ADAPTIVE CONTROL OF TECHNOLOGICAL MACHINE MODES TAKING INTO ACCOUNT CHARACTERISTICS OF RAW MATERIALS AND ENVIRONMENT

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Abstract. The object of the research is technological processes, soil characteristics, and a sensory experimental system for measuring soil moisture on the basis of a microcontroller. Methods for increasing the energy efficiency and technological productivity of industrial machines by adaptively regulating their operating modes based on the indicators of raw material properties and environmental characteristics are proposed. A sensor system based on the Arduino Uno R3 microcontroller has been developed and tested. It includes four-channel capacitive humidity sensors and a BME280 sensor. This system enables multi-channel measurement of soil environment parameters and atmospheric conditions and can be integrated into adaptive control systems for technological machines. The patterns of soil electrical conductivity changes depending on the increase in depth (5, 10, 15 and 20 cm) for moistened layers have been established. Nonlinear exponential two-factor 3D model of soil electrical resistance is obtained on the basis of experimental data. This model depends on the depth of cultivation and soil moisture and describes the experimental data with high accuracy (model error of 1.38%). Significant variability of environmental parameters (air temperature, atmospheric pressure and relative humidity) has been noted depending on the depth and measurement conditions, which confirms the need for their prompt consideration when controlling machine work processes. The informativeness of moisture indicators along the depth profile for predicting the physical and mechanical state of the soil has been established. The revealed patterns are recommended to be used as input factors under the conditions of adaptive regulation of speed, power and energy modes of machines. The use of this algorithm makes it possible to increase energy efficiency, reduce the load on working parts, and increase the stability of technological operations.

Keywords: adaptive control, technological machines, sensor systems, Arduino Uno R3, capacitive sensors, raw material parameters.

Introduction

Modern agricultural machines and aggregates operate under conditions of significant variability in the properties of the raw materials with which they interact. The external environment is also referred to as the determining factor of production efficiency. Traditional control systems operate mainly in fixed modes, which leads to energy overruns, premature wear of elements and a decrease in their use efficiency [1-3]. The significant influence of humidity, density and structural state of the soil environment on the traction resistance and productivity of machines was noted in studies [4-6]. Recent studies have established prospects on the basis of assessing the actual state of the environment using adaptive control of the machine operating parameters in real time [7; 8]. To implement this approach, reliable measurement systems are created that are able to obtain extensive information regarding the state of the raw material or material with which the machine interacts.

Adaptive control systems are widely used in transport, energy and agrotechnical machines [9]. However, a significant obstacle to their widespread use is the lack of operational data regarding material properties and technological environment. This applies, to a large extent, to machines interacting with loose, humid roomy or soil materials, the key parameters of which are humidity, density and structural state of the soil. These indicators are characterized by significant ranges of change in values, which causes corresponding fluctuations in loads on the working bodies [10].

Known approaches to adaptive control of technological processes are mainly based on generalized or surface parameters of the state of the environment. Spatial (deep) distribution of soil moisture, which significantly affects its physical and mechanical properties and loads on the working bodies of machines, is not taken into account enough under such conditions. An insufficient level of research on the integration of multi-channel sensor systems into the adaptive control circuit in real time has been noted. A practical version of the sensor module for assessing soil moisture parameters and atmospheric

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conditions, which has significant potential under conditions of integration into the adaptive control structure, is proposed in this paper.

Materials and methods

The purpose of the study is to increase the efficiency of technological machines by forming rational approaches to adaptive regulation of their operating modes based on the measurement of the parameters of raw materials and the environment.

To achieve this goal, the following tasks are defined:

1. Develop a sensor system for recording soil environment parameters using four-channel capacitive humidity sensors and atmospheric parameter sensors.
2. Study the change in soil moisture with the simultaneous establishment of air temperature, atmospheric pressure and relative humidity at the depths of the soil environment 5, 10, 15 and 20 cm experimentally.
3. Outline the requirements for the formation of an adaptive control algorithm by operating modes of technological machines (adjustment of speed, power and energy parameters in real time) based on the results of sensory monitoring of the soil environment.

