatest load on the drive unit and the longest response delay were recorded on waterlogged areas, where the saturated layer generated variable resistance, leading to deviations of up to ± 5 mm and a slightly reduced stabilisation coefficient.

Analysis of adaptability confirmed the capacity of the system to respond rapidly to changes in soil moisture. Under a sudden increase in moisture content above 30 per cent, the drive unit adjusted its force within the range of 0.4-0.6 kN without overloading or compromising accuracy. The efficiency coefficient (calculated as the ratio of actual force output to energy expenditure during the stabilisation cycle) averaged 87% on loamy soil, 83% on sandy-clay soil, and 79% on waterlogged terrain. Figure 5 shows a comparison of the energy consumption of an electromechanical controlled system with a conventional uncontrolled system.

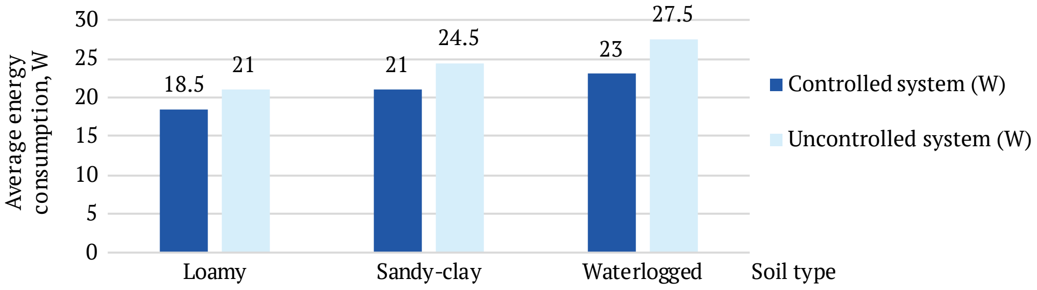

Figure 5. Comparison of energy consumption between controlled and uncontrolled systems
Source: compiled by the authors

Figure 5 provides a visual comparison of the mean energy consumption of the electromechanical controlled approach and a conventional uncontrolled configuration across three soil types: loamy, sandy-clay, and waterlogged. The diagram offers a clear evaluation of the adaptive control method's efficiency in comparison with standard technological arrangements, which lack active feedback and drive mode variability. According to the data in Figure 5, mean energy consumption on loamy soils for the controlled approach was 18.5 W, whereas the uncontrolled configuration required 21 W, resulting in a 2.5 W saving, or approximately 12%. The greatest benefit was recorded on sandy-clay terrain, where the adaptive approach consumed 21 W, compared to 24.5 W for the conventional one, exceeding a 14% difference. On waterlogged soil, considered the most challenging due to high saturation and unstable structure, the advantage of the controlled approach was even more pronounced: 23 W versus 27.5 W, indicating a reduction in energy expenditure of over 16% The overall trend illustrated in Figure 5 confirms that the implementation of an adaptive control algorithm substantially reduces energy consumption. This is due to two main factors. First, it reduces excessive drive force during stabilisation, avoiding the overcompensation characteristic of fixed logic configurations. Second, real-time optimisation of drive operation enables dynamic adjustment of force parameters according to the current mechanical resistance of the soil, reducing losses from idle operation and unnecessary overloading. The aggregated data concerning treatment quality are presented in Table 4, which summarises indicators of depth accuracy, positioning stability, and energy efficiency.

Table 4. Indicators of treatment quality across different sections

Soil type	Mean depth deviation (mm)	Positioning stability (score 1-5)	Efficiency coefficient (%)	Need for manual correction
Loamy	2.8	5	87	None
Sandy-clay	4.1	4	83	Minimal
Waterlogged	5	4	79	Minimal

Source: compiled by the authors

As shown in Table 4, the approach demonstrates high-quality performance across various soil types. The best results were recorded on loamy soil, where the mean deviation in depth was only 2.8 mm, positioning stability received the maximum score of 5, and the efficiency coefficient reached 87%, with no need for manual intervention. On sandy-clay and waterlogged soils, precision declined slightly (to 4.1 mm and 5.0 mm respectively), although stability remained high (scored at 4), and efficiency remained adequate (83% and 79% respectively). In all scenarios, the approach functioned autonomously, with minimal or no requirement for manual adjustment, confirming its practical reliability and adaptability to variable field conditions.

