PRZEGLĄD ELEKTROTECHNICZNY

Ukazuje się od 1919 roku **7'2023**
Organ Stowarzyszenia Elektryków Polskich • Wydawnictwo SIGMA-NOT Sp. z o.o.

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doi:10.15199/48.2023.07.01

Simple irrigation control system used in small-scale retention

Streszczenie.** W artykule przedstawiono koncepcję urządzenia oraz opis prototypu zastosowanego do zapewnienia optymalnej wilgotności gleby poprzez sterowanie nawadnianiem. Przedstawiono szeroką analizę opublikowanych badań z tego zakresu. Wobec braku prostego i niedrogiego systemu, który zapewniałby optymalne warunki wzrostu roślin, autorzy proponują rozwiązanie, które jest w stanie wypełnić istniejącą lukę. Zdefiniowano założenia i wymagania dla całego systemu oraz jego poszczególnych elementów. Artykuł zawiera opis budowy prototypu urządzenia sterującego oraz opisuje poszczególne elementy, wskazując na celowość zastosowanych rozwiązań. Artykuł kończą wnioski i zadania przyjęte do dalszych prac rozwojowych.* (Prosty system sterowania nawadnianiem stosowany w małej retencji***)

Abstract. The article presents the concept of the device and a description of the prototype used to ensure optimal soil moisture by controlling irrigation. A broad analysis of published research in this field is presented. In the absence of a simple and inexpensive system that would provide optimal conditions for plant growth, the authors propose a solution that is able to fill the existing gap. The assumptions and requirements for the entire system and its individual elements were defined. The article contains a description of the construction of the prototype of the control device and describes the individual elements, indicating the purposefulness of the solutions used. The article ends with conclusions and tasks adopted for further development work.

Słowa kluczowe: mała retencja, sterowanie nawadnianiem, pomiar wilgotności, systemy autonomiczne.
Keywords: small-scale retention, irrigation control, moisture measurement, autonomous systems.

Introduction

Water is an essential element for human, animal and plant life and for the economy. Its protection and management cross national borders. The Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy) obliges all Member States to take action to protect inland surface waters, transitional waters, coastal waters and groundwater. Its goal is to achieve, by 2027, good status of waters and ecosystems dependent on them [1,2]. The latest report of the World Meteorological Organization (WMO) shows that not only rivers and wells are running out of water [2]. Since 2019, the WMO has been publishing annual reports on the so-called the state of climate services, in which it presents the most important challenges and possible solutions in the field of adaptation to climate change. This edition of the report focuses on water and the problems that affect communities in every part of the globe and in every sector of the economy, which directly or indirectly depend on the quality and quantity of water resources.

Water is not a commercial product, but a common good and a limited resource that must be protected and used sustainably, However, it is under pressure from many different applications from different sectors such as agriculture, tourism, transport and energy. In 2012, the European Commission (EC) launched a long-term strategy to protect Europe's water resources. It provides for the establishment by Member States of water balances and water efficiency targets, as well as the development of European Union standards for water reuse. It is worth recalling that the water available to humans is the sum of all freshwater resources, including groundwater in individual layers of soil, groundwater, snow, ice, water stored in vegetation and surface waters of rivers and lakes. According to the WMO report, 2.3 billion people live in countries where water is scarce on a regular basis, of which 733 million live in areas of high and critical freshwater scarcity. In the submitted National Determined Contribution (NDC) declarations (national voluntary emission reduction commitments), as many as 79% of decision makers indicated water as the most important priority in the field of adaptation.

A good example of occurring phenomena is the situation in Central and Eastern Europe (e.g. in Poland). The data presented for Poland by the Central Statistical Office (GUS) in the years 2000-2021 are very disturbing [3].

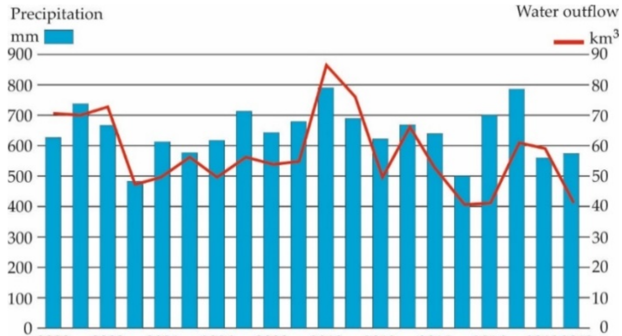


Fig. 1. Precipitation and runoff in Poland [3].

