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Event: Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2021 (WILGA 2021), 2021, Warsaw, Poland

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ABSTRACT

A mobile robot has been developed to monitor the state of the atmosphere and phyto-condition in protected ground facilities to form control strategies that maximize production profits. The free and open ROS (Robot Operating System) software shell was used as a basis for building a mobile robot information system. The paper considers a non-contact method of assessing the condition of plants (formation of the number of flowers in the inflorescence, the number of fruits per branch, average weight and ripeness of the fruit, fruit weight gain) using wavelet analysis, during which each image obtained with a video camera located on a mobile robot, decomposes into wave functions. The training on the accumulation of experience of trial and error of the route by the robot was conducted and it was determined that with the accumulation of experience the number of unsuccessful attempts and time of the route decreases, while the number of received incentives increases.

Keywords:mobile robot, phytomonitoring, industrial greenhouse, optical sensors

1. INTRODUCTION

Industrial greenhouses are complex biotechnical facilities where the biological component significantly affects the algorithms for controlling heat fluxes circulating in such facilities. The content of such algorithms is determined by technological requirements, natural disturbances (solar radiation, temperature and humidity of the outside air), construction structure, power capacity and plant condition. It is the condition of plants that determines the quality and volume of grown products, and therefore they need control and, preferably individually, throughout the technological period of cultivation.

The disadvantage of an individual approach to controlling the condition of plants is a significant investment in technical means and systems, which will definitely affect the cost of production. But this problem is solved by using a phytomonitoring mobile robot (PMR). On a movable platform that is able to move technological guiding, sensors are installed to assess the condition of the plant, including the visual observation of plants, technological parameters of the atmosphere, and the soil of the greenhouse. The computer-generated work information is processed, including the identification of the location of measurements, and the results are used to further move the platform according to a certain algorithm and to form appropriate control strategies for the central process control system in the greenhouse..

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Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2021
edited by Ryszard S. Romaniuk, Andrzej Smolarz, Waldemar Wojcik, Proc. of SPIE
Vol. 12040, 120400D · © 2021 SPIE · 0277-786X · doi: 10.1117/12.2613975

2. PROBLEM STATEMENT

The purpose of this article is to develop a control algorithm and a mobile robot with optical sensors for remote assessment of plant conditions and atmospheric parameters in an industrial greenhouse.

3. RESEARCH METHODS

The free and open software shell ROS (Robot Operating System) served as a basis for building the information system of the mobile robot [1-4].

To select the control points of PMR in the greenhouse in automatic mode, it is necessary to take into account a large amount of data (Fig. 1), such as the initial position of the robot, temperature distribution in the greenhouse space zones, the ability to inspect a point in the greenhouse space. A large amount of data needs to be structured for further processing. For this purpose, it is advisable to use methods of cluster analysis.

The use of clustering method is determined by the absence of priori hypothesis as to the number and content of classes to be obtained as a result. The section of the greenhouse area $s_i^R \in S^R$ is taken as a cluster unit. Based on the results of clustering, each section S_i^R turns into a certain cluster $k_i \in K$ according to its parameters.

Let us formulate the problem of cluster sections of the greenhouse space: we assume that there is a set of objects $S^R = \{s_1^R, \cdots, s_N^R\}$ and the function of distance between them $p(s_i, s_i')$. It is necessary to divide the sample $\{s_1^R, \cdots, s_N^R\}$ into non-intersecting sets (clusters) $K = \{k_1, \cdots, k_M\}$, so that each of the clusters $k_i \in K$ should consist of the objects, close in metric values p, with objects of different clusters substantially different. At the same time, each object s_N^R is assigned a cluster number n_k. The $f: S^R \to K$ function serves as a clustering algorithm, which assigns any element $s_i^R \in S^R$ a corresponding cluster number n_k. The classical Euclidean metric was chosen as a function of distance to determine the proximity of objects $p(s_i, s_i')$:

$$p(s_i^R, s_j^R) = \sum_{p=1}^{n_p} \left(\mu_k(s_i^R) - \mu_k(s_j^R)\right)^2 \qquad (1)$$

where $\mu_k(s_i^R)$, $\mu_k(s_j^R)$ – degree (measure) of possessing p-m parameter by i and j -sections of the greenhouse space correspondingly.

