Multi-agent approach for developing a digital twin of wheat

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***Abstract*—The paper is devoted to development of a digital twin (DT) of plant. It is built as a smart system based on the knowledge base on macrostages of plant development and multi-agent technology that allows for detailed monitoring and control of plant development, recalculation of forecast, namely, assessment of vegetation quality, future yield and timing for onset of next stages. It uses transition rules between stages upon receipt of data from agronomists on the state of plant development, as well as the actual and forecast weather data. The paper proposes a conceptual plant model based on ontologies and multi-agent technology, which is a network of linked states and transition rules that correspond to macrostages of plant development with the possibility of recalculating their parameters. The paper also covers the main principles of agronomist work with the digital twin of plant.**

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

I. Introduction

Nowadays, precision farming is gaining more and more application in crop production, involving detailed electronic field maps, accurate seed sowing, differential application of fertilizers and plant protection products (PPP), etc. Sensors of weather, agrochemical state of soil and daily-taken hyperspectral field images are now the everyday practice of farmers [1].

The very nearest future will bring integration of sensors and executing devices, computing and communication tools in order to create cyber-physical systems for managing plant growth. Together with the knowledge base on crop production and decision-making support tools, these systems are becoming smart cyber-physical systems (SCPS) applicable for more and more autonomous management of various resources of crop production in real time.

However, the truly intelligent SCPS requires a model of controlled plant, which can be used for computational experiments, what-if games and prediction for decision-making support.

This paper proposes an approach to creating a digital twin of wheat based on knowledge bases and multi-agent technologies for modeling wheat cultivation. The first chapter of the paper briefly discusses the need to develop cyber-physical systems for agricultural enterprise management. The second chapter provides problem statement for creating a model of control object, i.e. digital twin of plant, which will determine the entire cycle of plant growth and development, as well as production plan for the enterprise. The third 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 fourth chapter describes a multi-agent system for planning and modeling plant development, which is the main part of the digital twin of plant. The fifth chapter discusses development of ontology and knowledge base of plant development stages, which are the basis for the digital twin. The sixth chapter discusses the protocol of interaction between agronomist and the digital twin of plant. Conclusions describe advantages of using ontologies and multi-agent technology for developing a digital twin of plant, as well as outline directions for further development of research.

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II. PROBLEM STATEMENT

The computational model of plant can be designed as the digital twin of plant, mirroring its development phases in real time and making forecast of its development. Defined in such a way, the digital twin of plant is becoming the central element of precision farming - modern resource-saving technologies in agriculture [2]. Precision farming considers every field as a number of individual sections with values of topography, fertility, plant composition and other characteristics. In accordance with the data collected and processed at each of these sections, strictly defined and justified agrotechnological measures of crop growing are applied.

Digital twin is a new concept that has appeared with development of cyber-physical systems in industry, primarily integrating sensors, computing capacities, communication tools and executors in one system to support the whole product life cycle.

A digital twin of plant is a software package that simulates development of an average instance of plant variety under certain conditions by computational means.

The goal of creating a digital twin is to obtain digital value of plant response to an agrotechnological measure in order to evaluate its effectiveness.

The digital twin of plant is designed to solve the following problems:

- Help conduct continuous monitoring and control of the plant development process at each phase;
- Improve the accuracy of yield forecast through its adaptive recalculation taking into account the likelihood of risks of its loss, as well as the extent of damage at each phase;
- Develop recommendations on corrective agricultural measures on time;

Model the impact of agricultural activities (prior to their actual implementation).

Expected result of the use of digital twin of plant is higher validity, speed and flexibility in decision-making in case of any deviations: weather anomalies (rain, drought, heat or ground frost), non-sowing of seeds, pests or diseases, excess or lack of fertilizers, etc.

High relevance and significance of the task is determined by global climate change across the planet, when the theoretical and practical developments (including folk “weather wisdom”) developed over the centuries are no longer valid.

The task of modeling plant growth and development is a complex poly-subject problem requiring deep understanding and integration of knowledge of various scientific disciplines: from physics, chemistry and biology - to soil science, plant physiology, agronomy, etc.

