Use of centrifugal pumps with shielded asynchronous motors in precision irrigation systems for precision agriculture

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Abstract. Precision irrigation in the context of precision farming principles should be based on a systematic approach to achieve the targets of meeting the average spatial needs of crops for water and dissolved nutrients. Precision irrigation, based on advanced irrigation management technologies, combined with remote sensing and simulation technologies, provides a practical solution to the problem of managing the spatial and temporal components of water to meet the specific needs of individual plants. The spatial component of water equivalent to its volume is supplied to the irrigation zone by means of supply water pipes, and the temporary component equivalent to its flow is provided by means of booster pumps. With intensive water consumption, the supply pipelines do not provide the irrigation systems with the required volumes of water. In this case, the static water supply is provided by using storage tanks. In this paper, the need to use a storage tank as a technical component of irrigation management is considered from the point of view of solving a specific management problem related to ensuring the current value of the green mass per unit area of sowing to the level of its calculated value. The use of a storage tank and a group of centrifugal pumps of a special hermetic design as pumping equipment allows you to obtain a closed-type irrigation scheme that has the necessary reserve of static and dynamic stability of the flow characteristics.

1. Introduction
Increasing demand for food crops requires the correct use and application of the entire range of innovations in agriculture, including technical innovations that allow for more efficient soil cultivation, improved breeding and increased yields [1]. Technical innovations in agricultural production include intensive, high-intensity technologies, high-precision technologies and resource-saving technologies. Intensive technologists are characterized by a wide range of technological operations at all stages of cultivation of agricultural products, including the stages of sowing, growing and harvesting. High-intensity, high-precision and resource-saving technologies are characterized by the extensive use of modern electronic components, geoinformation systems, remote methods for monitoring the current state of crop rotation sites and managing the modes of their cultivation, cultivation and harvesting in real time.

Innovative technologies are considered to be highly efficient resource-saving technologies used in the field of agricultural production (agrotechnology). Highly efficient resource-saving agricultural technologies are the most important areas for improving production in the process of cultivating food crops, improving the quality of the products obtained and reducing their cost [2].
It is possible to achieve effective resource saving at a non-material level at a particular agricultural enterprise in relation to organizational methods and technical innovations with the help of information technologies. The use of information technologies makes it possible, ultimately, to monitor and regulate the use of all material and technical resources at all stages of agricultural production as accurately as possible [3].

The appearance of GPS satellites in the earth's orbit in 1995, which make it possible to effectively recognize various components of the natural environment on aerospace images, including the shape of the terrain and soil profiles of various types of soils, led to the formation of a new stage in the development of information technologies in crop production, called precision agriculture.

In precision agriculture, innovative and promising technologies include: electronic maps of fields and gardens, software for convenient work with them; high-precision agrochemical survey of fields; navigation systems for agricultural machinery; monitoring of agricultural machinery; soil samplers; mobile laboratories for soil and product analysis; individual meteorological stations and systems for differentiated fertilization [4].

At the initial stage of the development of precision agriculture, the need to apply a specific type of technological operations, for example, processing and watering the soil, the need of plants for pesticides and fertilizers, was previously calculated using the appropriate electronic components based on the initial data obtained using satellite imagery. In the future, the development of intelligent computer systems, ground-based and aerial unmanned platforms, such as unmanned aerial vehicles and UAVs, has made it possible to minimize the amount of aerial photography materials (images) obtained from aircraft or satellites in precision agriculture.

Unmanned aerial vehicles are capable of performing a wide range of tasks, including: inspection of irrigation systems, spot irrigation, field surveys, creation of digital transformed images of the terrain (object) from overlapping source photographs, electronic maps, digital terrain models, and field monitoring.

According to the US Department of Agriculture, the use of UAVs in precision farming is cost-effective in 60% of cases of crop data collection on areas of more than 60 acres, and in 20% of break-even [5].

