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CYBER-PHYSICAL SYSTEM FOR DETERMINING SOIL PARAMETERS

The relevance of a cyber-physical system for determining soil parameters in Ukraine is determined by several important factors, including climate change, declining soil fertility, and the need to implement efficient technologies to ensure sustainable agriculture. In Ukraine, where a large part of the economy depends on the agricultural sector, accurate soil monitoring is a key aspect to increase the efficiency of agricultural production, optimize the use of water and land resources, and reduce the cost of fertilizers and pesticides.

Cyber-physical systems can provide timely data collection on soil moisture, temperature, pH, and other critical soil parameters, allowing farmers to respond quickly to changes in environmental conditions. Such systems can reduce the negative impact of excessive irrigation and optimize the use of water resources, which is especially important in the face of drought, which is increasingly common in Ukraine due to climate change.

These systems also allow for accurate forecasts of yields and soil conditions, as well as the development of individualized recommendations for each field or plot. Since Ukraine has a wide variety of climatic conditions and soil types, cyber-physical systems are able to adapt to different agricultural needs, making them extremely useful for the development of precision agriculture.

The introduction of such technologies helps not only to preserve natural resources but also to improve the economic efficiency of agriculture. Therefore, the development and implementation of cyber-physical systems for soil monitoring is an extremely important step for the sustainable development of Ukraine's agricultural sector. Therefore, our research is devoted to the development of a method and a cyber-physical system for determining soil parameters.

The cyber-physical system for determining soil parameters consists of three levels: the level of sensors, the level of the controller to which the sensors are connected, and the system for collecting, monitoring, and managing data in real time. To build a cyber-physical system for determining soil parameters, we selected sensors, selected a controller, selected a data transmission standard, and developed a method for collecting, monitoring, and controlling data. The proposed method of data acquisition, monitoring and control for the upper level of the cyber-physical soil parameterization system allows for efficient data acquisition, monitoring and control in a cyber-physical system with various parameters stored in real time.

Keywords: cyber-physical system, soil parameters, sensors of soil moisture, soil temperature, soil electrical conductivity, soil acidity (pH), nutrient content (nitrogen, phosphorus, potassium) and organic matter and minerals in the soil, soil texture (density), controllers, data transmission standards.

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КІБЕРФІЗИЧНА СИСТЕМА ВИЗНАЧЕННЯ ПАРАМЕТРІВ ГРУНТУ

Актуальність кіберфізичної системи для визначення параметрів ґрунту в Україні визначається кількома важливими факторами, зокрема змінами клімату, зменшенням родючості ґрунтів та необхідністю впровадження ефективних технологій для забезпечення сталого сільського господарства. В Україні, де значна частина економіки залежить від аграрного сектора, точний моніторинг стану ґрунту є ключовим аспектом для підвищення ефективності сільського виробництва, оптимізації використання водних та земельних ресурсів і зменшення витрат на добрива та пестициди.

Кіберфізичні системи можуть забезпечити своєчасний збір даних про вологість, температуру, рівень pH та інші критичні параметри ґрунту, що дозволить фермерам оперативно реагувати на зміни в умовах навколишнього середовища. Завдяки таким системам можна зменшити негативний вплив надмірного поливу, оптимізувати використання водних ресурсів, що є особливо важливим в умовах посухи, що все частіше виникає в Україні через зміни клімату.

Ці системи також дозволяють отримувати точні прогнози щодо врожайності та стану ґрунту, а також розробляти індивідуальні рекомендації для кожного поля чи ділянки. Оскільки в Україні існує велика різноманітність кліматичних умов та типів ґрунтів, кіберфізичні системи здатні адаптуватися до різних аграрних потреб, що робить їх надзвичайно корисними для розвитку точного землеробства.

Впровадження таких технологій допомагає не тільки зберігати природні ресурси, але й покращити економічну ефективність сільського господарства. Тому розробка та впровадження кіберфізичних систем для моніторингу ґрунтів є надзвичайно важливим кроком для сталого розвитку аграрного сектору України. Відтак наше дослідження присвячене розробленню методу та кіберфізичної системи для визначення параметрів ґрунту.