Holes were formed in the soil at depths of 5, 10, 15 and 20 cm. Sensors were installed in such a way as to avoid additional aeration or disruption of the soil structure [8]. At the same time, atmospheric pressure, air temperature, and relative humidity were recorded.

Atmospheric conditions during the experiments were stable: the air temperature was 14-18 °C, relative humidity – 55-66%, atmospheric pressure – 1001-1015 hPa. This minimized the influence of external factors on the measurement results.

Specific conductivity was determined:

$$\sigma = 1/\rho, \tag{1}$$

where ρ – index of the specific electrical resistance of the soil, Ohm·m, which was determined by the Arduino Uno R3 microcontroller based on the results of establishing the electrical resistance of the soil at different depths of the study.

$$\rho = R \cdot S/l, \tag{2}$$

where R – electrical resistance of soil, Ohm; S – cross-sectional area, m^2; electrical conductivity was calculated in units of SI – siemens per meter (S·m^{-1});
l – soil depth, m.

Each measurement at the appropriate depth was performed in five repetitions, after which the average value of the indicators was calculated. The standard deviation was determined to evaluate the variation of the results.

The study was carried out on a site of loamy soil with a relatively homogeneous structure. Calibration of capacitive humidity sensors by comparing their readings with reference humidity values obtained by the gravimetric method was carried out before the experiments.

Primary experimental data were averaged, checked for abnormal values, and smoothed. Further analysis was performed using regression modeling techniques.

Results and discussion

The experimental module is based on the Arduino Uno R3 microcontroller, which performs the functions of signal collection and pre-processing. Four-channel capacitive sensors that provide relatively stable performance under conditions of salt content or temperature variation [9] are used to assess soil moisture. The total sample size was $N = 20$ measurements (5 replicates for each depth). The obtained data were used to build a regression model and estimate its accuracy.

The system contains the following components (Fig. 1).

- Arduino Uno R3 (main logic controller) is the main hardware component that contains the ATmega328 microcontroller in the Arduino Uno model and I/O elements. It has digital and analog pins (inputs/outputs) that can be connected to various sensors, modules, and other electronic components.

- 4 capacitive soil sensors (channels for depths of 5, 10, 15 and 20 cm). These sensors are based on the principle of changing the electrical capacity for detecting objects, measuring the liquid level, soil moisture or even touch. They are used in many projects due to their contactless work and durability.
- Integrated sensor BME280 5V I2C produced by Bosch Sensortec combines the functions of measuring atmospheric pressure, relative humidity and ambient temperature. The sensor supports two main communication interfaces – I2C and SPI. Module modifications compatible with the 5V supply voltage have additional components (voltage stabilizer and logic level converter) on the board, which makes it possible to use them safely with microcontrollers. Temperature – from -40 °C to + 85 °C (accuracy ± 1.0 °C), humidity – from 0% to 100% (accuracy ± 3%), pressure – from 300 to 1100 hPa (hectopascals), which corresponds to an altitude of 9000 m to -500 m above sea level (accuracy ± 1 hPa), power consumption – very low (about 0.1 mA in active measurement mode).
- LCD 12864 liquid crystal display, which uses organic LEDs to emit light, provides high brightness, contrast and wide viewing angle. The display is compatible with Arduino and other microcontrollers to output results.
- Power supply unit from four AAA batteries. Autonomous power provides mobility and the ability to work in the field without external current sources.

