Developing a smart cyber-physical system based on digital twins of plants

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***Abstract*— The paper proposes a multi-agent approach to development of "digital twins" of plants, which reflects phases of plant development and allows for more accurate forecasting of harvest and planning of agrotechnical measures. It also shows the possibility to formalize domain knowledge on new agro technologies for plant growing and automate decision-making processes when introducing precision farming technologies. A formalized model of the digital twin of plants is proposed in the form of a multi-agent state machine, acting on the basis of a knowledge graph of transitions between phases of plant development. Each stage (state) has its own software agent, which helps respond to unforeseen events and recalculate predicted harvest and risks of problem situations. Recommendations developed by the digital twin are to be further sent to smart cyber-physical precision farming management system for adaptive rescheduling of resources and differentiated use of fertilizers and crop protection tools. The developed approach becomes valuable in growing uncertainty because of global climate changes, destroying agronomist domain knowledge collected over centuries.**

Keywords—Cyber-physical system, digital twin, multi-agent system, ontology, knowledge base, decision making, precision farming

I. Introduction

One of the main tasks of modern agriculture during transition to sustainable development is introduction of modern precision farming technologies based on minimal and differentiated tillage systems and direct sowing of cultures in crop rotation, the use of combined tillage machines, taking into account changes in agro-climatic and soil conditions, material and technical resources of farms, the use of effective means of protecting crops from weeds, pests, diseases, etc. [1].

At the same time, introduction of precision farming in many countries faces serious difficulties: high cost of precision farming technology, lack of qualified personnel with knowledge in agronomy, means of communication, software systems, etc. Another challenge is global climate change that is affecting crop rotation, agro-technology, etc. At the same time, the key problem for modern precision farming is enterprise management, which is very much dependent on knowledge and competencies of agronomists.

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To solve these problems, integrate advanced technologies and support transition of modern crop production enterprises to precision farming, we propose a smart cyber-physical system (SCPS) combining capabilities of cyber-physical systems (data collection, processing, and managing precision machinery) with capabilities of smart decision-support systems with knowledge bases and digital twins of plants.

The first chapter of the paper discusses the need for widespread introduction of precision farming technologies. The second chapter provides problem statement for developing a smart cyber-physical system based on a model of plant development. The third chapter gives definitions of SCPS and digital twins of plants. The fourth chapter provides an overview of existing approaches to development of digital twins and proposes a new approach with ontological models and multi-agent systems. The fifth chapter discusses development of digital twins of plants as a smart system implemented on the basis of a knowledge base and multi-agent technology. The sixth chapter provides the main results of SCPS development and initial implementation stages. Conclusions cover prospects for system development.

II. Problem Statement

Crop production is a complex multi-domain field of knowledge dealing with living objects. Its operation principles are still not fully understood. Decision making on crop cultivation requires knowledge in chemistry and physics, biology of plants and insects, technology, agronomy, etc. Theoretical and practical knowledge in crop production has been accumulating for centuries, from both scientific research and everyday practice and experience. Even now this knowledge exists mainly in the form of "cases" or "precedents". Each agronomist builds his own knowledge base and causal models of plant development, integrating information from various sources.

However, recently, ongoing global climate change has been destroying this long-established sustainable knowledge system. Thus, in the Samara region (Russia) over a 110-year observation period (1904-2013), the average annual air temperature has increased by 1.787°C, with the largest temperature increase during winter months (December-February – by 2.976°C). An increase in the average annual precipitation (by 9.8%) has also been recognized mainly within the winter period. Besides, there has been redistribution of rainfall over spring and summer months. Thus, in May, the amount of precipitation over 22 years (1992-2013), compared with the beginning of the last century, has decreased by 21.5%, and in August - by 14.9%. The most favorable conditions for growth and development of crops have now shaped in June and July [2].

In Russia, in 2019, for the first time ever, the main volume of sunflower was produced not by the southern regions that traditionally cultivated it, but by the northern ones that significantly changed their business. Ongoing climate changes are leading to the need of reviewing crop cultivation technologies, structure of sown areas, sowing dates, selected crop varieties, protection from pests, diseases and weeds, techniques of fertilizing and land reclamation.