Кіберфізична система визначення параметрів ґрунту складається з трьох рівнів – рівня датчиків, рівня контролера, до якого приєднуються датчики, а також з системи збору, моніторингу та керування даними в реальному часі. Для побудови кіберфізичної системи визначення параметрів ґрунту було виконано вибір датчиків, вибір контролеру, вибір стандарту передачі даних та розроблено метод збору, моніторингу та керування даними. Пропонований метод збору, моніторингу та керування даними для верхнього рівня кіберфізичної системи визначення параметрів ґрунту дозволяє забезпечити ефективний збір, моніторинг і керування даними в кіберфізичній системі з різними параметрами, що зберігаються в реальному часі.

Ключові слова: кіберфізична система, параметри грунту, датчики вологості ґрунту, температури ґрунту, електричної провідності ґрунту, кислотності (pH) ґрунту, вмісту поживних елементів (азот, фосфор, калій) та органічних речовин і мінералів в ґрунті, текстури (щільності) ґрунту, контролери, стандарти передачі даних.

Introduction

The relevance of determining soil parameters is of great importance in a number of scientific and practical fields, as soils are the basis for agriculture, ecology, and construction.

To grow plants optimally, it is necessary to know parameters such as soil structure, acidity (pH), moisture, nutrient content (nitrogen, phosphorus, potassium), and organic matter. Determining these parameters allows us to develop precise recommendations for fertilization, watering, and selecting the most suitable crops for specific conditions [1].

Analysis of soil parameters is an important part of monitoring the environmental condition of territories. Changes in soil composition can signal pollution, erosion, or other negative processes. Soil surveys help determine the impact of anthropogenic factors on ecosystems and take measures to preserve biodiversity.

Soil parameters, such as bearing capacity, density, water permeability, and moisture capacity, are critical for the design and construction of various facilities, from residential buildings to large infrastructure projects. Knowing these characteristics helps to avoid problems with foundations, soil subsidence, or flooding in the future [2].

Soils interact with the atmosphere and regulate the carbon cycle, so their analysis is important for climate change research. Determination of soil parameters helps to assess the ability of soils to absorb carbon, which is important for understanding climate change and planning mitigation measures.

Soil contamination with heavy metals, pesticides, or other toxic substances requires rapid determination of parameters to take cleanup measures. Sustainable development technologies involve monitoring and improving soil quality, which directly affects agricultural productivity and the environment [3].

Determination of soil parameters is the basis for proper management of natural resources and sustainable development. The importance of this process is growing in light of current challenges, such as climate change, environmental pollution, and declining soil fertility. Since soil is not only a medium for growing plants but also an integral part of the ecosystem, its condition directly affects the health of people, animals and plants. Correct determination of the physical, chemical and biological properties of soil allows us to respond to environmental changes in a timely manner and develop effective strategies for the conservation and restoration of natural resources.

In addition, soil research is essential for the development of new technologies in agriculture. For example, determining the level of moisture in the soil allows for the creation of irrigation systems that use water as efficiently as possible, and helps to develop methods to combat droughts or other climatic phenomena. At the same time, analyzing the chemical composition of the soil allows for more accurate fertilizer dosing, which helps to increase yields without harming the environment [4].

In the context of construction, knowledge of soil parameters helps to avoid serious technical problems. For example, an incorrect determination of soil density can lead to building settling, which poses a risk to their stability. Convincing research and accurate data also help to reduce the cost of building materials, increasing the reliability of structures.

All of this confirms that the correct determination of soil parameters is a key element in maintaining a stable and healthy environment for both people and nature in general. Thus, this process is not only important, but also extremely relevant for the development of society, especially in the context of modern environmental and technological challenges [5].

So, determining soil parameters is essential for sustainable development, optimization of agricultural activities, as well as for environmental safety and conservation of natural resources.

A cyber-physical system (CPS) for determining soil parameters is an innovative solution that combines physical sensors, computer algorithms, and network technologies to monitor and analyze soil conditions in real time. Such systems allow automating the process of collecting data on soil parameters, which is extremely important for agriculture, ecology, and construction [6, 7].

The main components of a cyber-physical system [8-10]:

– Sensors - specialized sensors that measure various soil parameters, such as humidity, temperature, pH, electrical conductivity, organic matter and mineral content. The sensors can be embedded in the soil or installed on its surface, and can be integrated into automated systems for data collection.

– Data processing - the collected data is transferred to a central computing platform where it is processed using machine learning algorithms or analytical models. This allows us to identify correlations between different soil parameters and make accurate predictions about its condition.

– Data networks - wireless or wired networks are used to transmit information from sensors to processing systems. This allows for real-time monitoring and remote access to data from anywhere in the world.