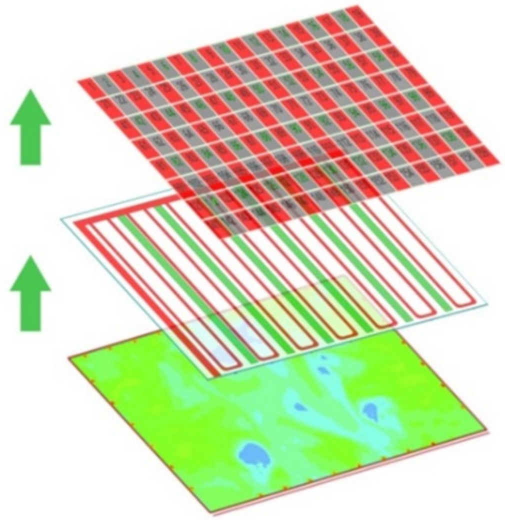

Figure 1. Overlap of different layers of data under analysis.

We define the route of movement $c_j^k(t)$ as a set of control points of time in which the mobile robot should be, after it begins its movement from the starting position$p_i^{start}(t)$:

$$p_i^k(t) = \{(p_i^{start}, t_i^{start}), \cdots, (p_i^{start}, t_i^{start}), (p_i^{start}, t_i^{start})\} \tag{2}$$

where p_i^{start} – starting point of the route, $p_{i,j}^K \epsilon P^K, j = 1, N_k^K$ – control points of passing the route, t_{ij}^K – defined time for the robot to visit control points, p'^{start}_{ij} – the specified return time to the starting point of the route, N_k^K – the number oft he control points of the route.

The issue of robot control is considered in the framework of the so-called intelligent robotics. The concept itself is not fully defined today. Most definitions of an intellectual robot are reduced to a list of intellectual properties that it must possess (“vision”, “hearing”, “planning”, etc., up to the specific mechanisms of artificial intelligence). A less formal definition is the ability of a system to solve problems formulated in general terms [5-8].

Since the greenhouse is an area of operation not only for work, but also for the people who service it and take care of the plants, it is not enough to move the work only along a certain route set by the operator. It must, by gaining experience, learn to avoid obstacles on its path, take into account the probability of an event and accordingly build its route according to these forecasts.

Therefore, when there is a need to design a control system for a robot that will move in an environment with variable parameters and the probability of interference and movement of people [3, 11-15], it is not enough to use simple control methods.

To construct control probability automata, methods are used that estimate the response of the automaton and in some way redistribute the probabilities associated with this reaction. In the general case, it comes down to checking a certain condition, based on which it is concluded whether the reaction was good or bad. In this case, the resulting machine will follow the desired strategy to a greater extent, because the learning algorithm does not take into account that a “good” reaction at this step can lead to a bad result in the next steps.

It is evident, that this problem can be solved by using more powerful algorithms, such as machine learning. However, these algorithms are not adapted to work directly with a probabilistic automaton. Therefore, an approach based on the use of stimulus learning algorithms is proposed [3].

The mobile robot interacts with the environment, performs certain actions. The environment responds to the robot’s actions and in some way stimulates or punishes it. In order for the robot to be able to choose the right tactics of behavior, it should monitor the incentives (punishments) from the environment.

The behavior of the robot in relation to the specified task is characterized by: *S* – the set of states in which the mobile robot can be; *A* – the set of available actions; *t* – is a discrete step in time. At each step, the robot recognizes the current state $s_t \; \epsilon S$ and selects an action $a_t \; \epsilon A$. After it, the environments returns the stimulus to the mobile robot $r_t \;\; = (s_t, a_t)$ and transfers it into a new state $s_{t+1} = \delta(s_t, a_t)$.