In connection with the emerging new challenges of global climate change, it is proposed to create computational models of plant development which would be accurate up to individual phases of plants. Thus, for example, more than 100 phases (microstages) are now distinguished for wheat [3]. Such a description is required in order to run detailed monitoring and control of plant development and to be able to develop suitable actions ahead of time when it is still possible to influence the plant, and not when it is too late to intervene and the crop is partially or completely lost.

It is not yet possible to manage precision farming enterprises with only one system, taking into account the use of technologies, machinery and equipment, knowledge about plant growth, analysis of images from UAVs and satellites, and predicting the impact of activities on crop yield online.

Development of smart cyber-physical systems that connect modern precision farming technologies with decision-making by agronomists based on formalized knowledge on plant development and real data in microstages can help overcome the above problems.

III. Digital Twins of Plants for Precision Farming

Cyber-Physical System (CPS) is a computer system integrating tools for receiving data from sensors, performing calculations and controlling processes using actuators and communication tools [4]. Thus, CPS are developing traditional automated systems through integration of computing, communication and physical capabilities to increase adaptability, flexibility and reconfigurability.

By “smart cyber-physical system” (SCPS) we mean combination of CPS functions with those of a smart system for implementing object management in real time. The quality and efficiency of decisions depend on the very moment of time. A digital twin (DT) of a physical object is a set of its virtual (digital) computer models and related processes and/or services, integrated with automated systems to implement control functions, simulate object behavior [5].

There is a number of definitions of digital twins, but not many of them consider the plant as a living organism - complex adaptive system operating as a whole but consisting of autonomous parts with continuous interactions. In contrast with deterministic technical systems in industry, plant models need to be designed as self-organized systems adaptively evolving in time under changing conditions.

In crop production, however, there are no adequate models of plant development yet – it is a too complex process. Moreover, in some cases there is lack of deep understanding of ongoing processes. Thus, proposed model of plants has to be open for researchers and practitioners.

By digital twin (DT) of plants we mean a computer model that imitates its life cycle and synchronizes with the living plant using examinations by agronomists and data on environmental conditions (weather, soil, etc.). Plant DTs can use actual data, mathematical or simulation models, machine learning models, and any other methods that can predict plant behavior under various conditions. The Smart Plant Digital Twin (SPDT) is a smart computer system with a knowledge base and methods of reasoning. SPDT is also developed for online management and modeling of plant behavior in sync with development of the real plant.

Compared to smart management systems already available on the market for machine-building production [6], where planning is based on a rigorous, tried-and-true technological process, in crop production it is very difficult to plan work - there is too much complexity, uncertainty and dynamics caused not so much by poorly predictable weather changes, but by significant lack of knowledge on biological, chemical, and physical processes in plants and soils [7].

However, systems that are close to the concept of CPS and DTs, but have limited functional properties, are already used in crop management systems [8]. OpenPD (Espirial Pixel, Portugal) [9] has developed a mobile application that provides rapid identification of pests and plant diseases based on the digital twin formed from photographs and descriptions of affected plants. However, again, there is no way to simulate development of plants with various diseases.

The paper [10] describes the architecture of Agricultural Cyber Physical Systems (ACPS), consisting of four elements: sensors and receiving nodes, the network, control center and the farm with agricultural objects that serve as digital twins. ACPS application is studied, in particular, in crop growth monitoring for disease prevention and harvest management. However, plant models represent only the current state and are not applicable for any simulations.

Information on plant growth and development and deviations from the norm, implemented by DTs, supplements environmental information (temperature, precipitation, humidity, etc.), and can be the “golden thread” for making decisions on managing enterprises of precision farming [11].

IV. Brief Overview of Existing Approaches to Creating Digital Twins of Plants in Crop Production

Currently, there are multiple studies of various approaches aimed at development of digital twins of plants.