– User interface - usually the system provides an interface for users (agronomists, engineers, environmentalists) through which you can get monitoring results, view statistics, configure sensor parameters, or receive warnings about changes in soil parameters.

Advantages of cyber-physical systems for determining soil parameters [11-13]:

– Accuracy and efficiency - CPS allows for accurate measurements of soil parameters in real time, which is especially important for agribusiness, where changes in soil moisture or acidity can directly affect the yield.

– Automation of the process - by automating data collection and processing, CFS minimizes the human factor and reduces the cost of manual measurements, which saves time and resources.

– Prediction and adaptation - based on the analysis of the data, the system can make predictions about changes in soil conditions, such as the risk of drought, erosion or changes in acidity, and offer optimal solutions for adaptation.

– Improving agricultural technologies - thanks to accurate data, farmers can develop individualized strategies for watering, fertilizing, and tillage, which helps to increase the efficiency of crop production and conserve natural resources.

– Environmental friendliness - determining precise soil parameters reduces the use of chemical fertilizers and water, which has a positive impact on the environment, contributing to sustainable agricultural development and ecosystem protection.

Cyber-physical systems for soil monitoring are actively used in agriculture to accurately control soil moisture and pH levels, as well as to monitor soil erosion or wear and tear. This allows not only to improve yields but also to reduce the cost of watering and fertilizing. In construction, such a system is used to determine soil characteristics, which helps to maintain the stability of construction projects and prevent undesirable consequences due to improper construction work [14, 15].

A cyber-physical system for determining soil parameters is a powerful tool that helps not only to optimize agronomy and construction processes, but also to conserve natural resources and ensure environmental sustainability. The introduction of such technologies significantly increases the efficiency of soil resource management, which is an important step towards sustainable development and environmental protection [16-18].

There are several well-known cyber-physical soil monitoring systems that are used to analyze various soil parameters such as moisture, temperature, pH, organic content, and other factors that affect agriculture and the environment [19-22].

There are some examples of such systems:

1. Agrilink (Soil monitoring system for agriculture) [23

Main functions:

– Measurement of soil moisture, temperature and pH levels.
– Data collection and analysis using wireless sensors.
– Prediction and optimization of irrigation based on the analysis of soil parameters.
– Adaptation to different crops.

Advantages:

– Reduced water and fertilizer costs.
– Increased efficiency of agricultural production.
– Interface for farmers to analyze and configure monitoring parameters.

2. SoilSens (Soil Sensors for Agriculture) [24]

Main functions:

– Uses sensors to measure soil moisture, pH, temperature, and electrical conductivity.
– The platform allows receiving real-time data through a mobile application or web interface.
– Can integrate with other agronomic systems to improve irrigation efficiency.

Advantages:

– Easy to install and configure the system.
– Increased yields through precise resource management.
– Support for sustainable agricultural development.

3. Sentek (Soil Moisture Monitoring Systems) [25]

Main functions:

– Specializes in monitoring soil moisture and hydrological characteristics.
– Measures the level of moisture at different soil depths, which allows the farmer to more accurately control irrigation.
– Uses a combination of sensors and a network to transmit data in real time.

Advantages:

– Improves irrigation efficiency.
– Allows to reduce water consumption, which is important for water-saving agricultural technologies.
– Helps to preserve soil resources and reduce erosion.

4. Smartfield (Soil conditions monitoring system) [26]

Main functions:

– Designed to measure soil parameters such as moisture, temperature and pH.
– It provides data for agronomists and farmers to fine-tune the conditions for crop growth.
– It has the ability to set up automatic watering and monitor irrigation.

Advantages:

– Easy integration with other agronomic systems.
– Automation of soil condition monitoring.
– Optimization of water and land resources use.

5. Field Climate (Platform for weather and soil monitoring) [27]

Main functions:

– Specializes in monitoring various parameters of weather conditions and soil conditions.
– It uses sensors to determine soil moisture, temperature, and other factors affecting plant health.
– It can provide accurate forecasts and recommendations based on the data collected.

Advantages:

– High level of monitoring automation.
– Integration with mobile applications for real-time data access.
– Possibility to reduce the use of water and chemical fertilizers.

6. iSyst (Smart Soil Monitoring System) [28]

Main functions:

– Uses high-precision sensors to monitor the amount of water in the soil, pH, electrical conductivity, and temperature.
– Data is transmitted via wireless channels to a central system for analysis and display on a user interface.