The currently known approaches based on systems of algebraic or differential equations, as well as machine learning methods, are not suitable for solving this problem. They do not account for the many stages of plant development where all the system parameters change discretely, or solve narrow classes of pattern recognition problems, without explaining the cause-and-effect relationship.

III. STATE OF THE ART

As defined by the Technical Consultancy Group (TCG) IBM UK: “A digital twin is a dynamic virtual representation of a physical object or system, usually across multiple stages of its lifecycle. It uses real-world data, simulation or machine learning models, combined with data analysis, to enable understanding, learning, and reasoning. Digital twins can be used to answer what-if questions and should be able to present the insights in an intuitive way” [3].

In agriculture, modern cyber-physical systems are based on the Internet of Things (IoT), and data from field sensors and satellite monitoring are sent to make computations and generate actions and recommendations. Developing this approach, one can imagine a system in which a digital twin “grows” every day and constantly receives data on development of the real plant to assess deviations from the “norm” indicated in the knowledge base and develop recommendations for implementation of agricultural measures.

Systems with limited functional properties, which are quite close to DT concept, are already used in crop management systems.

The company OpenPD (Espirial Pixel, Portugal) [4] has developed a mobile application that provides an operational system for 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.

OLIFLY (HarphaSea, Slovenia) [5] developed the OLIFLY application, which allows farmers to track growth and dynamics of the population of olive flies (pests of olive trees) on their farm using a phone or web page. The cameras display a pest trap and transmit information in real time over the Internet using a digital trap twin. Images are of sufficient quality to identify and distinguish olive flies from other species. Thus, it is possible to quickly respond to the growing population of olive flies, which leads to optimal and efficient use of pesticides in order to minimize damage and preserve the quality of olives, as well as save farmers’ time and money.

[6] describes the use of digital twins for farm water management within the Smart Water Management Platform, which is running under the Internet of Things (IoT). The digital twin is applied to determine soil moisture in fields using a soil probe and obtain weather forecast data from a weather station.

The work on modeling the morphological model of wheat roots and realistic visualization of root growth in various soil conditions deserves special mention. In that project, based on the topology of wheat root system, historical and experimental data, a morphological model of wheat root has been preliminarily developed, including submodels of appearance of roots and the rate of root growth. Based on technology of 3D visualization, a model for visualizing the root axis of wheat has been developed using the Visual C + (. Net) platform and the OpenGL library [7].

Analysis of these systems leads to the following conclusions:

- digital twins of plants currently have limited functional capabilities and are just at the start of development;
- developed machine learning methods do not explain the conceptual model of plant development and become weak under climate change;
- existing digital twins do not provide smart decision support at all stages of the crop growing cycle;
- adequate analytical models of plant growth and development, given in the form of systems of differential or algebraic equations that could be solved with various initial data, are not known today;
- accuracy of forecasts formed on the basis of digital twins, significantly depends on the adequacy of models of plant growth and development used in them;
- reviewed agricultural CPS provide data, but do not contain knowledge bases which are required for intelligent decision-making support.

It is important to create fundamentally new multi-agent models of plant behavior based on poly-subject knowledge from various disciplines that can explain and model plant behavior depending on various factors [8].

IV. MULTI-AGENT SYSTEM FOR PLANING AND MODELING PLANT DEVELOPMENT

To build a digital twin of plant, we can assume that the plant acts according to a cycle of autonomous behavior (like the Deming cycle) inherent in any living organism: reaction to an event, decision-making, planning actions based on available resources, executing the plan, comparing expected and observed results, development of corrective actions.

This principle is laid down in creation of the "Plant Stage Agent" - autonomous software that implements the indicated cycle of autonomous functioning and is responsible for making decisions at each stage of plant development, which will work in conjunction with the real plant.

In the course of its work, the plant stage agent (of wheat as the base culture) analyzes input events and adaptively reconstructs the calculated and forecasted stage-by-stage plant development plan for all stages.