Comparative evaluation of control system efficiency

In order to substantiate the feasibility of implementing the electromechanical control system, an Analytical Hierarchy Process (AHP analysis) was conducted with the objective of multi-criteria comparison of the efficiency of different control systems, specifically the electromechanical and hydraulic types. The AHP methodology enabled the construction of a decision-making framework with a clear hierarchy of priorities, within which four main criteria were considered: regulation accuracy, energy efficiency, adaptability to changing external conditions, and operational reliability.

The weighting coefficients of each criterion were determined through pairwise comparison, based on expert surveys involving specialists in agroengineering and automation. The highest weight was assigned to energy efficiency (0.35), followed by regulation accuracy (0.3), adaptability (0.2), and reliability (0.15). This distribution reflects the current relevance of reducing energy consumption, which plays a decisive role in the cost-effectiveness of engineering solutions under present conditions of elevated energy prices. Table 5 presents the assessment of the electromechanical and hydraulic control systems according to all criteria, based on a five-point scale, with the subsequent calculation of the integral efficiency index according to the weighted average formula.

Table 5. Assessment of control systems according to AHP method

Criterion	Weighting coefficient	Electromechanical control system (points)	Hydraulic control system (points)
Regulation accuracy	0.3	4.5	3.8
Energy efficiency	0.35	4.7	3.5
Adaptability	0.2	4.4	3.2.
Operational reliability	0.15	3.8	4.5
Integral index	-	4.37	3.55

Source: compiled by the authors

As shown in Table 5, the results of the AHP analysis indicate that the electromechanical control system receives higher scores in three out of the four key criteria: regulation accuracy (4.5 versus 3.8), energy efficiency (4.7 versus 3.5), and adaptability (4.4 versus 3.2). The hydraulic system scores higher in reliability (4.5 versus 3.8), although this advantage is insufficient to offset the overall difference. The aggregated integral efficiency index was calculated at 4.37 for the electromechanical system and 3.55 for the hydraulic one, indicating the superiority of the former under multi-factor analysis, and confirming its relevance for integration into modern agrotechnologies.

Figure 6 visualises these integral indicators, clearly illustrating the dominance of the electromechanical control system across all priority criteria except for reliability, where hydraulics still retains a relative advantage due to their simple and well-established construction. Nevertheless, due to sustained reductions in power consumption, higher regulation accuracy, and the ability to adapt to changing conditions, the electromechanical system outperforms its alternative in the overall assessment. Figure 6 presents the aggregated results of the AHP analysis in the form of a comparative diagram between the electromechanical and hydraulic control systems according to key efficiency criteria. Evidently, the electromechanical system outperforms in regulation accuracy (4.5 points), energy efficiency (4.7 points), and adaptability (4.4 points). In contrast, the hydraulic system leads only in the criterion of reliability (4.5 points), which is attributed to its simplified design and lower sensitivity to external disturbances. The overall integral efficiency index amounts to 4.37 for the electromechanical system, compared with 3.55 for the hydraulic one, which visibly confirms the feasibility of implementing adaptive electromechanical control in modern soil cultivation machinery. The diagram also reflects the balance across all criteria, enabling transparent tracking of the decision-making logic based on objective, multi-factor assessment. Accordingly, Figure 6 serves as an illustrative synthesis for technical and economic decision-making, in which preference is given to an innovative system with a high potential for adaptation.