As shown in Fig.1, in 2018 and 2019 Poland's water resources were much smaller compared to 2017, where they were estimated at 60.5 billion m^3. The observed decrease in the biologically active area means that rainwater, instead of soaking into the ground and feeding the local ecosystem, is quickly discharged through the sewage system, causing the formation and deepening of drying phenomena. One of the ways to prevent drought is the so-called. small retention. Small retention is all activities aimed at the development of the natural environment related to the collection, use and slowing down of rainwater and snowmelt runoff. Small retention includes the construction of above-ground and underground reservoirs, ponds or water gardens aimed at retaining rainwater in the place of its precipitation and its slow absorption by the soil. According to the assumptions of small retention, the collected water should be gradually released into the ground during periods when there is no rainfall. The least attractive and economically unjustified is the construction of absorptive wells or drainages that will only infiltrate water into the ground. This exhausts the assumptions of small retention without providing any additional benefits. Irrigation of agricultural land is practical and brings measurable benefits from the use of rainwater. By irrigating the soil with rainwater, we gradually infiltrate it into the ground, and at the same time we enable plants to develop properly and affect the size and quality of crops. By using the collected water in the dry season, we minimize the water intake from the water supply or well.

2. State of art

The issue of water saving in the broadly understood area of agriculture is the subject of intensive research in research centers located around the world. A good example of current trends is the work [4], which analyzes over 230 studies, both practical and theoretical, in the field of water protection technology. The authors conclude that the main remedial measure should be the use of advanced irrigation technologies, such as drip and pipe irrigation systems, which reduce water use in agriculture and thus free up water for alternative uses (e.g., the environment).

Surface irrigation is the most common method of irrigation. The efficiency of surface irrigation is affected by many factors, such as the precision of land leveling, irrigation system layout, irrigation control policies, and irrigation management. Compared to pressure irrigation, surface irrigation is more difficult to control. The paper [5] presents the state of application of surface irrigation technology as well as existing problems and ways of solving them.

When reviewing the literature in this area, two main tasks of advanced technology development can be seen. Firstly, two types of irrigation are being developed, drip irrigation and surface irrigation in various variants, and secondly, soil condition monitoring systems combined with advanced decision-making algorithms are being developed. One such characteristic solution is a pilot installation installed in olive groves located in the province of San Juan in Argentina [6]. Similar work was also carried out in Medellin, Colombia [5], where the relationship between the use of a diffusion tool used in irrigation systems in watermelon crops and modeling and simulation as a tool used for the same crop was investigated. The results showed that the system used is cost-effective and allows to increase production, especially for small and medium-sized growers.

For obvious reasons, African countries are exposed to drought problems. Paper [7] presents the role of small-scale irrigation in the Ethiopian economy, where the problem of sedimentation is the main threat to the effectiveness of small retention systems. In addition to physical irrigation of the soil, continuous monitoring of soil moisture is necessary to achieve high efficiency. In the work [8], vertical and horizontal soil wetting was investigated using drip irrigation and control systems using soil moisture sensors. Empirical relationships were developed to estimate the wetting radius at different soil depths using the non-linear regression method. Many times, in countries with a low level of urbanization, the problem of drought is related to the problem of access to electricity. Paper [9] presents an irrigation system located in Nigeria, powered by photovoltaic panels, giving full autonomy in terms of electricity supply. Similarly, in [10] it was proved that intelligent irrigation systems powered by renewable energy sources significantly improve crop yields and profitability of agriculture. It showed how a solar-powered smart irrigation system can be controlled and monitored using sensors and environmental data. The collected data is used to predict environmental conditions using the Radial Basis Function Network (RBFN). Similar issues are discussed in the work [11], where the effectiveness of drip and sprinkler irrigation was studied in fields in Saudi Arabia for the cultivation of wheat and tomatoes. In the paper [12], a drip irrigation management system was studied in tomato cultivation in greenhouses. The main goal of the work was to build a small control system with precise control of the amount and time of irrigation and fertilization. In the developed system, Penman-Monteith models based on water flow sensors to measure and control the amount of irrigation were used to assess the water demand at each stage of tomato growth.

One of the most important problems in intelligent irrigation systems is the problem of the efficiency of water supply to the soil. Paper [13] describes an automatic irrigation system based on data from soil water sensors used to control valves, pumps and dosing. A slightly different approach to this problem is presented in [14]. The aim of the work was to evaluate the performance of the Remote Surface Irrigation Monitoring and Control System (RIMCS) installed on two separate linear motion irrigation systems. RIMCS varies the water dispensing rates by pulsing the nozzles. The system was installed in an irrigation system in Prosser, Washington, USA, and in an irrigation system in Nesson Valley, North Dakota, USA. The built systems were subjected to can tests to assess the uniformity of irrigation.