For the case studied δ and r are a part of the environment and they are unknown to the robot. Only the finite sets *S* and *A* are considered.

The task of the robot is to find the optimal strategy for choosing the next step in relation to the current state $\pi: S \to A$. Different models are used to assess the optimality of the strategies found, but in practice the infinite horizon model is preferred. According to this model, the optimal strategy is to maximize the incentive to work in accordance with [5]:

$$V^{\pi}(s_t) \equiv r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \cdots \equiv \sum_{i=0}^{\infty} \gamma^i \, r_{t+i} \tag{3}$$

where $0 \le \gamma \le 1$ is a certain constant that makes it possible to take more account of an incentive received from the environment here and now than in the near future. This is true for most real tasks, because the sooner the robot receives an incentive, the better. The incentive that a robot should theoretically receive in twenty steps may not be awarded to it if it has only ten steps left.

The optimal strategy of the robot's behavior is expressed by the following ratio:

$$\pi^* = arg_{\pi} max V^{\pi}(s), \qquad (\forall s) \tag{4}$$

For convenience, we denote the profit function $V^*(s)$ that corresponds to the optimal strategy. Then, the provisional identity (4.37) shall be written as:

$$\pi^*(s) \equiv arg_\pi max\left[r(s,a) + \gamma V^*\left(\vartheta(s,a)\right)\right] \tag{5}$$

The main task of the robot is to find the optimal strategy π^*. However, it's difficult for it to calculate the function directly $\pi: S \rightarrow A$, since all the data, available to the robot, is a sequence of incentives from the environment a $r(s_i, a_i)$, where i = 0, 1, 2,...

This problem may be avoided through the introduction of the so-called Q-function:

$$Q(s,a) \equiv r(s,a) + \gamma V^*\left(\vartheta(s,a)\right) \tag{6}$$

The expression (6) for each state-action pair (s,a) returns the maximum incentive that the robot will receive if, in state s, it chooses action a. This identity for the optimal strategy can be re-written as:

$$\pi^*(s) \equiv arg_\pi max Q(s,a) \tag{7}$$

This formula shows that for finding the optimal work strategy instead of the function V^* it is enough to calculate the Q-function. Q-function allows to choose the optimal action for the current state without any knowledge about the functions δ and r.

Thus, to obtain the optimal strategy, it is necessary to find the value of the Q-function, which is calculated directly through the interaction of the robot with the environment (through the sequence $r(s_i, a_i)$ where i = 0, 1, 2, ...).

In order to implement the algorithm, some conditions for its successful execution are taken into account [3]:

- the mobile robot moves in the space of the greenhouse and must pass on its way certain control points set by the operator before starting the robot;
- because the robot is on the guides while moving between rows of plants, the number of its actions at this time is limited to moving forward or backward;
- arrival at guides is carried out by use of the color marking put on a floor of the greenhouse (Fig. 2);.

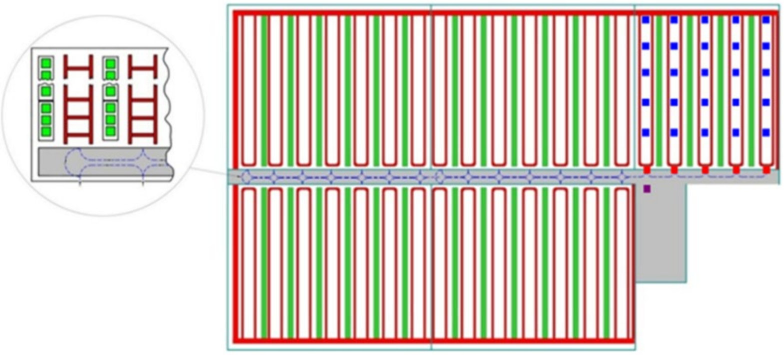

Figure 2. Visual plan of the greenhouse and marking for simplifying the orientation of the robot.