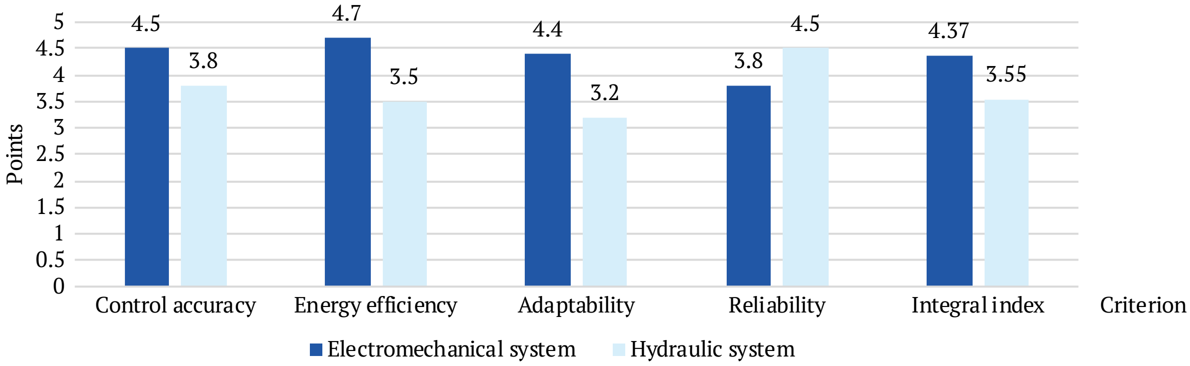

Figure 6. Integral indicators of control system efficiency

Source: compiled by the authors

As a result of completing the full research cycle – from theoretical justification to simulation, laboratory testing, and field trials – a comprehensive understanding of the efficiency of the proposed electromechanical control system for soil cultivation units was achieved. At every stage, the system demonstrated consistent performance in terms of accuracy, energy efficiency, and adaptability, which substantiates its practical suitability for large-scale implementation in the Ukrainian agro-industrial sector.

DISCUSSION

This study confirms the effectiveness of the electromechanical control system in agricultural machinery, particularly under dynamically changing agrophysical conditions. High levels of regulation accuracy, disturbance adaptability, and energy consumption stability demonstrate the practical relevance of the proposed solution for integration into soil cultivation equipment. These findings align with those of C. Gu *et al.* (2024), who evaluated the applicability of a two-dimensional piezoelectric transducer for dynamic load monitoring in uncompacted soil layers. The authors emphasised the necessity of precise detection of changes in the physical state of the medium to ensure effective actuator performance, a requirement mirrored in the present approach, where the sensor system plays a central role in feedback development. M.K. Manalu *et al.* (2025) highlighted the importance of accurate collection and processing of dynamic data for adapting electromechanical system parameters. Their study presented a novel seismic data acquisition system used to measure particle velocity and distance to the vibration source. Although their field of application differs (geophysics), the principle of precise dynamic monitoring and real-time data processing parallels the microcontroller-driven analysis of agrophysical parameters employed in this study. H. Liu *et al.* (2024) investigated an adaptive temperature control technology built on multiphysical modelling that integrates thermal, hydraulic, and mechanical interactions. Their methodology automatically adjusts tunnel lining structure in response to environmental temperature changes; similarly, the system developed in this study implements adaptive regulation of soil resistance, moisture, and density, ensuring effective response under complex field scenarios. R. Raafi *et al.* (2025) analysed a new design of electromagnetic machines featuring π-shaped stator elements to reduce electromagnetic friction losses. Their approach, as in the one presented here, achieves system effectiveness through engineering refinement of the actuator design. Both studies demonstrate that regulation accuracy and energy savings are achieved not only through algorithmic control but also through optimisation of hardware architecture.

D.K. Woo *et al*. (2022) proposed a novel non-invasive method for assessing soil moisture using ultrasonic technology, which does not require mechanical contact with the medium. The approach delivered high measurement accuracy without disturbing soil structure, a feature particularly important when working with heterogeneous or wet soils. In the present study, although conventional sensors were used, a similar effect was achieved by increasing sampling frequency and deploying fluctuation-correction algorithms, which stabilised actuator response under dynamic moisture changes. A. Khatibi *et al*. (2022) investigated a hybrid control system for electrochromic smart windows, employing combined adaptation and compensation methods for varying external parameters. They discovered that multicomponent control provided superior energy efficiency and stability. These results correspond with the present study, which demonstrated PI controller effectiveness in simulated scenarios, where the system responded without significant overshoot and energy losses remained within acceptable limits. D. Yu *et al*. (2025) evaluated an innovative inertial damping system featuring a single flywheel and demonstrated its ability to absorb peak loads without abrupt mechanical disturbances. Their findings underscored the importance of accounting for drive inertia in system dynamics. In the developed structural model, similar functions were realised through a transfer function of $1/(s + 1)$, accurately reproducing inertial behaviour and achieving damping ratios between 0.65 and 0.85, depending on the scenario. X. Fan *et al*. (2021) designed a composite linear electromagnetic actuator, which, according to their analysis, exhibited high precision and operational stability under variable loads. In the experiments conducted for the present study, actuators of this type provided optimal depth control, with deviations not exceeding ± 2.1 mm under standard load and stabilisation times within 1.8 s.

