DEVELOPING OF CONTROL SYSTEM FOR INDOOR HYDROPONIC VERTICAL FARMING

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Abstract
Vertical farming systems are engineering solutions aiming to increase agricultural productivity per unit area of cultivated land, on account of growing in multiple layers. This research focuses on developing of new control system, which is controlling individual factors, that have an effect on growth process and quality and yield of crops. To be able to monitor hydroponic solution, the electronic analyzer and conductometer were assembled. The methods for proposed quantities verification and calibration were proposed. To measure quantities such as concentration, and other ions, the ion selective probes (ISE) were chosen. To measure pH, DO and EC special measuring electrodes were used. The pH, EC and K+ probes were calibrated.

Key words: *vertical farm, hydroponics, control system, leafy vegetables.*

INTRODUCTION
Vertical farming systems were designed as an engineering solution that aimed to increase agricultural productivity per unit area of cultivated land. Production in vertical farming systems takes place in vertical dimension, which enhances crop production capacity, using less area. *(Eigenbrod and Gruda 2014; Hochmuth and Hochmuth 2001; Resh 2012)*. Vertical farming system has shown potential for producing high-quality crops and high yields. Hydroponic cultivation is the most common method in vertical farms, as the system consumes 90% less water compared to conventional agriculture. This is considered as one of the biggest advantages, as it resolves one of the biggest challenges of agriculture in the drought-affected areas *(Farhangi et al., 2021)*.
Leafy vegetables account for over half of the indoor farming operations worldwide *(Wong et al., 2020)*, especially lettuce which is commonly used as a model plant *(Safaei et al. 2015)*. Lettuce (*Lactuca sativa* L.) has short production cycle and is suitable for hydroponic growing. Moreover, lettuce is popular for tender taste, sweet and refreshing flavor, and nutritional and antioxidant compounds *(Riga et al.; 2019)*. Environmental factors can be fully controlled in a vertical farm *(Jin et al., 2022)*. However, there is a lack of precise data of the influence of different factors such as the concentration of the nutrient solution, light conditions, humidity, and temperature on the growth of different kind of plants in vertical farms *(Sihombing et al., 2018)*.
Concentration of dissolved nutrients that are absorbed by plant roots vary with temperature, light and growth stage. During the period of growth, plant roots are secreting several substances, whereas they are continuously absorbing specific nutrients. Therefore, some nutrients in the nutrient solution appear to be insufficient or excessive. Among the most commonly monitored parameters in the nutrient solution belong pH, electrical conductivity, dissolved oxygen and temperature. In the case the parameters exceed a threshold, relevant amount of nutrients should be supplied, in order to maintain the electrical conductivity and pH in the nutrient solution. Such system increases the workload *(Chang et al., 2018)*. Most of hydroponic regulating systems are focused on changes in pH, EC, and DO of nutrient solution, whereas only a few studies considered adding ion concentrations and flow rate control methods *(Genuncio et al., 2012; Neto et al., 2014; Ban et al., 2021)*.
Different light conditions (light quality, light intensity and photoperiod) induce various morphogenetic and photosynthetic responses in plants *(Lin et al., 2013; Bian et al., 2018; Yan et al., 2019)*. Unfortunately, electricity use for lighting in vertical farms causes high energy consumption, which is in the end substantially higher in comparison with conventional production *(Kozai, 2013)*. Light conditions, especially light intensity, seem to have a strong effect on nutrient accumulation in plant tissues *(Chen et al., 2021)*. It has been proposed, that the light environment needs to be optimized in order to provide optimal conditions for growth and to reduce electricity consumption *(Fan et al., 2013; O'Carrigan et al., 2014)*.

In indoor farms with controlled environment, CO_2 is often supplemented, as research reports have shown that CO_2 enhanced growth at CO_2 enrichment concentrations *(Kozai, 2018; Zheng et al., 2019)*.
Many researches have focused on the advantages of individual factors (such as light conditions, hydroponic solution, CO_2 etc.) but fewer studies have focused on interaction and on separate controlling of those factors. The aim of this research is to propose various methods to automatically regulate and replenish the nutrient solution, to measure and optimize light conditions and to supply the environment with higher CO_2 concentration. This system will measure the concentration of individual ions (N, P, K, Ca, Mg, S) in a nutrient solution, with the aim of maintaining the appropriate nutrient composition by supplying relevant amounts of only insufficient ions. Systems will also measure light intensity and spectra, same as CO_2 level in all layers of vertical farm.