A. DTs based on systems of mathematical equations

One of the approaches to creating digital twins of plants is based on a mathematical model with a set of variables (dry weight, humidity, temperature, soil content of nitrogen, carbon, potassium, phosphorus, other elements, and similar parameters), describing characteristics of plants and their growth environment. For these variables, a system of mathematical equations is compiled, forming a probabilistic forecast using a terrain map obtained from Earth remote sensing (ERS) and drones. Based on analysis of data on yield and soil collected by agronomists over the past years, as well as meteorological data, a reliable forecast is obtained about the best dates for planting different crops [12].

However, these models have a problem - the accuracy of the most general mathematical description. Creation of plant DTs is characterized by a high degree of uncertainty and environmental variability. A change in microstages also changes the plant model, i.e. requires a system of equation systems and linking microtages with each other.

B. DTs based on neural network models and machine learning

A promising approach in DT development is the use of neural networks for predicting crop yield. Data from ERS or drone monitoring and weather data is analyzed. Plant characteristics (for example, amount of fertilizer or water) and field condition in different areas are determined by contour photos, which serve as samples for deep training of convolutional neural networks. Then recommendations are developed for performing agronomic operations [13].

However, neural network models have significant drawbacks, such as a lengthy training procedure and the need for constant re-training in conditions of uncertainty and dynamics. It reduces adaptability. Although, the model of plant development is synchronized with growth and development of real plants, it is still limited to the obtained image. Whereas agronomists take samples and evaluate development of root system and other plant parameters.

In CPS for agriculture, training algorithms with reinforcement [14] and cloud-based machine learning algorithms [15] are already used today. Processing the data from each season makes it possible to more and more accurately assess the yield for the next year at the beginning of the season - however, only provided that climatic conditions, characteristics of plants or their cultivation technologies do not change, which is, of course, impossible.

C. DTs based on ontological multi-agent models

Analysis of the developed systems and approaches leads to the following conclusions: digital twins of plants currently have limited functional capabilities and are just in the beginning of development; they do not provide smart decision support at all stages of the crop growing cycle; accuracy of forecasts significantly depends on the adequacy of models of plant growth and development; reviewed agricultural CPS provide data, but do not contain knowledge bases which are required for smart decision-making support.

Previously, there have been no suitable tools for working with “heterogeneous” information of precision farming. However, now Semantic Web models, methods, and tools can represent and use this kind of knowledge. In this regard, it seems appropriate to build models of the “norm” of plant growth and development using ontologies as semantic networks, in combination with multi-agent technology [16].

This approach creates, on the basis of ontologies, a semantic graph of transitions between plant phases, at least specifying the initial conditions of each phase, rules for transition to another phase, required resources and output results. The plant agent should read the state graph from the knowledge base, become a representative of this plant in the given field and interpret the graph when specified conditions occur. For example, for germination of grain, a total of 100 degrees must be accumulated. The base plant agent can consist of state agents that adaptively recalculate their parameters and model the result when new event occurs.

In this regard, each plant can be represented as a complex adaptive system, built on the basis of multi-agent technology, customizable through ontology [17]. Such models of plant DTs could later become the foundation of the knowledge base for replenishment and modification at the end of each season through big data and machine learning technologies for extracting new knowledge and calibrating plant model.

V. MULTI-AGENT APPROACH TO DESIGNING SCPS BASED ON DIGITAL TWINS OF PLANTS

Let us consider construction of plant DTs as a smart system with knowledge base and multi-agent technology.

A. SCPS Architecture

The architecture of a smart cyber-physical system based on digital twins of plants is shown in Fig. 1.

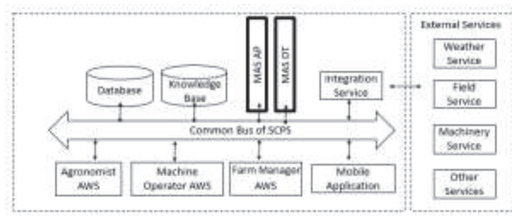

Fig. 1. SCPS Architecture.