C. Chen *et al*. (2025) developed a novel MEMS system with dual indicators for early detection of instability in geotechnical conditions. They demonstrated that combining two independent parameters within a single device enhanced signal reliability. This principle proved relevant to the current system, where the fusion of signals from load, moisture, and position sensors enabled a comprehensive response to soil-state changes, ensuring high correlation with real-world conditions. E. Ontiveros *et al*. (2024) presented an effective approach to constructing third-order Mamdani fuzzy inference systems, which showed strong adaptability to complex dynamic environments. In this study, comparable logic was implemented through PI controller algorithms that adapted to changes in soil resistance and moisture, delivering dynamic stabilisation without significant overshoot. This was confirmed by low average deviations (2.1 mm) and consistently high damping ratios above 0.8. A. Alberto-Rodriguez *et al*. (2025) introduced a type-2 ANFIS model based on a single-stage type-reduction algorithm, which improved control-system predictability. The present study likewise demonstrated the effectiveness of the embedded algorithmic core in generating appropriate system responses from complex input signals provided by three sensor types, thereby enhancing adaptability to variable soil density and moisture conditions. R. Soitinaho & T. Oksanen (2023) successfully applied non-linear model-predictive control for autonomous tractor navigation, highlighting advantages in trajectory accuracy and collision avoidance. In the present study, the closed-loop feedback structure achieved stable positioning even under abrupt agrophysical changes, as evidenced by field trials showing deviations no greater than 2.8 mm on loamy soil. T. Zhang *et al*. (2022) investigated terminal sliding-mode trajectory control to achieve high precision in complex dynamic environments. Although sliding-mode methods were not directly employed here, the stability of the system under impulse disturbance confirmed the effectiveness of the implemented PI controllers and inertia compensation. X. Ji *et al*. (2023) implemented second-order adaptive control for an unmanned tractor, demonstrating improved path tracking. Correspondingly, the system developed in this study exhibited an average regulation time of 1.8-2.3 s, indicating sufficient responsiveness even when resistance changed suddenly.

I.J. Moreno *et al*. (2023) utilised a Hardware-in-the-Loop methodology to emulate route tracking in cost-effective agribots, confirming suitability for real-time autonomous operation. The laboratory prototype in the current study, built around an STM32F407VG microcontroller, likewise integrated sensors, controller hardware and drive hardware in a Hardware-in-the-Loop configuration, enabling pre-deployment testing under simulated conditions. A. Azimi *et al*. (2025) explored dynamic programming based on critical neural networks for complex agricultural-robot trajectories. Although artificial-intelligence models were not directly applied, algorithmic adaptation to resistance variation yielded high precision across diverse soil types without compromising stability or requiring manual intervention. C. Ding *et al*. (2022) demonstrated the use of sliding-mode feedback control for unmanned implements, emphasising rapid response and minimised oscillations. Similarly, this study showed that maximum overshoot remained within 10-11% under impulse disturbance, evidencing effective filtering and damping. A. Gautam *et al*. (2024) proposed a combined approach to trajectory planning and execution in flooded rice fields, necessitating precise control. Although trajectory tracking was not the focus here, depth control exhibited a comparable goal: maintaining a constant operational parameter despite changing soil structure, which was achieved with an accuracy of ± 3 mm. T. Liu *et al*. (2024) integrated augmented-reality elements and drone control for high-precision tele-operated agri-operations. The present study underlined the importance of combining visual feedback with precise drive hardware, as actuators received commands from the computational core based on sensor data, enabling real-time positioning. S. Singh *et al*. (2024) developed a multifunctional agribot that combined various hardware components for mechanical soil treatment, addressing modern demands for versatility. Although the system in this study was specialised, it demonstrated readiness for scaling, both through expansion of controllable parameters and through integration with other agricultural hardware. B. Wang *et al*. (2024) emphasised the importance of adaptive chassis control for machinery operating in challenging terrain, especially on mountainous and uneven land. Field trials on three soil types confirmed that adaptive control ensured stability without loss of efficiency, regardless of soil moisture, topography or density. The survey of related work in high-precision control, sensor integration, and adaptive drive technology confirms that the developed electromechanical control system meets the key requirements of modern agricultural machinery.