The UAV equipped with modern professional measuring and computing equipment allows you to visualize the perception of crop attributes and remotely determine the yield of the green mass of the examined crop [6]. The variable array obtained from the UAV computer, which includes a set of measured parameters corresponding to the spectral brightness of the system soil profile-green mass normal to the Earth's surface, is further processed according to the specified algorithm. As a result, in accordance with the target task, the computer generates a set of remote control signals to the executive elements of mobile irrigation equipment, which is an integral part of the integrated irrigation system. The development of control signals in irrigation equipment allows irrigation in real time using remotely measured crop factors, including the components of the energy balance equation of the green mass.

2. Case Study

2.1. General approach to the development of remote control signals for the actuators of mobile irrigation equipment.

In point farming, a mobile irrigation system that performs precision irrigation consists of four main functional modules. The first module is a UAV. The second module is presented in the form of a mobile weather station with the necessary set of sensor sensors. The third module is directly an agricultural machine (sprinkler system) structurally adapted by the appropriate sensors and nodes that allow you to implement the function of precision irrigation. The fourth module is the control unit of the irrigation system that ensures the efficiency of the complex due to the practical implementation of the set of complex functions set by the block. For example, the control function regulates the parameters of the movement of the sprinklers and their location, as well as regulates the operation of the base pumping station and the pumps of the sprinklers. In turn, the sensing function allows self-
diagnosis and self-monitoring of elements and components of the irrigation system to ensure their smooth operation in real-time mode. The expert function includes elements of artificial intelligence and provides a systematic collection and processing of information about the current quantitative and qualitative parameters of the crop and the state of the soil. The simulation function provides a comprehensive assessment of the irrigation system based on the input and disturbance effects coming from the corresponding sensors and components of the precision irrigation system [7].

Precision irrigation, as the most advanced water management technology, involves 3D control of this process, taking into account the specific needs of individual plants, in contrast to precision irrigation, in which the process parameters are averaged over the entire crop area.

As a rule, the water supply to the irrigation zone is carried out using booster pumps. The volume of required water per unit of time is calculated in the control unit of the irrigation system, taking into account the expert assessment data and the simulation results. In most cases related to irrigation conditions in irrigation systems of any type, it is required to have a sufficient static supply of water in storage tanks. As a result, an additional subsystem must be introduced into the control system, which is inertial (with a delay) in relation to the main external system. Obviously, the operation of such a system should be determined by a set of initial data (control actions) that differ from the data of the original system. In this paper, it is proposed to consider as initial data the slowly changing parameters included in the equation of the energy balance of the green mass of the crop area.

Figure 1 shows a block diagram of the green mass control subsystem.

2.2. Determination of the amount of plant mass per unit area of sowing and the rate of its growth.

The value of the plant mass per unit area of sowing is determined by calculation according to the data obtained using the UAV at the initial and final moments of the interval of operation of the sealed centrifugal pump, due to the need to replenish the static water reserves in the storage tank.

When considering the vegetation cover in the form of a turbid medium, the dependence of the spectral brightness of the soil-vegetation system on the value of the green mass of the crop area can be described by the formula:

$$b_{sv} = \frac{b_{\lambda} (b_{\lambda} - 1) + b_{v} - b_{s} e^{-Em \alpha}}{(b_{\lambda} - 1) + b_{v} - b_{s} e^{-Em \alpha}}$$

(1)

where $b_{sv}$, $b_{\lambda}$, $b_{v}$, $b_{s}$ – respectively, the spectral brightness coefficient of the system soil-vegetation of one vegetation and soil; $m$ – value of the green mass per unit area of sowing; $\alpha$ - constant parameter that characterizes the spectral reflective properties of the green mass and its structure; $E$ - calculated coefficient:

$$E = \frac{1 - b_{\lambda}}{b_{\lambda}}.$$
Given that the grain structure is identical and depends only on two periods of vegetation (flowering phase or milk ripeness), the parameter $\alpha$ is found once for each phase separately due to the identity of the grain structure, regardless of which crop it is found on [8].