The main modules of SCPS include:

- The digital plant twin module (MAS DT) is designed to create an instance (clone) of a digital plant model for each of the farm fields.
- The module for adaptive planning of automated agricultural machinery (MAS AP) is intended for managing precision farming machinery using signals from plant DTs, forming a plan and route, and further monitoring their implementation.
- User interaction modules are designed to support decision making by agronomists, machine operators, managers and knowledge engineers.
- Data warehouse - contains data on fields and technological maps, crop rotation plan, machinery and personnel, ontologies, data models and scenes.
- Integration components - allow users to connect SCPS with precision farming machinery: load plans and routes, application maps for fertilizers, and receive data on the actual route and its parameters.
- The basic platform of the enterprise - contains services that are required for SCPS implementation.

In its turn, the digital plant twin module includes:

- The knowledge base –to support decision-making on plant development plan and includes knowledge on plants, their varieties, conditions and rules for changing microstages as the domain ontology.
- A plant DT service based on multi-agent technology for planning phases of plant development, in which

each stage has its own software agent that recalculates its state according to events.

The service for managing machinery includes:

- The knowledge base –to support decision-making on operations for machinery and personnel, including knowledge on plant cultivation technologies, field and farm infrastructure.
- The service for planning operations based on multi-agent technology, developing software agents for tractors, fields and employees. It helps users to more accurately specify operations, taking into account agrotechnical conditions, set machinery routes and reschedule machinery according to DT signals.
- The service for monitoring plan execution – controls implementation of plans and routes, identifies problems and informs farm specialists about them.

B. *Development of the Knowledge Base of Digital Twins*

Development of the knowledge base for digital twins consists of the following steps:

1. Creating an ontology of plant development describing classes of basic concepts and relations used for plant growth phases. To develop effective methods of mineral nutrition of plants, scales are used to rank and identify stages of organogenesis, taking into account morphological features of crop development. For example, The Zadok's scale is based on ten principal growth stages. Each of them is divided into 10 secondary stages, extending the scale from 00 to 99 [3].

2. Ontology describes the main controlled and uncontrolled factors affecting plants and yield – climatic factors: air temperature, precipitation, solar radiation (for example, in the Samara region it is enough even for 90 c/ha, in England it is not enough for 60 c/ha); soil (nitrogen, phosphorus, potassium, etc.); plant variety; agrotechnical measures (predecessors, sowing depth, soil cultivation technology, protection products from weeds, pests, diseases); plant structure (grain, root, stem, spike, leaf, others), functioning and interaction of organs with the environment.

3. Using the terms of ontology as an “explanatory dictionary”, a state graph of each plant variety is built. Fig. 2 shows a fragment of the state graph representing the first two phases of wheat development according to Zadok's growth scale – description of the “norm” (ideal case) as a graph of states and transitions for relations of phases with each other; detailed specification of each phase (conditions for phase onset, its duration, requirements of the plant in the current state for its transition to the next state, rules for transition, output results, variations in plant development at the given, previous and subsequent phases); description of possible deviations from the “norm” in case of weather or soil anomalies; managerial actions to achieve the required yield or return the plant to the “norm” (or lack of action when nothing can be changed and it is useless to further waste resources); economy of decisions (the model should be based on economic feasibility, and not just high crop productivity).

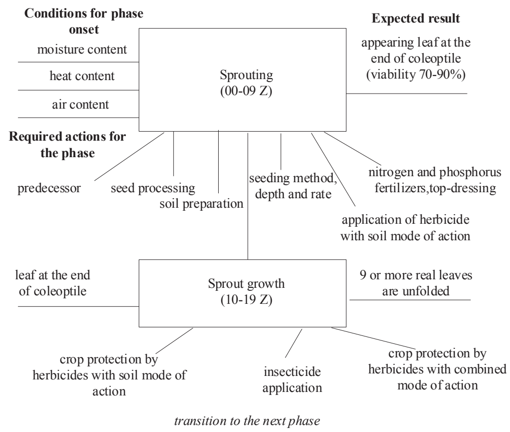

Fig. 2. A fragment of the state graph of the digital twin of wheat.