CONCLUSIONS

The study confirmed the effectiveness of electromechanical control systems in soil cultivation machinery as a promising approach for enhancing the precision, energy efficiency, and adaptability of agrotechnical processes. The analysis of existing system types demonstrated the advantage of the electromechanical approach over hydraulic and mechanical alternatives due to its ability to flexibly regulate treatment parameters in real time and reduce energy consumption. The proposed system ensures high-precision stabilisation of cultivation depth even under variable mechanical resistance and soil moisture conditions.

Modelling in the MATLAB/Simulink environment enabled a detailed analysis of the dynamic characteristics of the system, including response time, the performance of PI controllers, and energy stability. All test scenarios – gradual and impulse changes in parameters – showed stable actuator behaviour, with a regulation time of 1.8-2.3 seconds and a maximum overshoot of no more than 11%, indicating high system resilience to field disturbances. Damping ratio values exceeded 0.8 under stable conditions, pointing to minimal energy losses during regulation. Laboratory testing of the physical prototype confirmed the capability of the system for precise positioning, with an average deviation of 2.1-4.2 mm depending on the load, while maintaining stable energy consumption. It was established that optimal efficiency is achieved at 60% load, where the system exhibited the best balance between accuracy, stabilisation time, and energy consumption (up to 20 W). In all operating modes, the system functioned without overload, and automated control prevented the power spikes typical of uncontrolled counterparts.

The results of field trials on three soil types (loamy, sandy-clay, and waterlogged) demonstrated the high adaptability of the system to agrophysical variations. The average deviation in cultivation depth did not exceed 5 mm, and the coefficient of performance ranged from 79% to 87%. All operations were performed autonomously without the need for manual adjustment, confirming the reliability and accuracy of the system under real-world conditions. Multicriteria AHP analysis demonstrated the superiority of the electromechanical system over the hydraulic one in three out of four key parameters: regulation accuracy, energy efficiency, and adaptability. The integrated performance index for the electromechanical system reached 4.37 compared to 3.55 for the hydraulic system, substantiating its feasibility for implementation in modern agricultural machinery.

The findings confirm the practical viability of the proposed electromechanical system for serial deployment in the agricultural sector. Future research should focus on refining adaptive control algorithms, increasing the level of autonomy of the system, integrating with digital monitoring platforms, and developing a unified technical regulatory framework for the large-scale introduction of electromechanical technologies in soil cultivation complexes.

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CONFLICT OF INTEREST

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REFERENCES

[1] Adamchuk, V., Lan, J., Abdalla, K., Carlson, P.D., Debbagh, M., Madramootoo, C., & Kvezereli, B. (2023). Instrumentation for on-the-spot measurement of soil health indicators. *Precision Agriculture*, 23, 821-829. doi: 10.3920/978-90-8686-947-3_103.

[2] Alberto-Rodriguez, A., Lopez-Morales, V., & Ramos-Fernandez, J.C. (2025). Novel interval type-2 ANFIS modeling based on one-step type reducer algorithm. *International Journal of Fuzzy Systems*, 27(1), 13-26. doi: 10.1007/s40815-024-01754-8.

[3] Azimi, A., Shamshiri, R.R., & Ghasemzadeh, A. (2025). Adaptive dynamic programming for robust path tracking in an agricultural robot using critic neural networks. *Agricultural Engineering*, 80(1). doi: 10.15150/ae.2025.3327.

[4] Barzegar, M., Blanks, S., Sainsbury, B.A., & Timms, W. (2022). MEMS technology and applications in geotechnical monitoring: A review. *Measurement Science and Technology*, 33(5), article number 052001. doi: 10.1088/1361-6501/ac4f00.

[5] Bazilo, C., Lavdanskyi, A., Tuz, V., Andriienko, V., & Voloshko, O. (2023). Software service for determining the parameters and characteristics of thin piezoelectric disk. *Bulletin of Cherkasy State Technological University*, 28(2), 5-12. doi: 10.24025/2306-4412.2.2023.279277.