MATERIALS AND METHODS

Fundamental concept of the control system

The control system of the indoor farm is designed to be modular, low-power consumption, easy to expand and reliable. The control system has to be able to serve also big farming areas, up to several thousands of meters of farming technology. The proposed solution is based on custom made electronic which allows fulfil the specific requirement of concrete farm or experiment. For example, number of channels, type of power supply and variability of actuators, sensors required by the user etc. The basic concept of control system is shown in Fig. 1.
Main parts of control system in developing progress are:

- chemical analyzer with conductometer and pH measuring
- CO_2 probes
- ambient conditions measuring (relative humidity, temperature, atmospheric pressure)
- light switches
- pump and valve switches
- fan control
- light spectrum meter

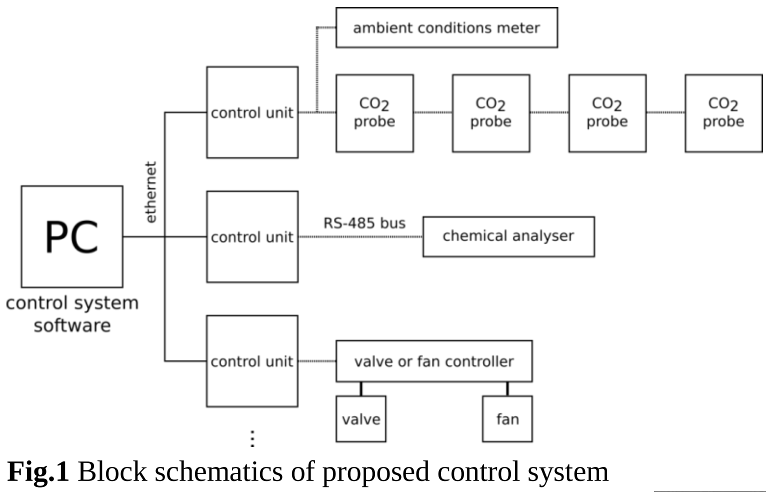

Fig.1 Block schematics of proposed control system

Electrical parameters of whole control system match the standard industrial properties, such as supply voltage 24 VDC, standard bus wiring etc. The communication is based on the RS-485 single twisted pair (100 Ω impedance) bus with proprietary protocol BeeCOM Hyperion, max. speed up to 1Mbaud.

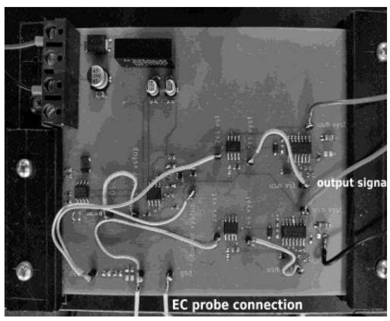

Fig. 2 Prototype of conductometer

Manufactured control system parts

The fundamental part of the control system is central unit, Fig. 4. Central unit could be connected to the standard LAN network. Present network infrastructure could be used. Central unit communicates with all others parts of control system.

The mail goal of the first stage of developing of the farm system is hydroponic solution monitoring. It means in-line measuring of these selected parameters:

- pH
- DO – dissolved oxygen
- EC – electrical conductivity
- NO_3^- – concentration of nitrate ions
- NH_4^+ – concentration of ammonium ions
- K^+ – concentration of potassium ions
- P – phosphorus

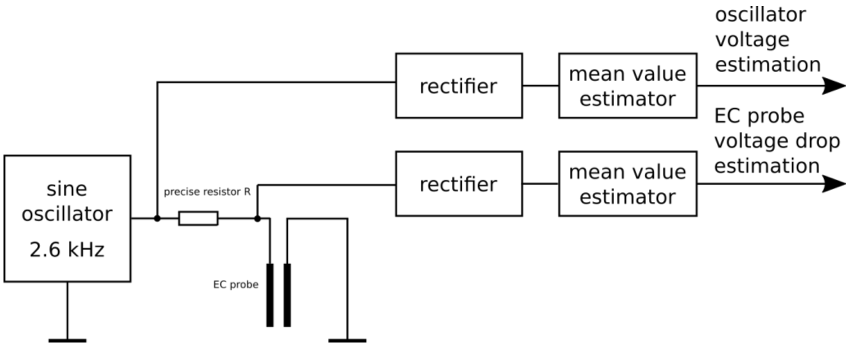

Fig. 3 Block schematics of conductometer

To achieve it, the electronic analyzer and conductometer were produced, Fig. 2 and Fig. 5. It is possible to connect to the analyzer up to 4 analogue outputs from ion selective electrodes (ISE), pH probe or dissolved oxygen (DO) probe and conductometer. Because of temperature dependency of the most quantities, one Pt100 temperature sensor could be also connected.