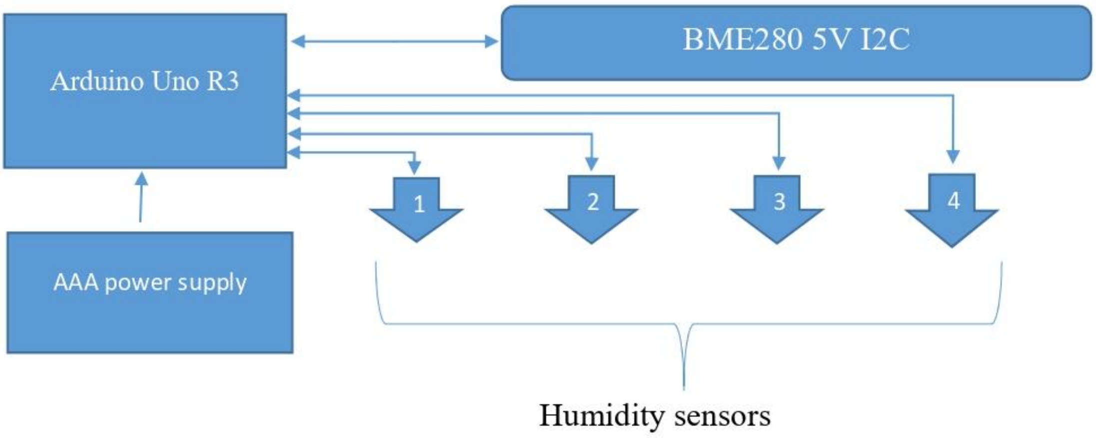

Fig. 1. **Structural and functional diagram of the soil environment moisture assessment system**

Measurements were performed at the test site of loamy soil under stable weather conditions (Fig. 2).

The obtained research results made it possible to form a list of parameters by which the technological machine can perform self-tuning. An algorithm based on certain assumptions has been developed for this.

Analysis of the intensity of humidity change in depth made it possible to determine the degree of compaction or the structure of the layer affecting the working load of the machine.

A two-factor 3D model of the electrical resistance of the soil was built according to the experimental data obtained $R = R(h, W)$, where R – electrical resistance of soil, Ohm; h – depth of cultivation, cm; W – soil moisture, %. The model of the form is used for approximation $R = ae^{(b \cdot h + c \cdot W)}$, where a, b, c – coefficients. After approximation, the following nonlinear relationship was obtained:

$$R = 53.19 \cdot e^{-0.0375 \cdot h + 0.00411 \cdot W}. \tag{3}$$

Coefficient of determination for this dependency $R^2 = 0.992$. The model describes approximately 99.2% of the variation of the experimental data. The standard error is 0.593 Ohm, which is less than 1 Ohm and very good for experimental soil measurements. The average relative error of the model is less than 2% and is 1.38%. The obtained average values were accompanied by 95% confidence intervals, which confirms the reliability of the measurement results.

Approximation of the results by a nonlinear exponential model made it possible to obtain an empirical dependence $R = R(h, W)$, and describes the experimental data with high accuracy.

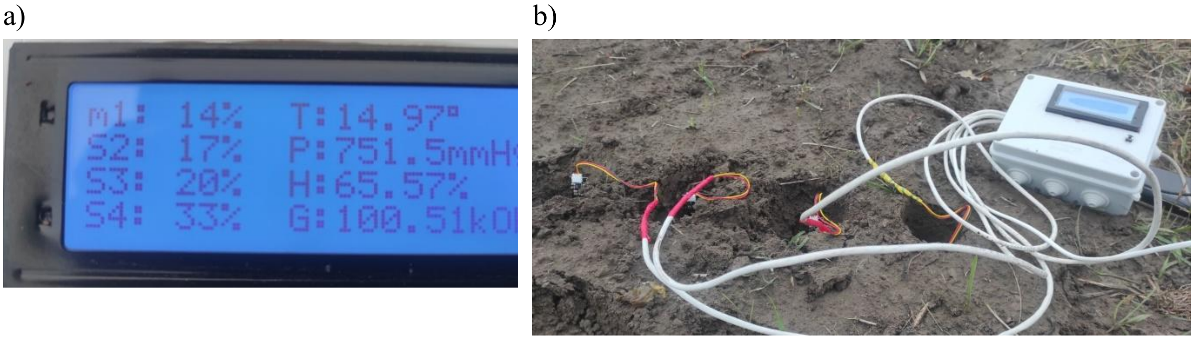

Fig. 2. **Equipment for measuring soil moisture:** a – established indicators of soil moisture; b –appearance of equipment for measuring soil moisture