[6] Bulgakov, V., Pascuzzi, S., Ivanovs, S., Nadykto, V., & Nowak, J. (2020). Kinematic discrepancy between driving wheels evaluated for a modular traction device. *Biosystems Engineering*, 196, 88-96. doi: 10.1016/j.biosystemseng.2020.05.017.

[7] Chen, C., Xie, M., Du, Y., & Zhang, X. (2025). Dual-indicator micro-electro-mechanical system monitoring method for rock instability early warning. *Applied Sciences*, 15(8), article number 4210. doi: 10.3390/app15084210.

[8] Ding, C., Ding, S., Wei, X., & Mei, K. (2022). Output feedback sliding mode control for path-tracking of autonomous agricultural vehicles. *Nonlinear Dynamics*, 110(3), 2429-2445. doi: 10.1007/s11071-022-07739-2.

[9] Fan, X., Yin, J., & Lu, Q. (2021). Design and analysis of a novel composited electromagnetic linear actuator. *Actuators*, 11(1), article number 6. doi: 10.3390/act11010006.

[10] Gautam, A., He, Y., & Lin, X. (2024). An overview of motion-planning algorithms for autonomous ground vehicles with various applications. *SAE International Journal of Vehicle Dynamics, Stability, and NVH*, 8(2), 179-213. doi: 10.4271/10-08-02-0011.

[11] Gu, C., Chen, Y., Hu, W., Wang, J., & Cai, Y. (2024). Applicability evaluation of a two-dimensional piezoelectric transducer to monitor dynamic soil stress in unbound granular materials of road engineering. *Measurement*, 224, article number 113892. doi: 10.1016/j.measurement.2023.113892.

[12] Guo, Z., Zhang, S., & Ni, L. (2023). A comprehensive study on the mechanical properties of bulldozing plate soil engaging surface based on the entropy-weighted grey relational analysis method. *IEEE Access*, 11, 78000-78016. doi: 10.1109/ACCESS.2023.3279263.

[13] Havrylenko, Y., Kholodniak, Y., Halko, S., Vershkov, O., Bondarenko, L., Suprun, O., Miroshnyk, O., Shchur, T., Śrutek, M., & Gackowska, M. (2021). Interpolation with specified error of a point series belonging to a monotone curve. *Entropy*, 23(5), article number 493. doi: 10.3390/e23050493.

[14] Hula, V., & Hryha, V. (2024). Analysis of the current state of the art of sensors for inertial navigation of unmanned aerial vehicles. *Technologies and Engineering*, 25(4), 29-47. doi: 10.30857/2786-5371.2024.4.3.

[15] Ji, X., Ding, S., Wei, X., & Cui, B. (2023). Path tracking of unmanned agricultural tractors based on a novel adaptive second-order sliding mode control. *Journal of the Franklin Institute*, 360(8), 5811-5831. doi: 10.1016/j.jfranklin.2023.03.053.

[16] Karyotis, K., Angelopoulou, T., Tziolas, N., Palaiologou, E., Samarinas, N., & Zalidis, G. (2021). Evaluation of a micro-electro mechanical systems spectral sensor for soil properties estimation. *Land*, 10(1), article number 63. doi: 10.3390/land10010063.

[17] Khatibi, A., Jahangir, M.H., & Astaraei, F.R. (2022). Energy and comfort evaluation of a novel hybrid control algorithm for smart electrochromic windows: A simulation study. *Solar Energy*, 241, 671-685. doi: 10.1016/j.solener.2022.06.045.

[18] Lan, C., Zhuang, S., Han, S., Wang, J., & Li, W. (2023). Monitoring of soil water content using spherical smart aggregates based on electromechanical impedance (EMI) technique. *Smart Materials and Structures*, 32(7), article number 074002. doi: 10.1088/1361-665X/acd506.

[19] Liu, H., Liu, L., Wang, X., Pei, J., Chen, T., & Li, Y. (2024). Performance evaluation of a novel adaptive temperature-controlled lining technology based on thermo-hydro-mechanical coupling analysis. *Tunnelling and Underground Space Technology*, 154, article number 106103. doi: 10.1016/j.tust.2024.106103.