Advantages:

– High measurement accuracy and the ability to customize system parameters.
– Helps in managing water resources and increasing agricultural productivity.

Cyber-physical systems for soil monitoring are actively used to accurately collect data on soil conditions and manage natural resources. They allow farmers and environmentalists to monitor soil quality more accurately and efficiently, which is important for maintaining soil fertility, increasing yields, and sustainable agricultural development. The systems also help reduce environmental impact by optimizing the use of water and fertilizers.

Thus, the task of creating a cyber-physical system for determining soil parameters is *relevant*. Therefore, our *research focuses* on the design of a cyber-physical system for determining soil parameters.

Cyber-physical system for determining soil parameters

Cyber-physical system for determining soil parameters is an integrated technology platform that combines physical sensors, computing resources, and software for automated monitoring, analysis, and management of soil conditions in real time. Such a system is an important component of modern smart agriculture, environmental monitoring, and sustainable use of natural resources.

In general, a cyber-physical system consists of three levels: lower, middle, and upper [29]. The lower level is the level of sensors. The middle level is the level of the controller to which the sensors are connected. The upper level is a system for collecting, monitoring, and controlling the data of a cyber-physical system in real time. So, to build a cyber-physical system, you should select sensors to form the lower layer, select a controller to form the middle layer, and develop scenarios and an algorithm for collecting, monitoring, and controlling data to form the upper layer. In addition, the method and standard of data transmission should be chosen to establish communication between the components of all three layers.

The main parameters to be determined by the cyber-physical system under development will be: soil moisture, soil temperature, soil electrical conductivity, soil acidity (pH), nutrient content (nitrogen, phosphorus, potassium) and organic matter and minerals in the soil, and soil texture (density).

The following sensors are used to measure soil moisture:

1) capacitive soil moisture sensors, which measure changes in the dielectric constant of the soil - the more moisture, the higher the capacitance; their advantages are accuracy and stability, insensitivity to salts, durability; popular models are DFROBOT Capacitive Sensor, SEN0193;

2) resistive soil moisture sensors, which are based on a change in electrical resistance between two electrodes that depends on humidity; their advantages are low cost and ease of use, while their disadvantages are lower accuracy and faster wear due to corrosion; a popular model is YL-69;

3) tensiometers, which measure the pressure that plants have to apply to absorb water from the soil; their advantages are accuracy (even in high humidity) and suitability for agricultural purposes; disadvantages are lower efficiency in dry soil and the need for maintenance;

4) gravimetric sensors (gravimetric method), which determine moisture content by weighing samples before and after drying; the most accurate, but unsuitable for automatic monitoring, used only in laboratories;

5) sensors using Time Domain Reflectometry (TDR), which measure the time of electromagnetic wave transmission through the soil; their advantages are high accuracy and operation in a wide range of soil types; the disadvantage is high cost; popular models are Decagon 5TE, Campbell Scientific CS616.

A comparative analysis of popular soil moisture sensors is presented in Table 1.

It is obvious that although the *Decagon 5TE sensor* is more expensive than simple single-parameter sensors, it measures three key parameters for our system simultaneously, so we will use the Decagon 5TE sensor to measure soil moisture, temperature, and electrical conductivity.

Table 1

Comparative analysis of popular soil moisture sensors

Model	Type	Accuracy	Power supply	Interface	Durability	Cost, USD	Purpose
YL-69	Resistive	Low (±10–15%)	3.3–5V	Analog + digital	Low (up to 6 months)	1-3	Initial training, amateur projects. Measures humidity only
DFROBOT SEN0193	Capacitive	Medium (±5%)	3.3–5V	Analog	High (1–2 years)	6-10	Household use, DIY projects. Measures humidity only
Decagon 5TE	Capacitive	High (±1–2%)	3.6–15V	SDI-12 / UART	High (3+ years)	200-250	Professional agricultural monitoring. Measures soil moisture, temperature and electrical conductivity
TDR Campbell CS616	TDR	Very high (±1%)	5–18V	TTL / RS-232	High (5+ years)	300-400	Scientific research, engineering systems. Measures soil moisture and dielectric constant

A comparative analysis of common sensors for measuring soil acidity (pH) is presented in Table 2.