The dynamic development of modern information technologies and their wide availability resulted in their use in irrigation techniques. Paper [15] presents an irrigation system based on a wireless network of sensors operating in the Internet of Things (IoT) technology. In the described system, various sensors such as air humidity, temperature, light intensity and soil moisture are used to analyze the current state of the soil. After exceeding the ground moisture thresholds, automatic watering is activated. A similar approach was presented in [16], where an intelligent field crop server was used to control the irrigation of rice fields using advanced information and communication technologies. The proposed system is powered by solar energy and consists of sensors that include lighting, air temperature, air humidity, water level, soil moisture, soil electrical conductivity and soil temperature. Due to the amount of data and transmission frequency, the narrowband Internet of Things (NB-IoT) was used for data transfer. The use of the IoT cloud to control a modern subsurface irrigation system for date palms in arid regions is presented in [17]. The built system is based on an autonomous network of sensors for collecting climatic parameters and volumetric water content in the soil in the study area in real time. For this purpose, the ThingSpeak cloud platform was used to handle sensor readings, perform data analysis and visualization, create event-based user alerts and send instructions to IoT devices. The use of IoT technology is increasingly found in irrigation control systems. Interesting research was presented in [18], where the use of commercial soil moisture sensors in the control of irrigation of horticultural nurseries was described.

Intensive research on agricultural field irrigation control systems has led in many cases to the patenting of the developed structures [19, 20, 21, 22]. With the development of technology and the availability of information technology, a new trend has emerged consisting in the development of the cheapest construction of irrigation systems that are not inferior in terms of the quality of the results obtained to much more expensive and more complicated solutions. An example of such an approach are works [23, 24, 25], which present irrigation monitoring and control systems based on the Internet of Things technology. In these systems, sensors and actuators controlled from the IoT level are designed to autonomously supply water from the tank to home crops. Work [26] goes in the same direction, where the application of the idea of distributed control to a drip irrigation system is described. Paper [27] presents a wireless irrigation control system using IoT technology and wireless communication in the ZigBee standard. Similarly, in [28], a wireless hydration control system was used. The proposed methodology is based on access to a communication network, thanks to which the system is a truly intelligent and autonomous wireless decision support system. Numerical validation and experiments carried out in a vineyard in northern Italy show significant water savings compared to other state-of-the-art thresholding methods. In addition, better use of irrigated water was achieved by reducing the phenomenon of percolation without affecting the quality of the crop. Similar solutions are presented in [29], where the details of the design and instrumentation for variable rate irrigation are described. Wireless sensor networks and software for real-time control of a precise linear surface irrigation system are described. The use of the ZigBee standard is very popular in wireless irrigation systems. Paper [30] presents a simple and cheap automatic irrigation control system based on the ZigBee wireless network. Software was proposed with an irrigation strategy based on models of substrate wetting pattern, lettuce root zone and evapotranspiration. The system can detect soil moisture in real time and automatically water according to soil requirements and irrigation strategy.

The conducted analysis clearly shows that currently most of the research work is focused on the development of simple and cheap, both in purchase and installation, irrigation control systems for agricultural crops. Looking for the optimal solution, it is concluded that the developed system should be fully autonomous in terms of power supply (photovoltaic panels), control ground moisture, ground and air temperature, and ensure trouble-free operation for a long time. The vast majority of the developed units are equipped with processors from the Arduino family, ensuring the implementation of basic irrigation control algorithms and communication modules. Depending on the expected distances of the measurement nodes from the central unit, they can be ZigBee modules or, for example, LoRaWAN at slightly greater distances. Most solutions use a liquid crystal display for direct communication with the user.

Particular attention should be paid to the measurement of soil moisture, which in the simplest commercial solutions is omitted or replaced with measurements of air parameters. According to the authors, the measurement of ground moisture is necessary for the correct operation of the control system. Considering the wide range of people interested in such a system, its price will play an important role. It should not exceed, on average, EUR 200 for a basic measurement and control unit.

3. System concept

Previously discussed devices used to irrigate plants have clear shortcomings in terms of functionalities, and design simplifications are particularly evident when their capabilities and functions are compared with plant crop requirements throughout their growth cycle. None of the marketed devices measures soil temperature, which determines the correct growth of the root system [34]. After a review of the devices available on the market, the authors adopted assumptions for a designed simple and inexpensive irrigation system:

- to be able to use water collected in reservoirs, outflowing under the action of gravitational forces,
- to have stand-alone electric power supply that enables installation and operation at any location,
- not to require device programming; device fitted with an adaptive algorithm to quickly adapt irrigation frequency and duration to operating conditions,
- to enable adjusting the desired soil moisture in order to provide plants with optimal growth conditions throughout their entire life cycle,
- to measure such plant growth parameters as soil moisture and temperature, air humidity and temperature, dew point,
- to store all collected data in the memory and display to the user on demand.