Analysis of the resulting model found that the electrical resistance of the soil is significantly dependent on the depth of measurement. A negative coefficient under the variable *h* indicates an exponential decrease in resistance with increasing depth. This is due to the physical properties of the soil environment. The choice of exponential dependence is due to the physical nature of the processes in the soil. With increasing humidity, the water content in the soil pores increases. This improves the conditions for the passage of electric current and leads to a nonlinear decrease in electrical resistance. Typically, less moisture content and more porosity, which causes increased electrical resistance, are observed in the upper layers of the soil. Soil density and its water saturation, which leads to an increase in electrical conductivity and a corresponding decrease in electrical resistance, increases with increasing the depth.

Soil moisture also significantly affects the electrical properties of the environment. Water containing dissolved salt ions acts as a conductor of electric current. Therefore, the concentration of moving ions in the pore space, which helps to reduce electrical resistance, increases with increasing soil moisture. This phenomenon is consistent with the known laws of electrical conductivity of dispersed media. The resulting model can be used to predict the electrical resistance of the soil under various humidification conditions and the depth of measurement.

Fig. 3 shows the three-dimensional surface of the dependence of the electrical resistance of the soil on the depth of measurement and its humidity $R = R(h, W)$.

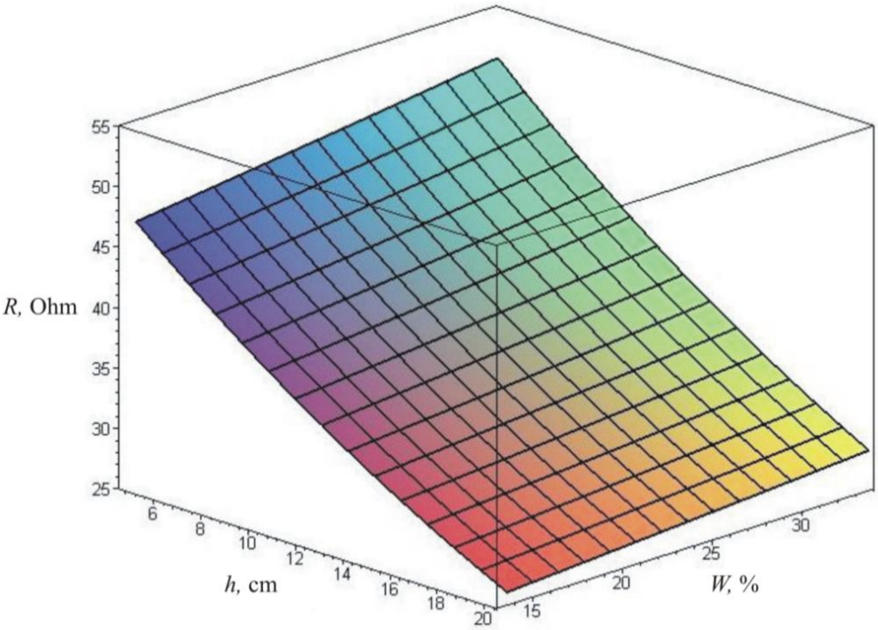

Fig. 3. **Three-dimensional surface of dependence of the electrical resistance of the soil on the depth of measurement in the soil and its humidity $R = R(h, W)$**

Changes in the calculated values of the specific electrical conductivity of the soil depending on the depth are given in Table 1.