Table 2

Comparative analysis of common sensors for measuring soil acidity (pH)

Model	Type	pH range	Accuracy	Interface	Cost, USD	Features
DFRobot Gravity pH Sensor	Galvanic electrode	0 – 14	±0.1 – 0.2	Analog, BNC	30-50	Calibration required; probe replaceable. Measures soil acidity only
Atlas Scientific pH Sensor	Laboratory electrode	0 – 14	±0.002 – 0.01	UART / I2C / Analog	70-150	Very accurate; calibration supported. Measures soil acidity only
SEN0161 (DFRobot v1.1)	Analog pH sensor	0 – 14	±0.1 – 0.2	Analog	20-35	Budget, suitable for Arduino. Measures soil acidity and temperature
Vernier Soil pH Sensor	Professional (trial)	2 – 10	±0.2	Analog, compatible with LoggerPro	100-150	Stable for long-term monitoring. Measures soil acidity only
Hanna HI99121	Portable meter	0 – 14	±0.02	Handheld, digital display	300-500	Field pH meter with built-in probe. Measures soil acidity and temperature
Bluelab Soil pH Pen	Portable	3 – 9	±0.1	Handheld	100-120	Easy to use, with display. Measures soil acidity, temperature

Given the comparative analysis, to implement our cyber-physical system we will use the portable *Bluelab Soil pH Pen sensor* to measure soil acidity.

A comparative analysis of different sensors for measuring the content of nutrients (nitrogen, phosphorus, potassium), organic matter and minerals in the soil is presented in Table 3.

Table 3

Comparative analysis of different sensors for measuring the content of nutrients (nitrogen, phosphorus, potassium), organic matter and minerals in the soil

Model	Measurement parameters	Measurement range	Type of measured substances	Cost, USD	Features
ECOFUEL Soil Nutrient Sensor	Nitrogen (N), phosphorus (P), potassium (K), organic matter, minerals	Nitrogen: 0–150 ppm, Phosphorus: 0–50 ppm, Potassium: 0–250 ppm	Nutrients, organic matter	500-700	Interface: Bluetooth, used for agronomy, horticulture
METER Group HydroSense	Nitrogen, phosphorus, potassium, moisture, soil temperature	Varies depending on specific sensors	Nutrients, soil moisture	600-900	Interactive system for monitoring water balance
LusterLeaf 1601 (Soil Test Kit)	Nitrogen, phosphorus, potassium	Varies depending on the test (different ranges)	Nitrogen, phosphorus, potassium	40-60	Possibility of home use, manual analysis kits
Hanna Instruments HI83200	Nitrogen, phosphorus, potassium, calcium, magnesium, iron and others	According to tests, from a few ppm to g/l	Nutrients, minerals	300-500	Multimeter, supports various testing methods
SoilOptix	Nitrogen, phosphorus, potassium, calcium, magnesium, organic matter	Variable, depending on soil type	Nutrients, organic matter	5000-10000	Uses spectroscopy to analyze soil
Bluelab Soil pH Pen (v2)	Soil pH, soil temperature, moisture (nitrogen, phosphorus, potassium)	pH: 0–14, Temperature: -5 to 60°C	Soil pH, soil temperature	100-150	Portable, fast measurement, ideal for field conditions
Yara N-Tester	Nitrogen (N)	0–250 ppm nitrogen in soil	Nitrogen	200-300	Portable, used for quick nitrogen content check

Given the comparative analysis conducted, to implement our cyber-physical system we will use the *ECOFUEL Soil Nutrient Sensor*, which offers the most accurate measurement of all major nutrients, including organic matter and minerals, and has a relatively low cost.

A comparative analysis of different sensors for measuring soil texture (density) is presented in Table 4.

Table 4

Comparative analysis of different sensors for measuring soil texture (density)

Model	Measurement parameters	Measurement range	Type of measured substances	Cost, USD	Features
Eijkelkamp Soil Moisture Sensor	Soil moisture, Soil density	Humidity: 0–100%, Soil Density: 1–2 g/cm³	Soil humidity, density	300-600	Suitable for studies requiring precise measurements
Campbell Scientific CS655	Soil moisture, soil temperature, soil texture	Humidity: 0–100%, Temperature: -40°C to 50°C	Humidity, temperature, texture	500-800	Uses for long-term soil observations
Veris Technologies 3100	Soil moisture, electrical conductivity, soil texture	Humidity: 0–100%, EC: 0–10 dS/m	Humidity, texture, soil EC	5000-10000	Mobile monitoring, uses in field conditions

Taking into account the comparative analysis, to implement our cyber-physical system we will use the *Eijkelkamp Soil Moisture Sensor*, which measures not only soil moisture, but also soil density, which is an important parameter for assessing soil structure, and has a relatively low price.