Fig. 2 shows a sketch of a developed measuring system that controls the irrigation of selected areas.

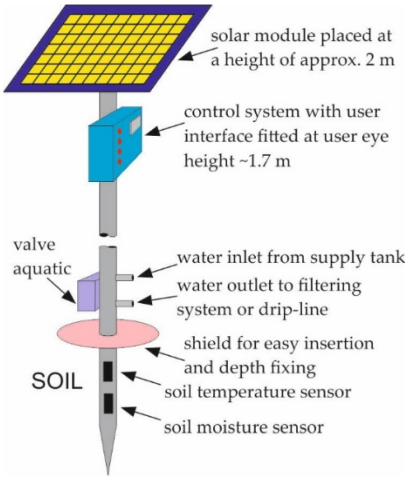


Fig. 2. Sketch of a device for monitoring vegetable crop growth

The structural sketch from Fig. 2 and the adopted assumptions directed the construction work and resulted in defining the ultimate form of the device being designed. A rectangular housing holds the electronic part of the irrigation system that contains the power supply system, control system and sensor signal conditioning modules. The front wall of the housing is fitted with a user-communication panel that contains a display, device switch and a button to turn off the display and for the user to respond to displayed messages. The rear wall of the housing, which is the least insolated, contains ventilation openings protected from rain, which enable free interior ventilation. The top part of the device holds a solar module that ensures sufficient energy to supply the system and protects the electronic system cover against sunlight and precipitation. The housing, together with the solar module, is fixed on a tubular base frame that enables easy installation through driving it into the ground. The bottom part of the device has a water valve, as well as soil temperature and moisture sensors.

4. Construction of a measuring system

The designed device was named Vegetable Crop Control System or “SDUW-2021” in short (the abbreviation comes from the Polish name of the device). The block diagram of the device is shown in Fig. 3.

Its operations are controlled by an ATmega328P-U processor by Atmel, encased in a through-hole housing with a 16 MHz quartz resonator. Owing to the application of the I2C bus in the communication system [37], all sub-assemblies that use it maintain connectivity with each other through only two wires: I2C Data and I2C Clock. It is very important in terms of savings in relation to the number of designed paths and using only two microprocessor ports – SDA and SCL. Within the designed system, the common bus connected to ATmega328 is used by 4 devices: an OLED display, DHT timer, DS3231 real-time clock and AT23C32 memory.

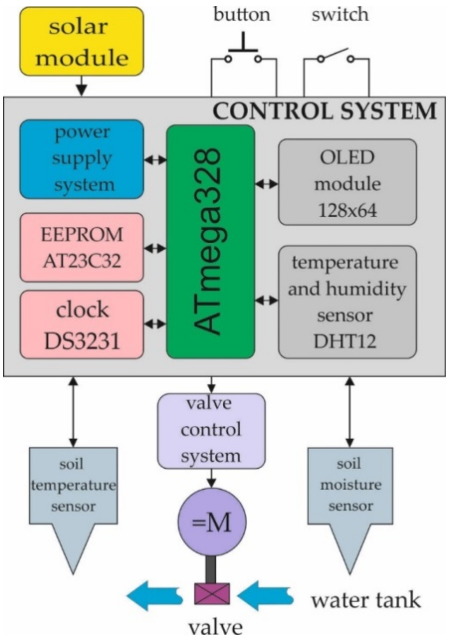


Fig. 3. The block diagram of the designed device

The proposed system employs an RTC DS3231 module, which enables real time determination for the purposes of the device and the user. Its high accuracy was achieved, among others, owing to the oscillator temperature compensation system. The DS3231 clock enables reading time in hours, minutes, seconds and reading date in months, day and year, and the built-in calendar contains leap years. After disconnecting the power supply, the module automatically switches to the power supply from an internal lithium-ion LIR2032 battery. The use of a rechargeable battery instead of an ordinary CR2032 lithium cell means that in the event of partial battery discharge, it is charged by the system to which the timer is connected. The designed device will operate during the spring-summer and the autumn periods, which is why the change to wintertime is not required. Prior to installation of the PCB, the clock module was set to UCT +2.

The constructed device employs several ready-made sub-assemblies in the form of modules. These include integrated circuits, such as: RTC DS3231, EEPROM memory and a DHT12 sensor, placed on a specially prepared printed circuit board. These elements have resistors, decoupling capacitors and LED indicators in the SMD technologies. It facilitates constructing the system, makes it more convenient and ensures its miniaturization.