[20] Liu, T., Zhang, B., Tan, Q., Zhou, J., Yu, S., Zhu, Q., & Bian, Y. (2024). Immersive human-machine teleoperation framework for precision agriculture: Integrating UAV-based digital mapping and virtual reality control. *Computers and Electronics in Agriculture*, 226, article number 109444. doi: 10.1016/j.compag.2024.109444.

[21] Manalu, M.K., Patrialova, S.N., Radhy, A., & Prahastudhi, S. (2025). Performance analysis of a novel seismic data acquisition system to measure peak particle velocity and source distance. *IOP Conference Series: Earth and Environmental Science*, 1458, article number 012043. doi: 10.1088/1755-1315/1458/1/012043.

[22] Moreno, I.J., Ouardani, D., Chaparro-Arce, D., & Cardenas, A. (2023). Real-time hardware-in-the-loop emulation of path tracking in low-cost agricultural robots. *Vehicles*, 5(3), 894-913. doi: 10.3390/vehicles5030049.

[23] Nazarenko, I., & Kovalov, O. (2021). Energy efficient electromechanical soil treatment system based on electric motorblock. *Bulletin of the National Technical University "KhPI". Series: Energy: Reliability and Energy Efficiency*, 2(1), 71-78. doi: 10.20998/2224-0349.2021.01.10.

[24] Ontiveros, E., Melin, P., & Castillo, O. (2024). Towards an efficient approach for mamdani interval type-3 fuzzy inference systems. *International Journal of Fuzzy Systems*, 26(7), 2172-2190. doi: 10.1007/s40815-024-01722-2.

[25] Panchenko, A., Voloshina, A., Kiurchev, S., Titova, O., Onopreychuk, D., Stefanov, V., Safoniuk, I., Pashchenko, V., Radionov, H., Golubok, M. (2018). Development of the universal model of mechatronic system with a hydraulic drive. *Eastern-European Journal of Enterprise Technologies*, 4(7-94), 51-60. doi: 10.15587/1729-4061.2018.139577.

[26] Raafi, R., Shirani, H., Ullah, W., Khan, W., Akuru, U.B., & Khan, F. (2025). Rotor poles analysis of a novel wound field flux switching machine with π – Shaped stator. In *Proceedings of the 33rd Southern African Universities power engineering conference* (pp. 1-5). Pretoria: IEEE. doi: 10.1109/SAUPEC65723.2025.10944347.

[27] Singh, S., Chauhan, P.S., Sethi, C., Jain, A., & Agnihotri, S.K. (2024). Design and development of multipurpose agriculture robot (Agrobot). In *Distributed intelligent circuits and systems* (pp. 389-420). Hackensack: World Scientific Publishing Co Pte Ltd. doi: 10.1142/9789811279539_0011.

[28] Soitinaho, R., & Oksanen, T. (2023). Local navigation and obstacle avoidance for an agricultural tractor with nonlinear model predictive control. *IEEE Transactions on Control Systems Technology*, 31(5), 2043-2054. doi: 10.1109/TCST.2023.3291533.

[29] Suglobov, V., Krupko, V., Krupko, I., & Vesnin, A. (2024). Mechanisms of earth-moving machinery with wave chain gears. *Mining Journal of Kryvyi Rih National University*, 58(1), 122-126. doi: 10.31721/2306-5435-2024-1-112-122-126.

[30] Tokarchuk, D., & Furman, I. (2021). Modern energy efficient technologies in the agriculture of Ukraine. *Economy, Finances, Management: Topical Issues of Science and Practical Activity*, 4, 99-116. doi: 10.37128/2411-4413-2020-4-7.

[31] Voloshina, A., Panchenko, A., Titova, O., & Panchenko, I. (2021). Changes in the dynamics of the output characteristics of mechatronic systems with planetary hydraulic motors. *Journal of Physics: Conference Series*, 1741(1), article number 012045. doi: 10.1088/1742-6596/1741/1/012045.

[32] Wang, B., Zhu, J., Chai, X., Liu, B., Zhang, G., & Yao, W. (2024). Research status and development trend of key technology of agricultural machinery chassis in hilly and mountainous areas. *Computers and Electronics in Agriculture*, 226, article number 109447. doi: 10.1016/j.compag.2024.109447.