In expression (1), the $b_s$ coefficient is determined remotely using UAVs by conducting situational field measurements for plowed soils using multichannel spectrometric systems topographically linked to the surveyed areas.

In turn, the remote determination of the $b_{sv}$ coefficient occurs twice. In the first case, the measurement of the $b_{sv}$ coefficient is made according to the normal to the Earth's surface. In the second case, such measurements are carried out at an angle to the Earth's surface, so that the condition of non-falling soil in the field of view of the spectrometer is met.

Taking into account that there is no 100% coverage for agricultural fields, when measuring the $b_{sv}$ coefficient, the working area of the spectrometer will include soil areas that are visible through the green mass. As a result, the measurement of the $b_{sv}$ coefficient is not performed remotely, but is performed locally and at a certain angle $\beta$ to the normal to the Earth's surface. The value of the angle $\beta$ is determined by the expression:

$$\operatorname{tg}x > \frac{l}{h},$$

where $l$ is the distance between the plants; $h$ is the height of the distances.

If the plant height is in the range of 30-50 cm (the current height of grain crops in the phase of entering the tube) and the existing seeding rate is 5 minutes per 1 hectare (500 seeds per 1m$^2$), the calculated value of the angle $\beta$ lies in the range of $40^\circ$÷$45^\circ$.

The parameter $\alpha$ is determined in advance on the spot by experimental means. At the initial stage, 25 plots with different green mass content are selected in the grain sowing. The coefficients $b_v$ and $b_s$ are measured over the selected divisions. The value of the green mass $m$ on the plots is made by preliminary cutting and subsequent weighing. Taking into account the found values $b_{sv}$, $b_s$, and $m$, the parameter $\alpha$ is determined by the expression (1). As noted earlier, the parameter $\alpha$ is determined twice a year: in the phase of exit into the tube and earing.

In the future, during the operation of a sealed centrifugal pump, the value of $m$ is determined by the expression (1).

To determine the rate of growth of the green mass of the crop area, we will make an equation of the energy balance. We will assume that the similarity theorem applies to the vegetation cover. In this case, we can assume that as the green mass grows, it retains a geometric similarity. Free energy (active substance) of any plant, including cereals, is obtained by photosynthesis. Free energy is spent on the process of photosynthesis, on the growth of the plant and on the rise of nutrients in an aqueous solution from the soil. For long periods of time, the plant receives a constant amount of light per unit of surface and can absorb from the soil the substances necessary for vital activity from an unlimited supply.

Let $f = x(t)$ be an integral function corresponding to the linear dimensions of the plant, which changes over time and can be used to express the height, surface area of the green part and the volume of the plant.

The components of the energy balance equation are determined by the left and right parts of the corresponding identity.

The free energy of the $E_{\text{free}}$ is formed by photosynthesis in the green mass of the plant, and its value increases in proportion to the surface of the green mass of the crop area:

$$E_{\text{free}} = k_1 \cdot x^2(t),$$

where $k_1$ is the proportionality coefficient, which depends on the geometric size and shape of the green mass, as well as on the intensity of photosynthesis; the value $x^2(t)$ corresponds to the surface area of the green part of the crop area, for example, the total area of the green mass.

The expenditure part of the energy balance equation is determined by three terms.
The energy consumed in the process of photosynthesis is \( E_{\text{phot}} \) is proportional to \( x^2(t) \), i.e.:
\[
E_{\text{phot}} = k_2 \cdot x^2(t),
\]
where \( k_2 \) is the proportionality coefficient \( (k_2 < k_1) \).

The energy \( E_{\text{transp}} \) required to transport nutrients by an aqueous solution to all parts of the plant is proportional to the volume of the plant and the height of the plant, since the consumption is associated with overcoming gravity, i.e., the flow rate:
\[
E_{\text{transp}} = k_3 \cdot x^3(t) \cdot x(t) = k_3 \cdot x^4(t).
\]

The energy \( E_{\text{grow}} \) consumed to increase the green mass due to its growth is proportional to the growth rate, i.e., the time derivative of the mass and is determined by the expression of the form:
\[
E_{\text{grow}} = k_4 \cdot \frac{dM}{dt} = k_4 \cdot (\rho \cdot x^3(t))
\]
where \( k_4 \) is the proportionality coefficient; \( \rho \) is the average density of the green mass; \( x^3(t) \) is the volume of the green mass; \( M = \rho \cdot x^3(t) \) is the mass of the green part of the crop.