Internal EEPROM AT24C32 memory installed within the real-time clock module is used to save average daily temperature and humidity values. It is a rewritable memory, the decoupling of which does not lead to erasing all data. Its capacity is 32 kB and the processor communicate with EEPROM via the I2C bus. The AT24C32 memory enables programming periodic alarms used to send a so-called hourly internal interrupt signal to the system initiating the execution of an instruction that involves collecting data from sensors, starting the watering procedure, saving the average daily value of measured parameters, etc. An OLED display that is resistant to strong sunlight and the associated high temperature has been used for communication with the use and data presentation.

Strictly interconnected air parameters, namely, temperature and humidity, are measured with the DHT12 sensor that enables determining both these parameters simultaneously.

Air humidity can be determined in several ways, depending on the type of required information [4]. Various measurement methods provide information on relative humidity – RH, absolute humidity – AH, humidity deficiency – HD and dew point temperature – Td.

Relative air humidity is the ration between water vapour in air and the maximum amount of water vapour (AHmax) that can be present in the air, before it starts to condense. It can be calculated using the formula (1)

$$RH = \frac{AH}{AH_{max}} \cdot 100\% \tag{1}$$

The AH_{max} parameter is dependent on ambient temperature T and at a temperature above 0 °C is expressed by the formula (2)

$$AH_{max} = 1342.5 \cdot \frac{10^{\frac{T \cdot 7,5}{T+237.2}}}{T+273.15} \frac{g}{m^3} \tag{2}$$

As indicated by formulas 1 and 2, relative air humidity RH depends on temperature and if it changes, it is only because of reduced or increased amount of water vapour in the air AH (precipitation, inflow of dry air) or upon a change in ambient temperature. An increase in AH_{max} does not change the amount of water vapour in the air but reduces its relative humidity. Increased amount of water vapour in the air (AH) and reduced temperature or both these processes simultaneously lead to air water vapour saturation. Temperature at which water vapour in the air starts to condense is the dew point T_d. It is calculated with an approximation of ± 1% for relative air humidity (RH) above 50%, using the formula (3)

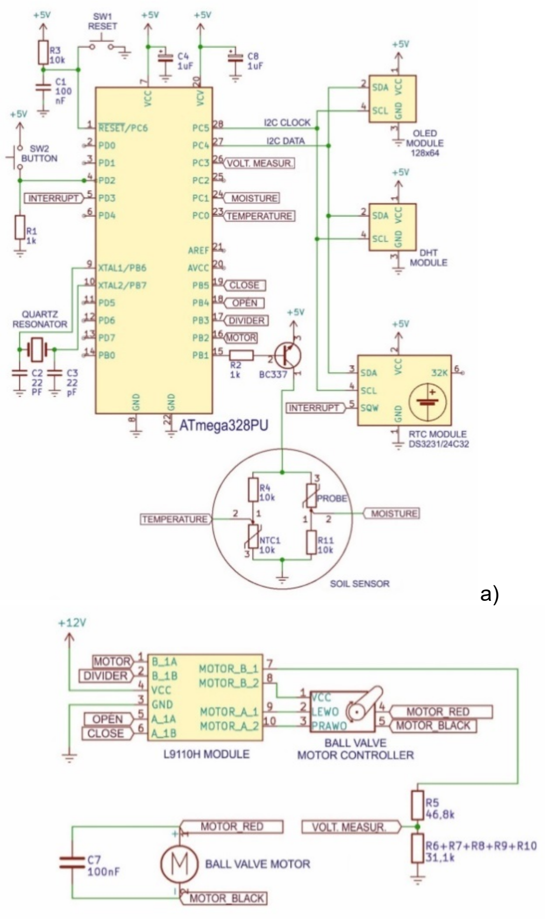
$$T_d = T - \frac{100 - RH}{5} \tag{3}$$

The DHT12 sensor, which measures relative air humidity (RH) and air temperature within the system has been selected based on its compact dimensions, option to communicate via I^2C, low price and its availability. In addition, the program library enables communicating with the sensor via the I^2C bus and offers a function to convert collected humidity and temperature data to dew point. The calculated dew point, together with other parameters, is displayed to the user by SDUW-2021.

In order to minimize energy consumption, soil moisture and temperature sensors are powered only when the system is conducting measurements.