Table 1

Changes in the calculated values of the specific electrical conductivity of the soil depending on the depth

Depth, cm	Electrical conductivity σ, S·m^{-1}
5	$2.16 \cdot 10^{-2}$
10	$2.51 \cdot 10^{-2}$
15	$3.08 \cdot 10^{-2}$
20	$3.48 \cdot 10^{-2}$

Using a sensor module allows to obtain data with sufficient accuracy to build an initial adaptive control model. Differentiation of humidity by depth makes it possible to predict the resistance of the processed material and optimize: energy consumption, load mechanisms, productivity of the technological operation.

Further development of the system involves expansion of the number of sensor channels, the use of wireless data transmission, integration with machine learning and introduction into real production machines.

The scientific novelty of the work is that there are such technical and technological solutions, the use of which made it possible to combine multi-level sensory monitoring of soil moisture with the concept of adaptive control of the modes of technological machines. The shift in the emphasis of assessing the actual state of the soil environment from the surface to the spatial (depth) provided the above. The results obtained are consistent with the data of other researchers who note the significant influence of soil moisture on its electrical and mechanical properties. At the same time, the deep distribution of humidity, which made it possible to increase the accuracy of modeling and expand the possibilities of applying the results in adaptive control systems, is taken into account in this work, in contrast to existing approaches.

Scientific and practical novelty is the development of an adaptive method of controlling technological machines based on multi-level sensory monitoring of soil moisture, taking into account its change in depth. Unlike existing solutions, the proposed approach allows the formation of input control parameters taking into account the spatial heterogeneity of the medium and the established nonlinear dependence of the electrical resistance of the soil.

The practical value of the obtained results lies in creating an affordable, energy-efficient and mobile sensor complex, suitable for integration into the control systems of tillage agricultural machines and units. The accumulated information and reference data will be used to establish rational modes and parameters of machines and units.

Prospects for further research are related to:

- expansion of the number of sensor channels and nomenclature of measured parameters;
- implementation of wireless data transmission and remote monitoring;
- using machine learning methods to build predictive soil state models;
- experimental verification of the efficiency of the adaptive control algorithm on real technological machines.

Conclusions

1. A sensor system based on the Arduino Uno R3 microcontroller containing four-channel capacitive humidity sensors and a sensor BME280 designed and tested. This system enables multi-channel measurement of soil environment parameters and atmospheric conditions and can be integrated into adaptive control systems for technological machines.
2. The patterns of changes in the specific electrical conductivity of the soil depending on the increase in depth (5, 10, 15 and 20 cm) have been established. A two-factor 3D model of the electrical resistance of the soil from the depth of cultivation and soil moisture was built according to experimental data. This model describes experimental data with high accuracy (model error is 1.38%). A significant variability in the parameters of the medium (air temperature, atmospheric

pressure and relative humidity) in depth and measurement conditions was noted. This confirms the need for their operational consideration during the management of the working processes of machines.

3. Informativeness of humidity indicators along the depth profile for predicting the physical and mechanical state of the soil has been established. The identified regularities were recommended to be used as input factors under conditions of adaptive regulation of high-speed, power and energy modes of machines. The use of this algorithm makes it possible to increase energy efficiency, reduce the load on the working bodies and increase the stability of technological operations.

Author contributions

Conceptualization, V.S. and O.H.; methodology, V.S. and O.H.; software, V.S., O.H. and M.T.; validation, V.S. and O.H.; formal analysis, V.S. and O.H.; investigation, V.S., O.H. and M.T.; data curation, V.S., O.H., M.T., M.S., Y.F. and L.P.; writing – original draft preparation, V.S., O.H. and M.T.; writing – review and editing, V.S., O.H., M.T., M.S., Y.F. and L.P.; visualization, V.S., O.H. and M.T.; project administration, V.S. and O.H.; funding acquisition, M.T., M.S., Y.F. and L.P. All authors have read and agreed to the published version of the manuscript.

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