On the basis of the law of conservation of energy, taking into account the introduced notation, the identity corresponding to the law will take the form:
\[
E_{\text{free}} = E_{\text{phot}} + E_{\text{transp}} + E_{\text{grow}}
\]
\[
k_1 \cdot x^2(t) = k_2 \cdot x^2(t) + k_3 \cdot x^4(t) + k_4 \cdot (\rho \cdot x^3(t))
\]
(2)

Equation (2) is converted to the form:
\[
\frac{d x(t)}{dt} = \alpha - \beta \cdot x^2(t)
\]
(3)
where the auxiliary coefficients \( \alpha \) and \( \beta \) are defined by the expressions:
\[
k_2 \cdot k_1 \quad k_2 \cdot k_1 \quad \alpha = \frac{k_1}{3 \cdot k_4 \cdot \rho} \quad \beta = \frac{k_1}{3 \cdot k_4 \cdot \rho}.
\]

The solution of equation (3), corresponding from the physical point of view to the law of green mass growth, is determined by the equality:
\[
x(t) = \sqrt{\frac{\alpha}{\beta}} \cdot e^{\frac{2}{\sqrt{\alpha \beta}} (t-t_0)} - 1.
\]
(4)
Here \( t \) is the current time value corresponding to the moment of observation; \( t_0 \) is the initial time value at which the value \( x(t) = 0 \).

Crown and root architecture, organ morphology, anatomy, and aquaporin activity affect the plant's ability to absorb water, transport efficiency, and water loss (transpiration). Accordingly, the energy for the transport of the nutrient solution of \( E_{\text{transp}} \) can be determined using a model based on the energy balance between the internal evaporation of the green mass and its exchange with the external environment [9]. In this case, the algebraic form of writing the energy balance equation has the form:
\[
E_{\text{transp}} = E_{\text{exch}} + E_{\text{evap}} + E_{\text{therm}}
\]
(5)
where \( E_{\text{exch}} \) is the energy of the exchange of green mass with the external environment (long-wave radiation); \( E_{\text{evap}} \) is the energy of evaporation of water from interstitial tissues into the atmosphere; \( E_{\text{therm}} \) is the thermal energy of the green mass from the absorbed radiation.

The physical constants, input and calculation parameters required to determine the terms of the right side of equation (5) are given in Table 1.
In accordance with the notation used in Table 1 and the energy balance equation (5), a schematic representation of the energy flows in the direction of the external normals of the volume part of the green mass of the vegetation cover is shown in Figure 2.

**Table 1. Definition of key variables**

| Symbol | Description |
|--------|-------------|
| Physical constants | |
| $c_p$ | Heat capacity of air and helox, $c_p = 29.1$ and $20.8$ J mol$^{-1}$·K$^{-1}$ for air and helox, respectively. |
| $\Delta$ | Rate of change of saturation vapor pressure change with temperature, kPa °C$^{-1}$. |
| $\Lambda$ | Latent heat of evaporation/condensation, $\lambda = 44,000$ J·kg$^{-1}$. |
| Input parameters | |
| $g_b$ | Boundary layer conductance for water vapor and heat, $g_{bl} = 2.84$ mol·m$^{-2}$·s$^{-1}$ as for LI-6400. |
| $\Psi_m$ | Water potential of the source, $\Psi_m = -1\div0$ Mpa. |
| $\Psi_e$ | Water potential of the epidermis, $\Psi_e = -1.5\div0$ Mpa. |
| $Q_{abs}$ | Absorbed radiation, $Q_{abs} = 10\div500$ W·m$^{-2}$. |
| $T_e$ | Epidermis temperature, $T_e = 5\div35$°C. |
| Calculated parameters | |
| $E_e$ | Partial pressure of water vapor on the inner side of the epidermis, kPa. |
| $E_m$ | Partial pressure of water vapor of the source, kPa. |
| $E_{sat}$ | Saturation water vapor pressure at a given temperature, kPa. |
| $E_{out}$ | Transpiration rate between epidermis and atmosphere, mol·m$^{-2}$·s$^{-1}$. |
| $G_t$ | Total leaf conductance, $1/g_t = 1/g_s + 1/g_{bl}$, mol·m$^{-2}$·s$^{-1}$. |
| $T_{air}$ | Air temperature, °C. |
| $T_m$ | Source (mesophyll) temperature, °C. |