Designed and manufactured soil moisture sensor consists of two, 80 mm long rigid wires made of stainless steel that are positioned 6 mm apart. The resistance between them changes depending on soil moisture. The signal read by the system, similarly to the temperature sensor, is a voltage signal. Despite the design that suggest driving it into the ground, the used sensor should not be positioned vertically in the ground, since soil moisture may vary at different depths due to water penetrating deeper into lower strata. The soil moisture sensor should be positioned horizontally, at half the depth of a plant's root system. Detecting moisture at this depth ensures the user that the plant may draw water through its root system. The sensor was connected in the voltage divider system.

Fig. 4a shows the diagram of the SDUW-2021 irrigation system control circuit to which soil moisture and temperature sensors are connected. PB4 and PB5 outputs of the ATmega microprocessor send signals to the control module of the motor cooperating with a ball valve. Fig. 4b shows the connection diagram of the ball valve control system.



a)

b)

Fig. 4. Irrigation system control circuit diagram (a), valve control system diagram (b)

The SDUW-2021 irrigation control system requires two supply voltages. One constant 12 V for the DC motor that opens and closes the water valve and one 5 V for supplying electronic circuits of the system, such as: ATmega328, moisture and temperature sensors, OLED display and DC motor controller. Irrigation system power supply diagram is shown in Fig. 5.

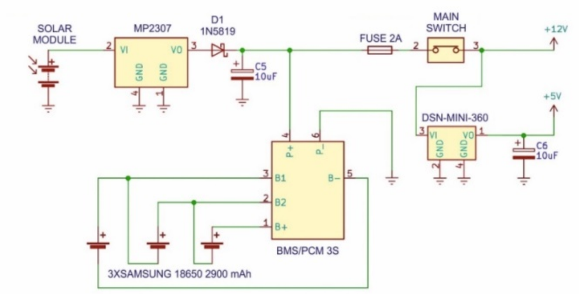


Fig. 5. Irrigation system power supply diagram

The basic electricity source for the irrigation system is the polymorphic solar module with an operating voltage of 18 V, current of 277 mA and a maximum capacity of 5 W, which cooperates with three Li-Ion batteries with a source voltage of 3.7 V connected in series. Solar module electricity is transformed by a DC-DC converter that reduces MP2307 voltage to a required value of 12 V. The batteries that act as an electricity storage within the system are charged by the BMS/PCM 35 (*Battery Management System/Protection Circuit Module*), which ensures optimal operating conditions and protects against overvoltage, excessive discharge and overcharging. Owing to its design, the module controls voltage level at each of the batteries separately.

Energy demand of a complete device was calculated in order to determine the minimum battery capacity, as well as solar module power and current. The conducted analyses indicated that the entire system shall satisfy the daily power demand at a level of 5.46 Wh, which corresponds to a battery capacity of 1.37 Ah, assuming that the device operates with battery backup for at least 3 days. These requirements are fulfilled, for example, by the INR-18650-29E battery by Samsung, which has a capacity of 2.9 Ah. A constant voltage of 5 V is required to supply electronic circuits of the irrigation system. It is obtained at the output of the DSN-MINI-360 pulsed converter, which transforms electricity from the solar module during normal operation or batteries during battery-based operation.

The use of an electric motor to open and close the water ball valve forced the application of battery voltage control within the power supply system. The valve cannot remain open if the energy accumulated in the batteries is insufficient to close it. Valve adjustment depends on the battery bank voltage value. Detecting a too low voltage leads to the control program preventing valve opening. In the case of an insufficient battery charging status, the valve will remain closed until they are charged by the solar module. An analogue-to-digital ATmega328 transducer was used to monitor the battery bank voltage level. However, this required lowering the battery bank voltage level to 5 V by using a voltage divider. The battery charger is also their protection against discharge and disconnects power supply to the system at a level from 2.95 V to 3.05 V on each battery. Assuming that watering lasts for 50 minutes (0.83 hour), the system consumes (4)

(4) $(0.83h \cdot 0.33W) + (0.01h \cdot 7.8W) = 0.348 \cong 0.35Wh.$

After analyzing valve operating conditions, it was found that, for safety reasons, the valve would have to remain closed until 3 batteries are not charged to a level of 9.9 V (3x3.3 V).

A number of actions aimed at minimizing energy consumption were conducted also due to the power supply from the batteries. The initially used Arduino UNO controller was replaced with the ATmega328P-U. This eliminated the need to power additional Arduino peripherals, such as the USB programmer, diodes or voltage regulators. Only the processor is powered. The device remains in sleep mode owing to the SLEEP_MODE_PWR_DOWN function, which deactivates the processor and suspends its operation, lowering power consumption of the microprocessor to virtually nothing. Waking up from the sleep mode can only be achieved by an external interrupt signal from the real-time clock or via a button pressed by the user. The execution of the “DEEP_SLEEP_MODE” function is preceded by isolating peripheral systems, such as moisture and temperature sensors. This is aimed at maximizing the reduction in power consumption when the device is in standby mode 5 V power is disconnected by the BC337 transistor.