To form an average level of cyber-physical system for determining soil parameters, a comparative analysis of controllers was conducted, the results of which are presented in Table 5.

Given the comparative analysis, to implement our cyber-physical system, we will use the *ESP32 controller*, which is a powerful device with many connectivity options, is an energy-efficient option, especially for autonomous systems where low power consumption is important, is an excellent option for wireless systems with low power consumption, especially considering its low price.

As a data transmission standard in the designed system, we will choose Wi-Fi, which supports high data transfer rates, allows you to connect to the network without the need for wires, is supported by most modern devices, has a relatively inexpensive infrastructure, is easily scalable, supports modern security protocols, has low data transfer latency, allows you to connect many devices simultaneously without significant losses in speed or connection quality.

Table 5

Comparative analysis of controllers that can be used for an average level of cyber-physical system for determining soil parameters

Controller	Input ports	Output ports	Communication protocols	Features	Cost, USD
Arduino UNO	14 digital, 6 analog ports	12 digital, 6 analog ports	I2C, SPI, UART	Easy to use, large support community, cheap	20-30
Raspberry Pi 4	40 GPIO pins, support for digital and analog signals	HDMI, USB, GPIO pins, Ethernet	I2C, SPI, UART, Ethernet, Wi-Fi	Powerful, Linux support, large selection of peripherals	35-100
ESP32	34 analog digital ports, 15 digital ports	34 outputs for servos, LEDs, sensors	Wi-Fi, Bluetooth, I2C, SPI, UART	Built-in Wi-Fi and Bluetooth, energy efficient	5-15
BeagleBone Black	69 digital/analog ports	GPIO, UART, SPI, I2C, PWM	Ethernet, UART, SPI, I2C, CAN	Powerful, Linux support, multi-functional	45-60
Intel Edison	20 digital pins, 6 analog ports	20 digital pins, 6 analog outputs	Wi-Fi, Bluetooth, UART, SPI, I2C	Compact, built-in Wi-Fi and Bluetooth, for industrial applications	50-80
Adafruit Feather M0	20 digital pins, 6 analog ports	20 pins for connecting sensors	I2C, SPI, UART	Small size, easy to use, supports various sensors	20-30
NXP i.MX RT1060	144 pins for digital/analog ports	GPIO, SPI, UART, CAN, Ethernet	I2C, SPI, UART, Ethernet	High performance, suitable for complex applications	60-100

The method of data collection, monitoring and management for the upper level of the cyber-physical soil parameter determination system includes several main stages:

1) system initialization – configuration loading (reading settings parameters from the database or configuration file: data collection intervals, sensor types, monitoring parameters, alarm thresholds); connecting to mid-level controllers (checking communication with the mid-level (controllers) via Wi-Fi protocol, determining whether all sensors are correctly connected); checking the operability of sensors (initializing all sensors and checking their operability, checking whether the data is read correctly and whether there are no errors);

2) collecting data from sensors – sensor polling (the controller regularly polls the sensors at the lower level); data collection (sensors transmit their readings to the mid-level via Wi-Fi protocol); data quality checking (before transmitting data to the upper level, the system checks the correctness of the received values);

3) data processing at the mid-level – filtering and processing (the received data can be pre-processed at the mid-level); instant analysis (evaluating collected data to detect anomalies, such as high humidity or abnormal temperatures, and generating alerts for the upper level); transferring results to the upper level (data is transmitted to a central data collection system (upper level) for further processing);

4) monitoring and visualization at the upper level - data collection and storage (sensors transmit their readings to a server or central monitoring system; data is stored in a database for further analysis and reporting); visualization (graphs and charts are created on a web interface or mobile application to present data; the ability to view historical data and analyze trends over different periods); real-time monitoring (the upper level system provides real-time data display for users or operators, this can be displayed in the form of interactive panels or automatically updated interfaces);

5) analysis and decision-making – anomaly and threshold detection (based on the collected data, the system can apply algorithms to detect anomalies or thresholds, for example, when the soil temperature exceeds a given norm; if the parameters go beyond safe values, the system should send an alarm signal (warning via SMS, email or interface)); control algorithms (when the system detects that the parameters go beyond the norm, it can automatically trigger certain actions); support for decisions based on artificial intelligence (if necessary, the system can use machine learning or artificial intelligence algorithms to predict changes in parameters and recommendations for actions);