*Figure 2. Schematic representation of green mass energy fluxes.*
The symbols used in Figure 2 correspond to: blue lines - latent heat fluxes ($\lambda E$); red line - sensitive heat fluxes (H); LWnet – the volume of heat radiation; black and blue line-the flow of an aqueous solution.

3. Experimental Study
For the symbols used in Figure 1, the signal with the sign (+) received by the comparing device corresponds to the value of the green mass $M = \rho \cdot x^3(t)$. In this case, the value of $x(t)$ is determined by the expression (4) and is equivalent to a mathematical representation averaged over time by the law of growth of the specified mass. In turn, the signal with the sign (−) reflects the value of the green mass $m$, the value of which can be implicitly calculated using the expression (1). The misalignment signal $\Delta$ is a control signal that ensures the start of operation of a sealed centrifugal pump that fills the storage (control) tank with water.

Figure 3 shows a closed-type irrigation scheme that allows you to increase the technical efficiency of the water supply source for a closed-type irrigation scheme, including a precision irrigation system [1].

![Figure 3] Closed type irrigation scheme with separation chamber and storage tank: 1-separation chamber; 2- storage tank; 3- sealed centrifugal pump No.1; 4- sealed centrifugal pump (turbine) No.2; 5- diesel; 6-sealed centrifugal pump No.3.

The laboratory installation created at the University allows you to test the operation of individual units of the water supply system with a storage tank in practice. The principle of operation of the unit is based on the reproduction of a given volume flow of the working fluid equivalent to the value $\Delta$ using a hydraulic system, and the measurement of the volume (mass), volume flow of this fluid by reference measuring instruments. The operation of the installations is carried out in a closed cycle.

Figure 4 shows the main components of the laboratory setup.

![Figure 4] General view of the components of the laboratory installation.
4. Conclusions

By the example of advanced remote sensing technologies and modeling of crop and soil conditions, the two-stage problem of controlling the green mass of the crop area from the point of view of synthesized algorithms and hardware implementation is solved.

The proposed algorithm for determining the yield of the green mass of agricultural crops, which includes measuring the spectral brightness of the soil-vegetation system along the normal and at an angle to the Earth’s surface, allows us to calculate the value of the plant mass per unit area of sowing in real time. Using a model based on the energy balance between the internal evaporation of the green mass and its exchange with the external environment, it was possible to analytically determine the law of growth and the weight of the green mass of the crop and present it as an objective function. The discrepancy between the target function of the green mass and its calculated value corresponds to the control signal that provides the start of operation of a group of sealed centrifugal pumps of a closed-type mobile irrigation system.

To ensure the required water flow rates in the linear water pipes of the irrigated areas, a storage tank has been introduced into the mobile system. At the same time, to ensure the dynamic stability of the pipeline system as a whole, a separation chamber and an additional centrifugal pump operating in reverse-turbine mode were introduced into the mobile complex.

The use of centrifugal pumps with sealing elements made it possible to increase the reliability of the system by eliminating leaks, reducing the length of the suction line of the centrifugal pump of the diesel pumping unit and increasing the technical efficiency of the drainage networks and pumping equipment in the system by transferring the centrifugal pump of the separation chamber to the reversed turbine mode of operation.

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