- in case there is an obstacle on the route, the robot detects it with an ultrasonic sensor, if it is possible to bypass the obstacle, it does maneuvering, if it is impossible to reach a certain destination, the robot beeps, sends a message to the operator and goes to the next destination.
- to simplify the orientation of the robot, the greenhouse space is conditionally divided into sectors; the robot tracks the change of sector, using the color of the label on the pots of plants.

By training a mobile robot according to the described methods, we get an automatic model of the given problem, which is a stochastic matrix of transitions. The rows of this matrix correspond to the mobile robot's state cells, the columns correspond to possible actions. Thus, the stochastic transition matrix compares each state-action pair with the probability value of this action for each pair [5, 9, 12-16].

To successfully pass the route of the algorithm you need to go through a period of training to gain experience of trial and error. With the accumulation of experience, the number of unsuccessful attempts and the time of the route decreases, and the number of received incentives, on the contrary, increases (Fig. 3).

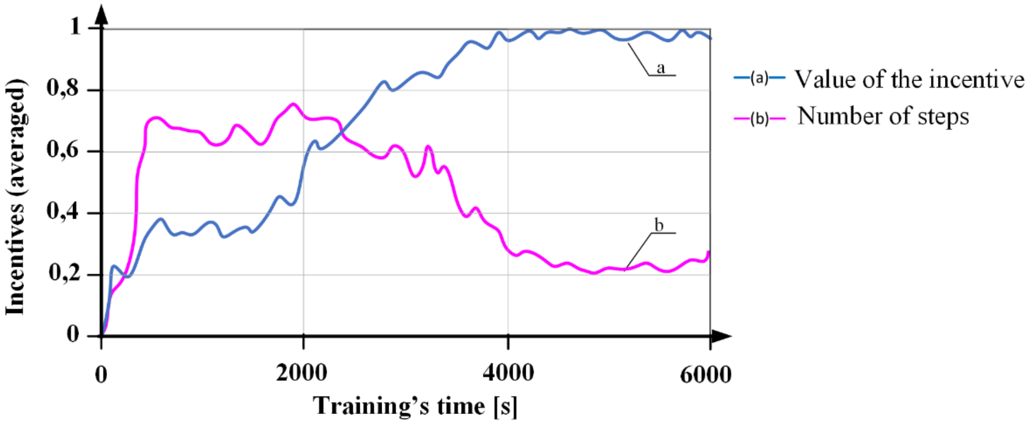

Figure 3. Graph of the dependence of training time and received incentives.

To implement the robot control algorithm, additional marking [1] of the greenhouse is performed (Fig. 2). To determine the labels and guide lines the optical sensor TCS230 is used to determine the color of the object at a distance of 10 mm to 15 cm. The sensor recognizes 4 colors: red; blue; green; white. The TCS230 chip is used as a sensitive element, which converts the intensity of the color spectrum into an output meander (50%) of different frequencies. The higher the frequency of the output signal, the lower the intensity of the color spectrum. Schematic diagram of the TCS230 sensor is shown in Fig. 4.

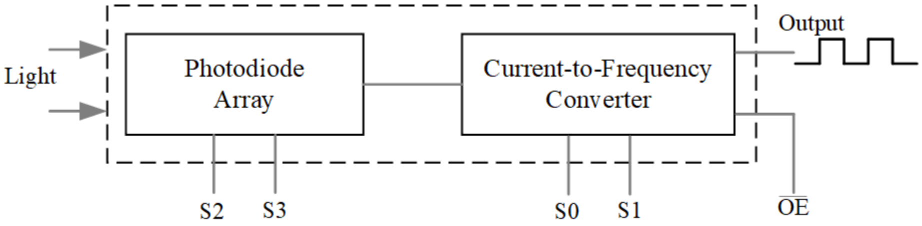

Figure 4. Structural diagram of the TCS230 sensor.