This plan provides the possibility to adjust assessment (forecast) of crop yield for each event for programming of crop yield, i.e. timely development of measures for influencing the plant, for example, choosing time points for fertilizing and volumes of introduced substances.

The general structure of the digital twin of plant (wheat) is shown in Figure 1.

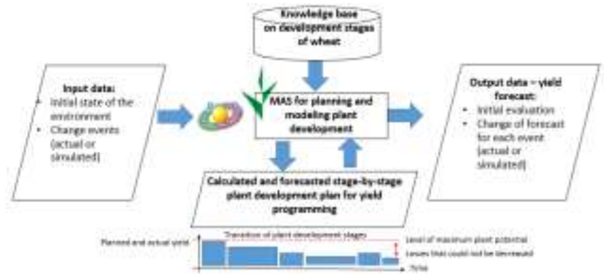

Fig. 1. The general structure of the digital twin of plant.

The general structure of the Digital Twin of plant (wheat) includes the following:

1) Input data:

- initial information on the climate of the region, current weather and weather forecasts, information on soil composition, plant variety, environment, etc.;
- change events: weather changes, attack of harmful insects, fertilizing, etc.

2) The knowledge base on stages of plant development and the surrounding world:

- contains information on the climate, soils, organ structure and phases of plant development, as well as other data for decision-making.

3) Multi-agent system for planning and modeling plant development:

- provides a response to events, planning and re-planning of plant development stages, compares the planned and expected results at each phase, and produces corrective actions. It operates on the basis of a knowledge base, in which it finds all the features of development phases of a particular plant variety. As a result of the agent's work at each step (for each event), the plan for development of plant phases is adjusted. Thus, it is possible to evaluate the predicted yield.

4) Forecasted stage-by-stage plan of plant development:

- structure of intermediate operational data, containing the current plan for development of plant phases and adapted for the latest event. Can be further used for crop programming, i.e. development of corrective actions (fertilizing, etc.).

5) Output:

- initial forecast for plant yield;
- changes in the forecast caused by emerging events.

Multi-agent system for planning and modeling plant development will be built based on agents of plant development stages. For wheat, 100 development phases are known on the Zadoks scale [9].

The knowledge base about stages of plant development contains a state graph (SG) corresponding to the stage of plant growth and development.

The plant stage agent must be able to:

- find the SG of its plant variety in the knowledge base and load it from there;
- generate agents of each state of plant development, linked through succession relation;
- interact with agents of agronomist, soil and others;
- re-evaluate and re-forecast the potential yield and risks (damage) for each event;
- delete itself, sending all the information about plant development on the field to the knowledge base.

The agent of plant development stage will be created for each SG state from the knowledge base. This agent is responsible for execution of each stage. Its description is received from the knowledge base. When something has changed, the state agent reports this to the next state agent, which immediately recalculates its parameters.

If you submit a "virtual" event to the input of the digital twin, an impulse will run through the network (chain) of agents and they will recalculate their states in order to show what will happen to the plant under the given conditions (what will be the yield, by what date, etc.).

The agent of plant stage is created for each field, and in the future, with development of precision farming, even for each of its sections.

When creating a plant DT, each agent is responsible for a separate plant state corresponding to the macrostage (Figure 2). Here, each state (macrostage) is described by onset conditions (input data), transition rules, and result (output data).

As a result, plant development is represented by a network of connected "state machines", a change in one of which immediately leads to recalculation of the dependent ones. For example, as soon as the total temperature is 100° C, the seed begins to germinate in the plant DT and the coleoptile appears. Plant DT builds a plan and forecast, developing solutions for each stage and passing the result to the next stage agent.

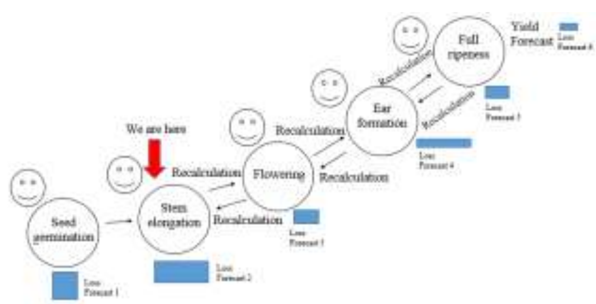

Fig. 2. Agents of macrostages of wheat development.