4. Ontology and descriptions of state graphs of different plant varieties forms a public free knowledge base for the plants processed by the enterprise (region).

5. Each enterprise (agronomist) can adjust the public free state graph and create its own modified state graph, offered at an affordable price with royalty to the author.

6. Certain percent of such sales will be used for development of the free knowledge base for regional plants.

Ontology of plant DTs includes several levels. The first and the most abstract level (metaontology) uses concepts defined in RDFS and OWL standards [16]. Next is a unified basic planning ontology, configured at the following levels to support planning of transition through the state graph. The specialized domain ontology contains concepts, classes, relations, and attributes for describing crop production. Ontological model of a specific agricultural enterprise allows users to configure the DT model according to the state graph of crop (for example, wheat). Fig. 3 shows the plant-growing ontology represented as a semantic network. In the future, ontology of plant DTs will be connected with well-known more general agricultural ontologies, such as Planteome [18].

Fig. 3. Plant-growing ontology represented as a semantic network.

Ontology editor has been developed to ensure the possibility of accessing the knowledge base and editing it directly by end users (employees of agricultural enterprises), so that they can replenish it with new knowledge (Fig. 4).

Fig. 4. The interface for editing descriptions in the knowledge base.

C. Development of an Agent of SCPS

The next step, after developing the knowledge base, is to create a class of plant agents, which should be capable of: finding a suitable state graph in the knowledge base and downloading it; generating agents of each state, which will be interconnected through consequence relation; interacting with agents of agronomists, soil and others; re-evaluating and reforecasting the possible yield and risks (damage) in case of significant events; deleting themselves and sending all information about plant development to the knowledge base.

The plant agent is created for each field and in the future for each of its sections. State agents are responsible for execution of each phase, receiving its description from the knowledge base. When something changes, the state agent reports it to the next state agent, which immediately recalculates its parameters. Fig. 5 and Table I show the protocol of interaction and data exchange between services of digital twins and machinery adaptive planning.

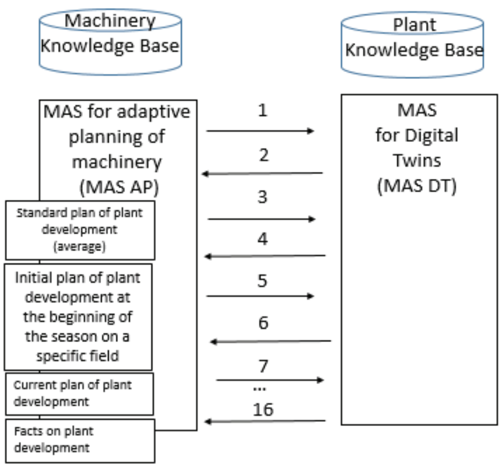

Fig. 5. Protocol for interaction of DT services and adaptive planning.

TABLE I. INTERACTION PROTOCOL FOR MAS AP AND MAS DT

#	Operations
1	MAS AP states the crop culture and expected sowing date for each field based on the averaged seasonally information.
2	MAS DT creates DT agents for different fields, which connect to weather services and field parameters to produce the best sowing date.
3	MAS AP reports on the planned dates for the start of sowing, taking into account available machinery and other resources.
4	MAS DT confirms receipt of a new date, which may differ from the desired due to lack of machinery.
5	MAS AP informs MAS DT about the facts of sowing in order to start planning plant growth.
6	MAS DT starts the countdown of the initial phase of plant development (T0) in the fields where sowing is finished and reports the expected completion date of the first phase.
7	MAS AP plans when agronomists should visit the fields for visual inspection of plants and identification of deviations from the plan.
8	MAS DT receives data on plant parameters and recalculates the plan so that MAS AP can accordingly re-construct its plans.
9	MAS AP plans a new agronomist visit to control the onset of the phase and enter plant data.
10	MAS DT, based on weather data, recalculates the forecast of its phase and informs MAS AP that the dates have changed.
11	MAS AP changes the dates for inspection of those field that are behind or ahead of development plans.
12	MAS DT shows visual growth of plants within certain intervals. The agronomist observes dialogs of MAS AP and MAS DT, sees where the plants are behind or ahead of their growth plan and decides whether to introduce growth stimulator or plant nutrition.
13	The agronomist makes a "virtual request" to MAS DT for modeling: what happens if we add growth stimulator on day X?
14	MAS DT creates its copy to simulate the new situation, returning the answer to MAS AP.
15	If assessment of the answer is positive, the agronomist starts real planning of machinery for introducing the growth stimulator.
16	MAS DT confirms the date and starts calculating development phases, etc. according to the new program.