6) user interface – management (users can manually control the system via a web interface or mobile application, changing settings, thresholds and activating or deactivating certain devices; there may be integration with voice assistants); data analysis (the ability to create reports based on collected data, for example, to derive forecasts or resource planning; access to historical data to view changes and trends over time);

7) automated event response – automatic adjustment of parameters (if the system detects negative trends (for example, soil drying out), it can automatically activate the necessary devices (irrigation systems)); sending alerts (the system automatically sends messages (via SMS, email, or other channels) in case of critical events);

8) analysis and storage of results – after collecting and monitoring data, statistical and predictive analysis can be performed to improve the system's operation, as well as using historical data to determine the best operating conditions or improve the model.

The proposed method of data collection, monitoring and management for the top level of a cyber-physical system for determining soil parameters allows for effective data collection, monitoring and management in a cyber-physical system with various parameters stored in real time.

Conclusions

The relevance of a cyber-physical system for determining soil parameters in Ukraine is determined by several important factors, including climate change, declining soil fertility, and the need to implement efficient technologies to ensure sustainable agriculture. In Ukraine, where a large part of the economy depends on the agricultural sector, accurate soil monitoring is a key aspect to increase the efficiency of agricultural production, optimize the use of water and land resources, and reduce the cost of fertilizers and pesticides.

Cyber-physical systems can provide timely data collection on soil moisture, temperature, pH, and other critical soil parameters, allowing farmers to respond quickly to changes in environmental conditions. Such systems can reduce the negative impact of excessive irrigation and optimize the use of water resources, which is especially important in the face of drought, which is increasingly common in Ukraine due to climate change.

These systems also allow for accurate forecasts of yields and soil conditions, as well as the development of individualized recommendations for each field or plot. Since Ukraine has a wide variety of climatic conditions and soil types, cyber-physical systems are able to adapt to different agricultural needs, making them extremely useful for the development of precision agriculture.

The introduction of such technologies helps not only to preserve natural resources but also to improve the economic efficiency of agriculture. Therefore, the development and implementation of cyber-physical systems for soil monitoring is an extremely important step for the sustainable development of Ukraine's agricultural sector. Therefore, our research is devoted to the development of a method and a cyber-physical system for determining soil parameters.

The cyber-physical system for determining soil parameters consists of three levels: the level of sensors, the level of the controller to which the sensors are connected, and the system for collecting, monitoring, and managing data in real time. To build a cyber-physical system for determining soil parameters, we selected sensors, selected a controller, selected a data transmission standard, and developed a method for collecting, monitoring, and controlling data. The proposed method of data acquisition, monitoring and control for the upper level of the cyber-physical soil parameterization system allows for efficient data acquisition, monitoring and control in a cyber-physical system with various parameters stored in real time.