In the RGB color model, each color can be represented as a combination of three colors: R (red), G (green), B (blue). Therefore, to determine the color of the object it is necessary to measure three spectra: red, blue, green. The TCS230 chip is shown in Fig. 5a and consists of an array of photodiodes 8x8, 16 photodiodes have a blue filter, 16 photodiodes – a green filter, 16 photodiodes – a red filter and 16 photodiodes are without a filter. The sensor allows you to install a filter (by supplying a combination of digital signals) to measure each component of the R, G, B spectrum. There are four light-emitting diodes on the body of the sensor used to illuminate the measurement site.

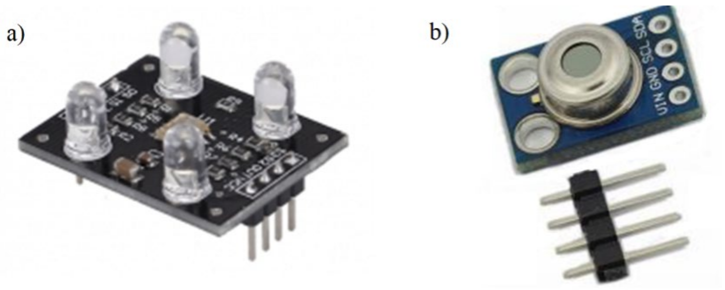

Figure 5. Exterior appearance of the (a) TCS230 sensor and (b) MLX90614 sensor.

The optical module of non-contact temperature sensor MLX90614 (Fig. 5b), designed for non-contact measurement of absolute temperature of objects, was chosen for the non-contact determination of plant temperature. Temperature data can be read both via the SMBus digital interface (similar to I2C) and via the PWM output with a PWM frequency of 10Hz or 1000Hz. The MLX90614 sensor has a wide range of programming, calibration and configuration. The module has an internal stabilizer, power filter capacitors and pull-up resistors on the digital bus. Technical characteristics of the MLX90614 sensor are given in [6, 13-17].

In addition to plant temperature, other phytometric parameters (plant formation of the number of flowers in the inflorescence; number of fruits per branch; average weight and ripeness of the fruit; fruit weight gain) are subject to measurement, which will also form data matrices. Obtaining such data in a non-contact manner is possible provided that appropriate images of plants are obtained. Images of plants are stored in the form of photographic images. The analysis and processing of the relevant data is carried out by using wavelet transforms, when each photo image is decomposed into wave functions (wavelets). Calculations were performed in MathCAD environment [2, 10, 18-21].

Images of fruits and inflorescences of plants are recognized, and then the results of comparative analysis form conclusions about their ripeness and future number of tomatoes: images of fruits and flowers $f(x,y)$, obtained using mobile visual aids, perform wavelet transform to find the wavelet coefficients:

$$f(x,y) = \sum_{i=-\infty}^{\infty}\sum_{j=-\infty}^{\infty}\lambda_{r,i,j}^{HH}\phi_{k,i}(x)\phi_{r,j}(y) + \sum_{y=r}^{\infty}\sum_{i=-\infty}^{\infty}\sum_{j=-\infty}^{\infty}\left(\lambda_{r,i,j}^{HV}\phi_{y,i}(x)\psi_{y,j}(y) + \lambda_{y,i,j}^{VH}\psi_{y,i}(y)\phi_{y,j}(x) + \lambda_{y,i,j}^{VH}\psi_{y,i}(y)\psi_{y,j}(x)\right), \varphi_{y,i}(x) = 2^{y/2}\varphi(2^{y}x - i), \psi_{y,j}(x) = 2^{y/2}\varphi(2^{y}x - j) \quad (8)$$

where r – is the depth of the wavelet decomposition function; $\lambda_{r,i,j}^{HV}, \lambda_{y,i,j}^{VH}, \lambda_{y,i,j}^{VH}$ – wavelet transform coefficients.