Based on detected deviation from the norm, plant agent asks agronomist agent for possible solutions of the problem. Agronomist agent issues recommendations based on its knowledge. Recommendations are then sent to SCPS. Fig. 6 shows interaction of DT agent with user in mobile application.

Fig. 6. Interaction of DT agent with the user.

Agronomists can see a map of all fields of the enterprise, select one field to assess its condition, obtain indicators of this field, as well as information about existing problems, appoint equipment and performers for agricultural activities. The digital twin of plant complements this SCPS to provide better quality and efficiency of decisions for farmers.

VI. Results and discussion

The paper covers modern general approaches to creation of DTs in agriculture. A number of computer tools (data from sensors, images from ERS or UAVs, etc.) can already be used to synchronize DTs with real plants, but not all of them provide complete and reliable data. This is due to complexity of creating models, the need to use and integrate multi-subject data, lack of appropriate sensors, etc.

Analysis of various approaches to creating plant DTs has shown that models based on systems of mathematical equations have low accuracy in mathematical description of plants. Besides, deep learning models of convolutional neural networks and machine learning methods based on big data have low adaptability. Thus, conceptual model of DTs based on ontologies and multi-agent technology has been selected as the most promising, with the following advantages: knowledge base with a domain-specific ontology and semantic network to support planning of agricultural operations and making decisions; effective support of distributed activity of heterogeneous resources based on group cyber-physical management (platform, communications, network interaction, knowledge base); monitoring of problem situations, informing users in real time via mobile devices.

The paper proposes ontological formalization of stages of wheat development with description of transition rules, taking into account soil composition, weather conditions, etc. and gives examples of knowledge subject to formalization.

To synchronize DTs with real plants, a protocol for interaction of DTs and adaptive planning services is proposed. The paper also shows the possibility of cloning the plant DT for each field or even its sections for more accurate growth tracking and forecasting based on data on accumulation of positive temperature, moisture at a given horizon, etc.

Currently, SCPS with plant DTs has been launched in Peschanokopskaya Agrarian Group (Rostov Region). It has over 30 thousand hectares of fields and keeps its own financial statements. Topcon equipment is the technical base for precision farming management system. It is planned to create a single Center for managing crops, machinery and equipment, including means of monitoring through regular field surveying by UAVs. Hardware (server, workstations) will also be available. Base stations are located so as to ensure maximum coverage with Real-time Kinematic radio signal by a minimum number of installations.

VII. Conclusions

The paper proposes a multi-agent approach to development of digital twins of plants, which reflects phases of plant development and allows for more accurate forecasting of yield and planning of agrotechnical measures. It also shows the possibility to formalize domain knowledge on new agro technologies for plant growing and automating decision-making processes in precision farming.

Digital twins help simulate plant growth and provide real-time forecast. In conditions of global climate change, they help accumulate invaluable agronomic experience and take into account new realities. Continuous monitoring of plant phases allows for timely identification of deviations from the norm and developing recommendations to reduce risks and damage from weather changes or mistakes of specialists. Modeling helps predict yield and evaluate the possible effect of agricultural activities. This gives agronomists a new opportunity to materialize and commercialize their knowledge and experience, expanding the paid-for part of knowledge base.

At the moment, conceptual model of plant is developed for the first computational experiments. The next step is to provide open access to knowledge base for researchers and practitioners in different areas of wheat farming.

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