References

1. Marzouk I., Oberhollenzer S., Tschuchnigg F. An automated system for determining soil parameters: Case study. E3S Web of Conferences. 2024. Vol. 544. P. 04002.
2. A novel web based application for storing, managing and sharing geotechnical data, illustrated using the national soft soil field testing facility in Ballina, Australia / J. P. Doherty et al. Computers and Geotechnics. 2018. Vol. 93. P. 3–8.
3. Determination of fine-grained soil parameters using an automated system / I. Marzouk et al. Cone Penetration Testing 2022. London, 2022. P. 540–545.
4. Mayne P. W. Stress History of Soils from Cone Penetration Tests. Soils and Rocks. 2017. Vol. 40, no. 3. P. 203–216.
5. Robertson P. K. Cone penetration test (CPT)-based soil behaviour type (SBT) classification system – an update. Canadian Geotechnical Journal. 2016. Vol. 53, no. 12. P. 1910–1927.
6. Palágyi Š., Štamberg K., Vopálka D. A simplified approach to evaluation of column experiments as a tool for determination of radionuclide transport parameters in rock-groundwater or soil-groundwater systems. Journal of Radioanalytical and Nuclear Chemistry. 2015. Vol. 304, no. 2. P. 945–954.
7. Determination of SAR System Parameters Constraints from a Soil Moisture Retrieval Scheme / F. Grings et al. 2016 IEEE International Symposium on Geoscience and Remote Sensing, Denver, CO, USA, 31 July – 4 August 2016. 2016.
8. Uncertainty's Effects Assessment and the Relevant Parameters on Soil-Pipe Interaction (SPI) System Responses Using Sobol Sensitivity Analysis / C. Bacha et al. Periodica Polytechnica Civil Engineering. 2024.
9. Binh N. V., Duc T. T., Hoa H. T. T. Assessment of Soil Quality Parameters under Rice and Maize Cropping Systems in Hilly Region of Central Vietnam. Indian Journal Of Agricultural Research. 2024.
10. Valentina-Daniela B., Simona-Elena I., Ancuța P.-N. Advanced Autonomous System for Monitoring Soil Parameters. Technologies. 2025. Vol. 13, no. 1. P. 38.
11. Blessing S., Giering R., van der Tol C. OptiSAIL: a system for the simultaneous retrieval of soil, leaf, and canopy parameters and its application to Sentinel-3 Synergy (OLCI+SLSTR) top-of-canopy reflectances. Science of Remote Sensing. 2024. P. 100148.
12. Data set on soil physicochemical parameters, biomass accumulation and carbon credit generation in different management systems in Rio Verde, GO, Brazil / A. Thomazini et al. Data in Brief. 2024. P. 110682.
13. Sengar K. P., Chandrasekaran K. Grounding Systems Transient with Frequency Dependent Soil Parameters: A Time Domain Approach. 2024 IEEE 3rd International Conference on Electrical Power and Energy Systems (ICEPES), Bhopal, India, 21–22 June 2024. 2024. P. 1–6.
14. An IoT-Based System to Monitor Soil Parameter of Harumanis Tree / M. F. A. M. Zaini et al. Lecture Notes in Mechanical Engineering. Singapore, 2024. P. 241–255.
15. Perfection of an Energy-Economic and Environmental Parameters of the Ground Source Heat Pump Systems with Preventing Freezing of the Soil around Ground Pipes / A. Denysova et al. Problems of the Regional Energetics. 2024. No. 2(62). P. 107–120.
16. Moradi M. Comparison of Different Approaches for Incorporating Frequency Dependence of Soil Parameters in Time Domain Simulation of Grounding System. IEEE Transactions on Power Delivery. 2024. P. 1–13.
17. Temperature and Soil Parameter Monitoring System / P. U. Sharma et al. Recent Advances in Civil Engineering for Sustainable Communities. Singapore, 2024. P. 385–393.
18. Doan M.-T., Chen S.-S., Shi J.-Y. A Lumped-Parameter Model for Soil-Pile-Foundation Systems Undergoing Horizontal-Rotational Motions Based on Multiobjective Optimization. Lecture Notes in Civil Engineering. Singapore, 2023. P. 981–989.

19. Environmental and Soil Parameters for Germination of Leaf Spot Disease in the Groundnut Plant using IoT Enabled Sensor System / P. Garg et al. IEEE Sensors Letters. 2023. P. 1–4.
20. The effectiveness of the multi-soil-layering system in reducing pollutant parameters of crumb rubber industrial wastewater / S. R. P. Primandari et al. Teknomekanik. 2023. Vol. 6, no. 2. P. 122–135.
21. Soetedjo A., Hendriarianti E. Development of an IoT-Based SCADA System for Monitoring of Plant Leaf Temperature and Air and Soil Parameters. Applied Sciences. 2023. Vol. 13, no. 20. P. 11294.
22. The Effect of Reduced and Conventional Tillage Systems on Soil Aggregates and Organic Carbon Parameters of Different Soil Types / E. Tobiašová et al. Agriculture. 2023. Vol. 13, no. 4. P. 818.
23. AgriLink. Agricultural Knowledge: Linking farmers, advisors and researchers to boost innovation. URL: https://cordis.europa.eu/project/id/727577.
24. Make the smartest irrigation decisions with SoilSense. URL: https://soilsense.io/.
25. Sentek: Your soil moisture monitoring specialists for smarter irrigation. URL: https://sentektechnologies.com/.
26. SmartField Technologies. URL: https://smartfield.tech/.
27. FieldClimate: The robust and powerful platform for all your AG decision needs. URL: https://metos.global/en/fieldclimate/.
28. iSyst (Smart Soil Monitoring System). URL: https://isyst.de/en/.
29. Yaici W., Entchev E., Longo M. Internet of Things (IoT)-Based System for Smart Home Heating and Cooling Control. 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Prague, Czech Republic, 28 June – 1 July 2022. 2022.

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