The device is fitted with a water ball valve controlled by a 12 V DC electric motor. The water valve used for watering is opened and closed by ATmega328 via a module with a L9110H integrated circuit. The used module can work with voltages up to 12 V and can be controlled by a 5 V voltage that also supplies the ATmega328.

It is the computer software and not the user that decides to turn off the valve, and for this reason, the water valve cannot be controlled mechanically, since the system is able to turn on and off the valve only via an electric signal. A conducted analysis led to employing a mechanical water ball valve controlled by a low-power electric motor. Unlike other devices available on the market, full valve opening, or closing does not require pressure in the water system. This enables irrigating with rainwater accumulated in the tank and outflowing due to gravity. The valve must also be resistant to weather conditions due to the intended use of the entire system it is a part of Fig. 6 shows the irrigation system control program algorithm.

The control software operates in a closed loop, and the system remains in sleep mode, reacting only to two external signals, namely, an interrupt signal from a programmed algorithm and an interrupt signal sent by a button pressed by the user.

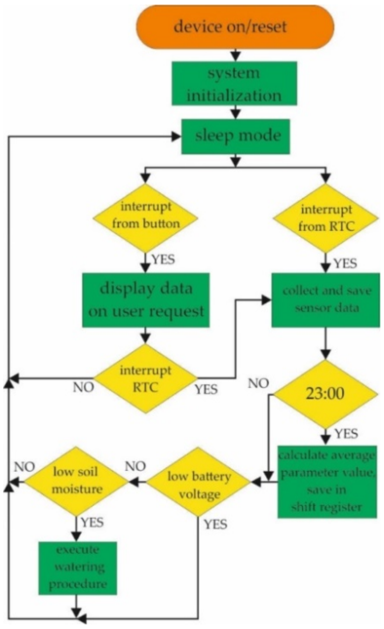


Fig. 6. Control program block diagram

The interrupt signal is sent every hour, at 00 minutes of each hour. After receiving the signal, the algorithm turns on sensor power supply via the BC337 transistor, followed by collecting and saving sensor data, as well as the ordinal number of the measurement to calculate the average daily air temperature value, soil moisture and soil temperature. If it is after 23:00, the software calculates average daily values of the parameters and saves them in a shift register so that the user is able to start browsing data starting from the day before, followed by the day before yesterday and up to 5 days back. Next, the program decides to start watering, which may occur in the morning, i.e., from 05:00 to 10:00, and in the afternoon, i.e., from 16:00 to 20:00. The ball valve actuation signal is sent when soil moisture (WG) is lower than watering threshold value (WPP), and watering duration T is set by the adaptive algorithm presented in Figure 7.

The initial value of time T is saved in the control program and can be changed by the adaptive algorithm. After data processing and irrigation procedures end, the software disconnects sensor power supply and shifts the processor into standby mode in order to save energy.

The second signal that wakes up the system from standby mode originates from the button intended for the user to press. The software understands it as a request to display collected data. After receiving this signal, sensors are powered and then data is collected. In each case upon the device being deenergized and its later activation, and upon pressing the *reset* button, the system is initialized, and its primary settings are restored.

Equipping the device in a soil moisture sensor and controlling the watering process via an algorithm eliminated the disadvantage of most such apparatuses, which involves the need to frequently program time and intervals between individual watering cycles. Due to the assumed possibility of installing the device in any location and with any irrigation system, the watering process is executed according to an adaptive algorithm, which matches irrigation start and stop times to varying conditions. It was decided that watering would be activated in the morning and afternoon hours, to protect the soil against water evaporation during highest sun exposure or against the appearance of diseases resulting from excessive moisture around the plants at night.

The water solenoid valve may be activated only at hours saved in the memory and when the measured WG parameter value is lower than WPP. The WPP is saved in the control software and is 60% by default. In each case when displaying data, the user will be able to change the WPP parameter value. The parameter can be changed in the range of 0% to 99%.