Schematically, the wavelet transform of the image is given in Fig.6 [2]:

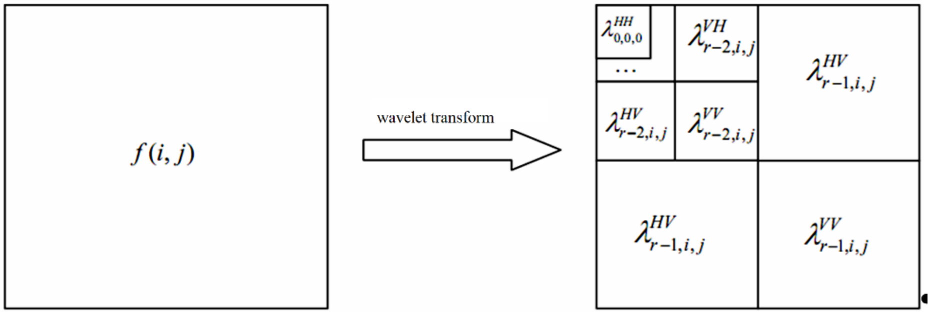

Figure 6. Wavelet transform scheme.

The obtained wavelet coefficients decompose in the space of eigenvectors. Thus, there is a vector of attribute for the input image. Then there are the distances between the obtained attribute vector and each of the vectors of the training sample. An object that corresponds to the condition of the minimum difference of the distance between the obtained attribute vector and each of the vectors of the training sample, and is a recognized object.

The general algorithm for controlling the mobile robot for monitoring the phytosanitary condition and the state of the atmosphere in closed ground structures is presented in (Fig.7). Implementation of a multilevel hierarchical control structure of the PMR, which includes strategic, tactical and executive levels, requires the use of different types of software [3].