The principle of conductometer is shown in the Fig. 3. An electric conductivity probe with sink electrodes is used. Principle of measuring is based on the voltage drop on the EC probe and known sensing resistor compared to oscillator voltage. When the oscillator voltage is used as reference voltage of AD converter, we can estimate the conductivity (admittance) of the measured solution between electrodes of EC probe as:

$$Y = \frac{ADC_{range} - 1 - ADC_{code}}{R_{sense} \cdot ADC_{code}} \; [S]$$

RESULTS AND DISCUSSION

Fig. 4 Central unit

To verify the analyzer and the conductometer, the measuring chain was connected (PC, central unit and analyzer with conductometer). All quantities are converted to electric voltage. The verification was made on the level of electrical measuring without real chemical solution measurement. The result of verification is to determine the calibration polynom, it is assumed the 1st or 2nd order, end error fit estimation.

In the case of Pt100 temperature probe and conductometer, the calibrational resistance decade was applied to the input. Resistance of decade was measured with laboratory ohmmeter with verified accuracy 10 mΩ. ISE analogue

Fig. 5 Chemical analyzer DPS with 4 channels ISE connections, Pt100 temperature probe connection and conductometer input

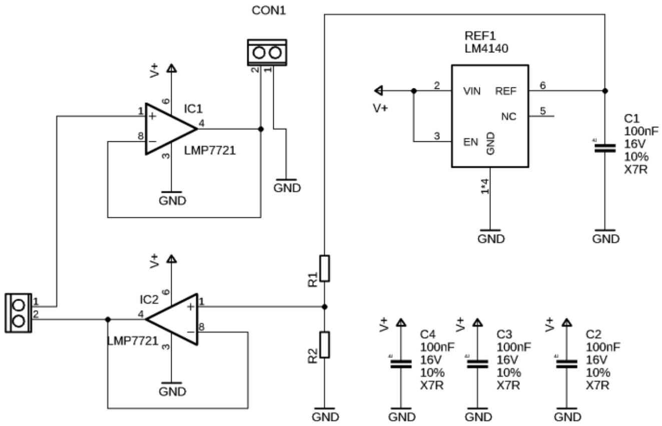

Fig. 6 Analogue buffer

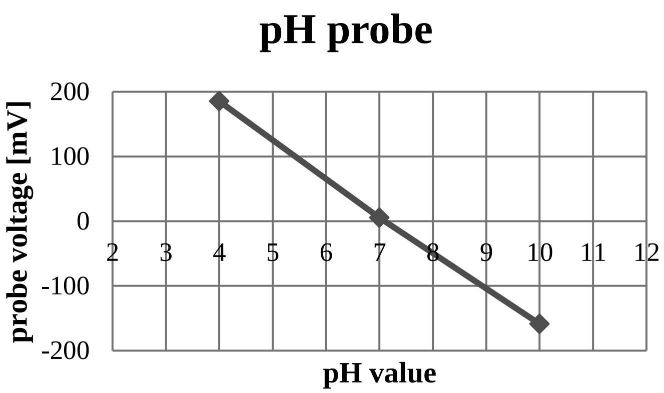

Fig. 7 pH calibration graph

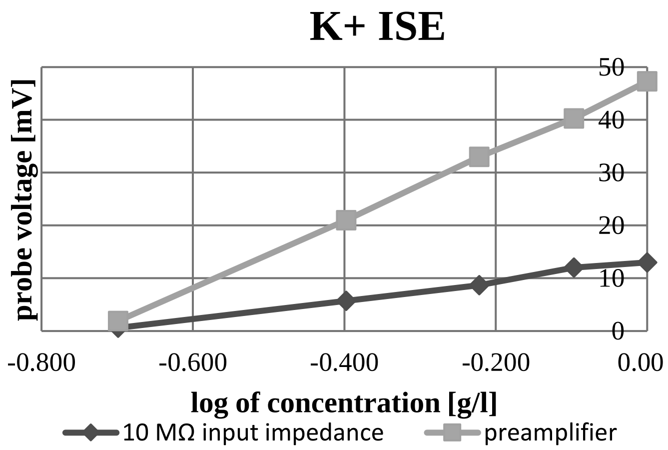

Fig. 8 K+ calibration graph

input channel was verified by appliing DC voltage and, used voltmeter had verified precision 0.2 mV.

Maximal absolute error of Pt100 temp probe after polynomial fitting, using minimalisation of root mean square error, is $|\Delta_{Rm}| = 18\ \mathrm{m\Omega}$, this value corresponds to the used ohmmeter accuracy.

Maximal absolute error of conductivity measurement after polynomial fitting is $|\Delta_{Gm}| = 0.763\ \mu\mathrm{S}$, this value corresponds, in resistance, to 275 mΩ. This corresponds also with accuracy of resistance decade 0.5 % and ohmmeter accuracy.

Maximal absolute error of voltage (ISE) measurement after polynomial fitting is $|\Delta_{Um}| = 0.347\ \mathrm{mV}$. The verification prooved, that accuray of analyzer (Pt100 and ISE measuring) and conductometer is appropriate, comparable to laboratory multimeter measurement.

Ion-selective electrodes (ISEs) are promising technology as they can directly measure the analyte with a wide sensitivity range. Above that, they are are small and portable *(Kim et al., 2013)*. Therefore, to measure quantities such as concentration K^+, NH_4^+ and other ions, the ion selective probes (ISE) were chosen. To measure pH, DO and EC also special measuring electrodes were used. To this time, the calibration of pH, EC, and K^+ is done, other quantities will follow.