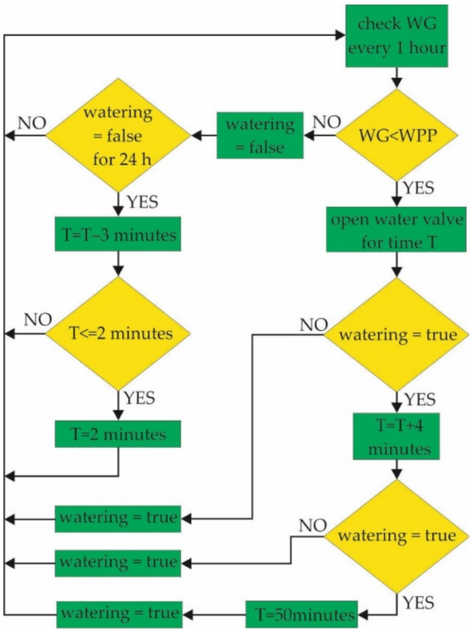


Fig. 7 Adaptive algorithm block diagram

A manual modification of the WPP parameter improves device functionality and provides the user with a possibility to react in a situation of erroneous soil moisture readings that can appear depending on soil type (e.g., humic, sandy, clayey).

The device will notify the user of watering duration and its end time through showing information on the display, when the valve is open.

Due to the large freedom in selecting the sensor installation location and depth, and lack of knowledge on the rate of water infiltration into the soil, conditioning watering duration upon soil moisture sensor readings was deemed unreliable. Watering will be stopped upon the software-save time T elapses and not after receiving information from the sensor after reaching sufficient moisture.

By default, the watering duration is 5 minutes and, depending on device operating conditions, will be increased or reduced. Watering duration will increase every hour, if there is a need for watering every hour, i.e., when the duration of the previous watering cycle was too short. Watering duration may be increased by adding 4 minutes to the previous value. The maximum watering duration is 50 minutes. The adaptive algorithm will not increase watering duration if the need for watering is less frequent than every hour.

Gradual increase of the watering duration up to the maximum value may occur in the first days after installing the system, when the soil is dry. For this reason, the preset watering time may be too long and in order to prevent that, 3 minutes will be deducted from time T every 24 h, when watering is not activated. The minimum watering duration cannot be shorter than 2 minutes.

5. Conclusions

Already based on the design of the irrigation system, it was possible to initially evaluate its advantages, but its reliable assessment was possibly only after its prototype was constructed. The finished prototype is shown in Fig. 8. After constructing and launching, the control system was subjected to comprehensive testing. These involved both intuitiveness and resistance to all kinds of interference. The results obtained so far are positive and confirm the validity of adopted assumptions and solutions. The system is still under long-term testing. After they are completed, it will be possible to assess its actual suitability under conditions of small-scale horticultural crops. The constructed irrigation system prototype is undoubtedly innovative on an unprecedented scale, which, among others, opens up a wide spectrum of applications. It can be used to irrigate crops using not only accumulated rainwater through a water valve that does not require water pressure to open and operate correctly, but also using water from the water network. Within 1 to 2 days, the employed adaptive algorithm adapts watering duration to system operating conditions and will also respond to long-term weather changes associated with passing seasons of the year.

The use of batteries charged by a solar module enabled making the device independent of the mains power supply or galvanic cells. This allows the user to not only install the device at any location but also leave it operating when leaving the house or allotment garden for a longer time and turning off mains power supply for safety reasons, at least in terms of external sockets. In the same scenario, the options of saving and reading parameters can be useful for the user to get acquainted with what happened to the crops during his/her absence.

The application of additional moisture and temperature sensors provides the user with additional knowledge useful in growing plants, and also enables utilizing the SDUW-2021 as a local weather station. The satisfactory cost of the prototype below EUR 110 is particularly noteworthy.

Fig. 8. Photographs of a finished irrigation system prototype

Work on the vegetable crop monitoring system lasted for more than 18 months, and the knowledge and experience gathered throughout this period allow a conclusion that the European market of cheap and simple irrigation devices has just began developing and its offer is very poor. The decreasing amount of rainfall or at least their reduced frequency, and the growing water consumption prices will surely lead to increased interest in irrigation systems. The developed system is constantly modified, in terms of both software and hardware. The main tasks to be implemented in the nearest future include:

- linking the adaptive algorithm with the average temperature for the day before; average daily temperatures in the summer are 20 °C, therefore, if the calculated average daily temperature exceeds this value, the algorithm should automatically extend the watering duration,
- averaged daily air temperature records should be divided into the average temperatures during the day and night,
- installation of a Wi-Fi module and transmission of collected data to an application, which will improve the attractiveness of the devices and its user convenience.

The built system has been operating for over 8 months now and systematic observations clearly indicate an increase in the efficiency of the use of rainwater with a noticeable improvement in the vegetation of cultivated vegetables. A full assessment of the functionality of the constructed device can be carried out after at least two vegetation cycles.

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