At the same time, a signal about a change in weather or soil composition can appear at any time for any stage. In this case, not only the current stage will be recalculated, but also the forecast of its output will be transmitted to the next stage input, etc. However, if according to the plant forecast there may not be enough resources, the decision to move to the next stage can be adaptively redefined back.

Information about growth and development of plants and their deviation from the norm, implemented by the plant DT, will supplement information on the environment, including temperature, precipitation, humidity, etc., and will become the basis for decision-making on management of precision farming enterprises.

V. Building Ontology and Knowledge Base for Description of Plant Development Stages

The plant DT is represented by a conceptual (ontological) model in the form of a graph of states and transitions between stages. Each macrostage corresponds to a software agent that continuously checks conditions for stage onset, based on expert knowledge, determines its date and duration, and recalculates its output parameters, including yield (followed by a wave of recalculations throughout the whole chain).

Ontology is built as a semantic network of base classes of concepts and relations of the domain area. It acts as an "explanatory dictionary" for agents [10]. Ontology gives us the possibility to take a step towards digitalization of knowledge, moving from manuals and reference books, which so far cannot be understood by computers, to the format convenient for computer processing.

For the digital twin, it is necessary to describe ontology of plant development, including classes of base concepts and relations used for phases of plant growth and development (approximately 100 phases for wheat).

A fragment of ontology of plant DT is shown in Figure 3.

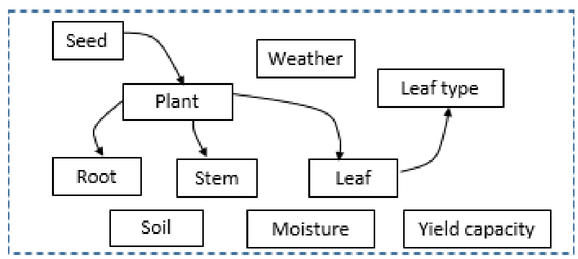

Fig. 3. A fragment of ontology of digital twin of plant.

Based on concepts and relations, various decision-making rules can be built for agents.

Here are some examples of rules for transition from state to state:

If (control point X1)

and (macrostage = Germination 00-09)

and (total temperature=100° C) and (total moisture=....)

and (emergence of germinal root from the kernel)

and (appearance of coleoptile on the soil surface)

and (appearance of leaf at the end of the coleoptile),

then (transition to macrostage = Seedling growth 10-19)

and (control point after X2 days).

A "State Graph" is built in ontology terms for each plant variety and each state (macrostage). It reflects the following:

- initial conditions of each state;
- the needs of the plant in its current state for transition to the next state;
- rules for transition to the new state;
- duration of each phase;
- next condition;
- work results for each phase.

Ontology and descriptions of state graphs of different plant varieties form a publicly available free knowledge base of plants processed in a certain enterprise or region. Each enterprise (agronomist) can adjust and modify the publicly available free state graph, creating his own modified SG of plant variety.

VI. Interaction of Agronomist and Plant Digital Twin

Agronomists work with the digital twin of plant in the following way:

1. Agronomists form ontology and knowledge base of plant development;
2. The knowledge base contains state graphs of the norm for plant growth;
3. The plant agent operates on the basis of the loadable state graph of the "norm" in plant development.
4. An instance of the plant agent is created for each field;
5. The plant stage agent is represented both by agents of parts and agents of states;
6. The state agents "mirror" the states of real plants;
7. Each state agent gets data from sensors or asks the agronomist for confirmation;
8. Agent of plant stage recalculates the yield forecast with the view on new data;
9. It narrows down uncertainty and evaluates losses from the maximum yield;
10. Then it generates recommendations on mitigating risks of damage;
11. And simulates their impact (up to actual execution);
12. During the season, the plant agent generates big data with the "fact", analysis of which can adjust the "norm" in the knowledge base.