[33] Woo, D.K., Do, W., Hong, J., & Choi, H. (2022). A novel and non-invasive approach to evaluating soil moisture without soil disturbances: Contactless ultrasonic system. *Sensors*, 22(19), article number 7450. doi: 10.3390/s22197450.

[34] Xu, S.Y., Khan, M.I., Kannangara, K.P., & Lee, Y.Y. (2024). An experimental investigation on progressive failure mechanism of the earth-retaining structure with sloping backfill using image analysis. *Acta Geotechnica*, 19(12), 7893-7922. doi: 10.1007/s11440-024-02392-y.

[35] Yi, N.-E., & Yang, Y. (2024). Impact of key factors on shield scraper performance in gravelly soil strata: DEM and experimental investigations. *Computers and Geotechnics*, 174, article number 106592. doi: 10.1016/j.compgeo.2024.106592.

[36] Yu, D., Wei, J., Liang, Q., & Li, L. (2025). Performance analysis of a novel single-flywheel resettable-inertia damper with eddy-current damping. *Journal of Dynamic Disasters*, 1(1), article number 100001. doi: 10.1016/j.jdd.2024.100001.

[37] Zeng, K., & Liu, H. (2023). Experimental study on the time-dependent oedometric compression behavior of calcareous sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 149(5), article number 04023025. doi: 10.1061/JGGEFK.GTENG-10739.

[38] Zhang, T., Jiao, X., & Lin, Z. (2022). Finite time trajectory tracking control of autonomous agricultural tractor integrated nonsingular fast terminal sliding mode and disturbance observer. *Biosystems Engineering*, 219, 153-164. doi: 10.1016/j.biosystemseng.2022.04.020.

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Розробка та впровадження електромеханічних систем для управління ґрунтообробними агрегатами

Анотація. Необхідність удосконалення ґрунтообробних технологій вимагає впровадження електромеханічних систем керування, які забезпечують енергоощадність, стабільність параметрів і підвищення ефективності механізованих процесів у сільському господарстві. Метою дослідження було проектування інтелектуальної системи управління, здатної до динамічної адаптації робочих режимів обробітку на основі сенсорних даних і принципу зворотного зв’язку. Методологія дослідження включала багаторівневе комп’ютерне моделювання в середовищі MATLAB/Simulink, розробку прототипу фізичної системи управління з використанням мікроконтролера STM32F407VG, а також експериментальне тестування в лабораторних і польових умовах на ділянках з різними типами ґрунтів. Система складалася з модулів сенсорного моніторингу вологості, щільності та навантаження, блоку обробки сигналів, пропорційно-інтегрального регулятора та електроприводів, що здійснюють регулювання глибини і зусилля обробітку. Випробування засвідчили високу стабільність системи при змінних агрофізичних параметрах, час реакції на зовнішні зміни в межах 1,8-2,3 секунди, а середнє відхилення глибини не перевищувало п’яти міліметрів. Отримані експериментальні результати показали зменшення середнього енергоспоживання на 12-18 % порівняно з традиційними некерованими системами, а також підвищення коефіцієнта корисної дії до 87 % на суглинкових ґрунтах. За результатами багатокритеріального аналізу ефективності, проведеного методом аналізу ієрархічного процесу, електромеханічна система отримала інтегральний індекс ефективності 4,37 бала, що суттєво перевищує аналогічний показник гідравлічної системи, який становить 3,55 бала. Практична реалізація системи управління довела її технічну придатність до серійного впровадження у сучасні зразки сільськогосподарської ґрунтообробної техніки. Запропоноване технічне рішення дозволяє підвищити якість обробітку ґрунту, знизити енергетичні витрати, мінімізувати потребу у втручанні оператора, а також сприяє сталому розвитку агропромислового комплексу. Результати дослідження можуть бути безпосередньо використані в агропідприємствах для оснащення ґрунтообробних агрегатів сучасними електромеханічними системами управління з метою підвищення точності, зменшення витрат пального та підвищення продуктивності техніки під час виконання польових робіт

Ключові слова: сенсорний моніторинг; адаптивне регулювання; комп’ютерне моделювання; польові випробування; мікроконтролер; електропривод; цифровий інтерфейс