Because of high internal resistance of pH probe (approx. 150 MΩ), the special analogue buffer with precise operational amplifier with low input current (pA) LMP7721 was designed. Also offset voltage was added to be able to measure negative probe voltage. See Fig. 6. The calibration of pH probe was based on the known pH of solution (pH puffers 4, 7 and 10). In Fig. 7 we can see the linear dependency of probe voltage on the pH of solution. The determined slope of electrode is 57 mV/pH.

Electrical conductivity determines the amount of mineral salts dissolved in the hydroponic solution *(Ashley, 2015)*.

During the electrical conductivity measurement, the solutions with defined conductivity were prepared – 1491, 745, 497 and 372 μS/cm. These conductivities match with conductometer range 0.2 – 5 mS.

In the case of ISE calibration of K^+ and also for the other ions measuring, the calibration graph was drawn, see Fig. 8. The slope of ISE could be determined from the graph in accordance with the equation:

$$S = \frac{U_{con1} - U_{con2}}{\log\left(\frac{c_{con2}}{c_{con1}}\right)}\ [mV \cdot g^{-1} \cdot l]$$

Where S is slope, c is ion concentration and U is according ISE voltage. Two measurements were done, direct voltmeter measurement with 10 MΩ input resistance and with analogue buffer with analyzer. The internal resistance of ISE is also high, the measurement should be done with the high input resistance voltmeter (more than 10 MΩ) or with analogue buffer, e.g. from Fig. 6. The determined slope using analogue buffer is $57.5\ \mathrm{mV} \cdot \mathrm{g}^{-1} \cdot \mathrm{l}$.
The methods for proposed quantities verification and calibration were proposed. The uncertainty of measurement should be also determined in the next steps.

CONCLUSIONS

We carried out a comprehensive proposal of control system for indoor hydroponic vertical farming. Part of the chemical analyzer and conductometer were implemented. We verified the function of presented system and performed the basic calibration procedures. Currently, we are working on the testing part, that takes place in the phytotron at University of South Bohemia. Simultaneously, we adjust nutrient solution pumping control, in-line chemical analysis, lighting control, taking into account the qualitative analysis of plant biomass. Future studies with growing plants would provide the evidence of utility and applicability of control system for indoor hydroponic vertical farming. This would give us an overview on the whole process of vertical farming, so we will be able to implement technologies to a various farms, including different modifications.

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