For coordinated decision making, special protocols are developed for phase agents (Figure 4).

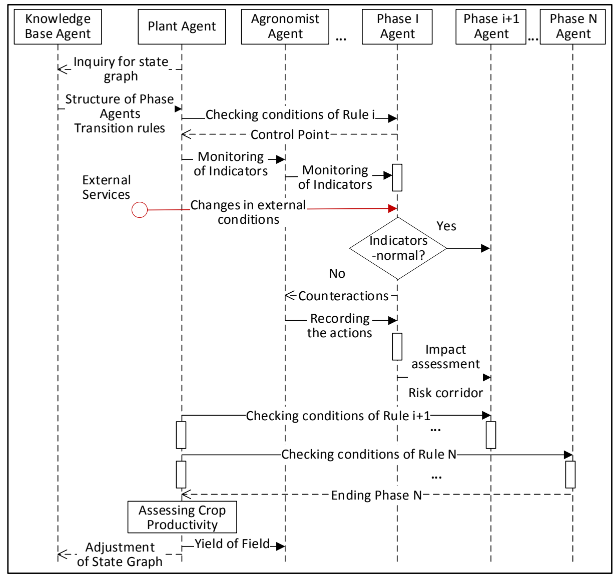

Fig. 4. Interaction protocols of phase agents in DT of wheat.

Interaction of DT agent with agronomist via mobile phone is shown in Figure 5.

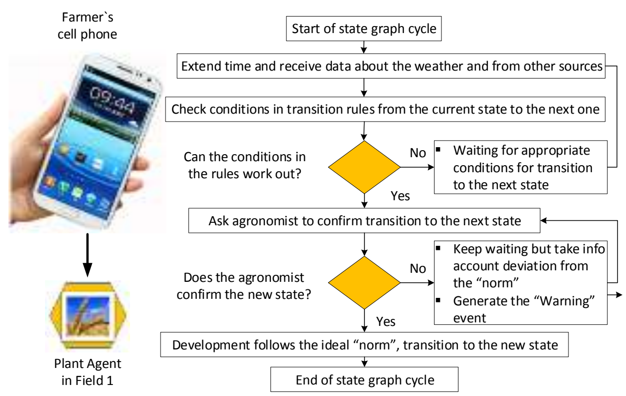

Fig. 5. Interaction of DT agent with the user.

The digital twin of plant will complement the smart cyber-physical systems to provide better quality and efficiency of decision-making for farmers.

VII. Conclusion

In conditions of global climate change, it is possible to create a system that helps accumulate invaluable agronomic experience and take into account new realities of crop production.

Continuous monitoring and control of plant development phases will allow for timely detection of deviations from the norm and prompt development of recommendations for measures to reduce crop risks and damage:

Simulation capabilities will allow agronomists to predict the yield and evaluate the possible effect of agricultural activities due to the following advantages of using digital twins of plants:

- reduced risks and possible damage from weather changes or human errors;
- for agronomists, it is a new opportunity to materialize knowledge and experience, loading their observations into the knowledge base;
- reduced dependence on qualified, expensive professionals;
- prospect of creating a system that can learn from experience.

Advantages of using ontologies and multi-agent technology for building a digital twin of plant are the following:

- continuous extraction and formalization of knowledge on plant growth and development and the work of agricultural enterprises for decision-making based on analysis of incoming data;
- using a knowledge base built upon the domain-specific ontology and semantic network to support planning of agricultural operations and making agrotechnological decisions;
- effective support for distributed activities of heterogeneous resources in the network based on the principles of group cyber-physical management (platform, communications, network interaction, knowledge base);
- monitoring of problem situations, support of mechanisms for informing users about their occurrence in real time on mobile devices.

In the future, it is planned to integrate distributed group management models based on the principles of situational awareness, self-organization of agents and domain-specific ontologies of agriculture with machine learning and big data processing methods.

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