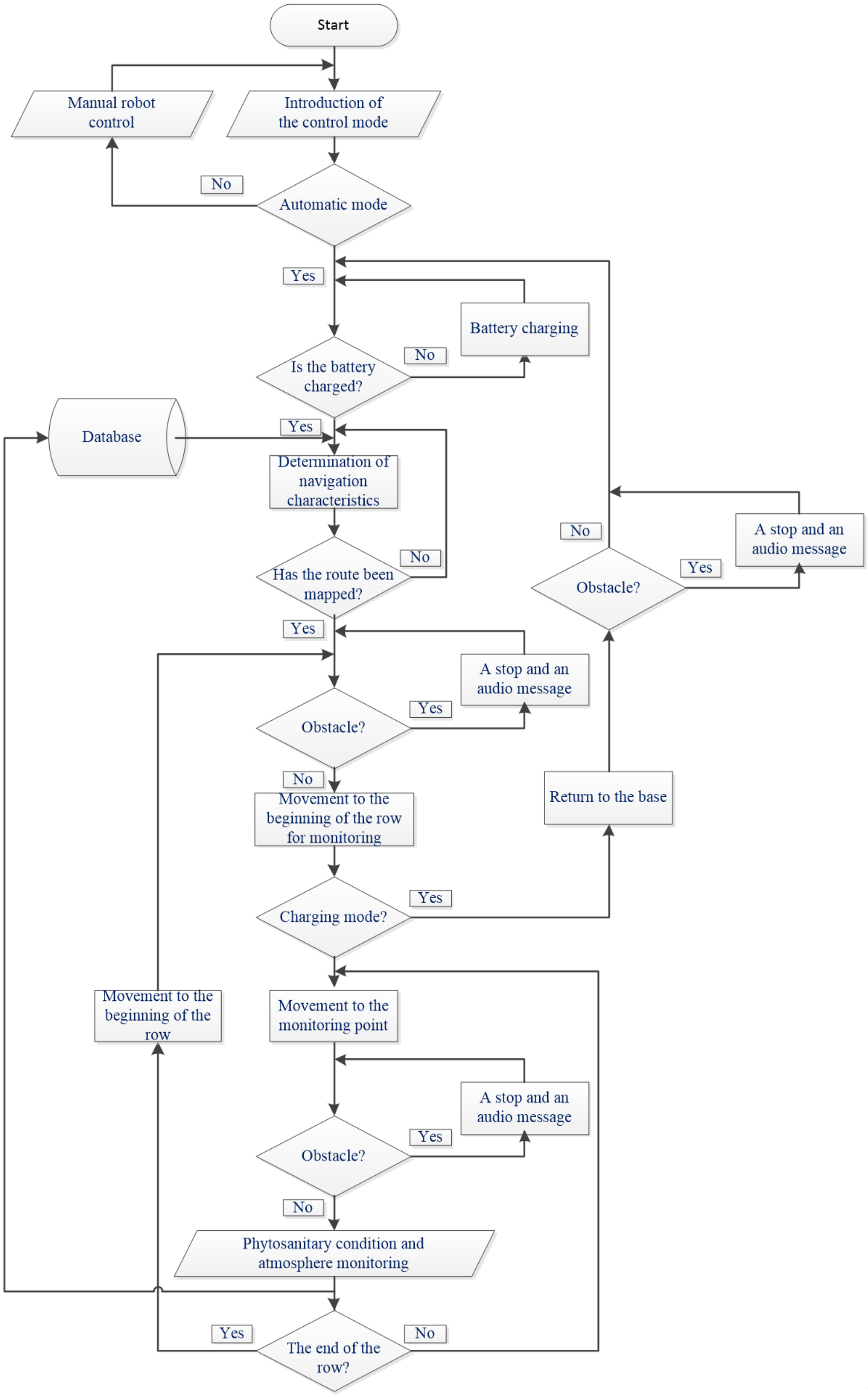

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Figure 7. Block diagram of the PMR control algorithm in closed protected ground.

For complete information about the design features of the greenhouse, you should configure the PMR software:

- specify the number of rows where measurements will be made;
- set the number of measurements in a row;
- input the coordinates of all markings into the robot's field of motion, manually or with the help of a robot.

If there is an obstacle on the route, the robot detects it with an ultrasonic sensor; if it is possible to bypass the obstacle – maneuvering is carried out; if it is not possible to reach a certain control point, the robot beeps and sends a message to the operator and moves to the next point [3].

Being on the blue marks, the robot performs technological measurements. While on the red marks, the on-board battery discharge measurement system continuously checks the state of charge of the robot battery. If during the mobile robot operation the battery voltage is below the set threshold, it stops carrying out technological works and moves to base of recharging.

The sensor system of the mobile robot collects information about the coordinates of its location: it includes two subsystems of optical motion sensors and a system of technical vision. Industrial tests of PMR were conducted in the greenhouse No.9 PJSC "Greenhouse Plant" ("Teplychnyi"), of Kyiv region, Brovary district (Fig. 8).

Figure 8. Exterior appearance of the PMR.

The use of PMR in greenhouse complexes allows to save energy by increasing the yield and quality of tomatoes, which allows to obtain additional income of 104.11 UAH/m2 and thus reduce the cost of production by 5.7%. In the process, the PMR demonstrated a high level of reliability.

CONCLUSION

A control algorithm and a mobile robot with optical sensors for remote assessment of plant conditions and atmospheric parameters in an industrial greenhouse have been developed. The process of moving a mobile robot in a greenhouse is described, where its movement is provided by color marks, which are recognized by using the TCS230 optical sensor. For phytomonitoring, a non-contact method of measuring plant temperature with the MLX90614 optical sensor is proposed. The paper describes a non-contact method of assessing the condition of plants (formation of the number of flowers in the inflorescence, the number of fruits on the branch, average weight and ripeness of the fruit, weight gain) using wavelet analysis, during which each image obtained with a video camera located on a mobile robot, decomposes into wave functions. Training was provided to gain experience of the trial and error of the route by the robot and it was determined that, as experience gained, the number of unsuccessful attempts and travel times decreased and the number of incentives received increased (learning time of 2,500 seconds). Industrial testing of PMR in PJSC “Greenhouse Plant” (“Teplychnyi”), Kyiv region, Brovary district, village Kalynivka, made it possible to save energy by increasing the yield and quality of tomatoes, additional profit amounted to 104.11 UAH/m2, while the cost of production decreased by 5.7%.

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