Internet of Things as an element of the frost protection system in orchards

M Awtoniuk¹, T Nowakowski¹, J Chlebowski¹, A Świętochowski¹, M Dąbrowska¹, J Klonowski¹, M Sypuła¹, A Strużyk¹, D Wrona², W Kowalczyk² and K Bąk³

¹ Warsaw University of Life Sciences, Institute of Mechanical Engineering, Nowoursynowska 166, Warsaw, Poland
² Warsaw University of Life Sciences, Institute of Horticultural Science, Nowoursynowska 166, Warsaw, Poland
³ MCMS Warka Sp. z o. o., Gośniewska 160, Warka, Poland

michal_awtoniuk@sggw.edu.pl

Abstract. Frosts cause serious damage to fruit and vegetable crops. In Poland, temperature decreases, and the occurrence of inflow (advective) frosts most often fall during the flowering period, i.e., in a phase extremely important for the development of the plant. For orchards, this causes the inflorescences of early flowering trees (cherries, plums and certain varieties of apple and pear trees) to freeze. A modern idea for reducing frost losses in orchards is to heat the air with mobile heaters. Protection by these machines consists of passing using an agricultural tractor in rows of trees or shrubs and heating and mixing the air. The problem that farmers may encounter during frosts is the awareness of when exactly such a weather condition occurs in their orchard. Weather forecasts are not detailed and usually apply to the entire region. Dangerous temperature declines below the critical minimum can occur locally and are also conditioned by geographical location and terrain diversity. The aim of the article is to present a measuring system that allows the construction of an individualised temperature model taking into account the unique shape of the orchard surface. The system is made in Internet of Things technology using long-range radio communication protocol LoRaWAN. Data from distributed measurement sensors are processed on a network server and displayed as a final application. The task of the system is to monitor the current situation in the orchard and to notify the farmer of the need to initiate a protective procedure. The operation of the system also supports the efficient use of mobile heating machines. The system facilitates the location of the areas in the orchard with the lowest temperature, as well as provides feedback on temperature changes inside the treetops caused by the passage of the mobile heater.

1. Introduction
Frosts cause serious damage to fruit and vegetable crops. For Polish conditions, in the temperate climate zone, cultivated fruit plants, especially apple trees, are each year exposed to damage to flowers and fruit buds as a result of the occurrence of spring frosts [1,2]. Significant decreases in temperature most often occur in early spring and autumn at night or in the morning. The most dangerous for apple trees are spring frosts because in this period flower buds develop and trees bloom [3]. The damages are caused directly by negative temperature in the form of ice crystals in the intercellular spaces, which in turn results in gradual dehydration of the cell. This phenomenon may result in multidirectional changes leading to complete death of blooms and plants, e.g., loss of turgor, reduction of the cell volume,
destruction of cell membranes and increase in the concentration of cell juice. Frosts may be of a different nature, from mild, ranging from -0.1°C to -2°C, to severe frosts, exceeding -4°C [4]. In addition to the temperature range, for causing damage to fruit plants the length of frosts occurrence is also important [3,5–7].

There are several methods to prevent spring frosts. The simplest methods are passive methods, i.e., “avoiding” frosts. They consist of the establishment of orchards outside frost pools, the use of late-flowering varieties with flowers that are as resistant to low temperatures as possible, or the use of appropriate soil cultivation [8].

The active methods of fighting frosts include sprinkling trees during frosts, the use of chemical preparations to prevent the formation of ice crystals in plant cells, the use of stimulants that activate the plant’s defence mechanism due to the absorption of iron, magnesium, aluminium, silver and other sulphates. Moreover, a very efficient method is air heating as a result of the combustion of various materials (sawdust, briquettes, straw) in order to obtain heat increasing the air temperature in the orchard. And mobile heating devices cooperating with a tractor are commonly used [4]. The use of air heating devices in orchards allows for increasing the temperature around plants, causing air movement and lowering its relative humidity [9]. An example of a mobile air heater is shown in Figure 1. This is the UZP-350/4 model produced by MCMS Warka [10].

![Figure 1. Mobile air heater UPZ-350/4.](image)

The problem that farmers may face during frosts is the awareness of the exact time of such a weather condition to occur in the orchard. Regional weather forecasts are not detailed and usually cover the entire region. Dangerous drops in temperatures below the critical minimum may occur locally and are also conditioned by the geographic location and diversity of the terrain. This creates the need to build a local air temperature monitoring system that provides continuous information. Modern technologies based on the Internet of Things (IoT) can be used for this purpose [11,12]. The information bits provided by the IoT system installed in the orchard help to make the right decisions regarding the protection of the crop.

The basic assumption of IoT technology is the communication of various objects (Things). Those objects can be sensors, actuators, gateways, mobile devices or servers. Servers, also those located in the cloud, may contain implemented services of various types, e.g., a database or SCADA supervisory systems [13,14].

One of the most widely used networks in IoT systems is LPWAN (Low Power Wide Area Network). The main standards of LPWAN networks include SigFox, NB-IoT and LoRaWAN [15–19]. It is estimated that by 2026 more than half of all LPWAN networks will use the LoRaWAN standard.
The aim of this article is to present a measurement system designed to monitor the air temperature in orchards. The system is made on the Internet of Things technology using the LoRaWAN standard. Using this technology, it will be possible to develop an individualised temperature model taking into account the unique shape of the orchard surface.

2. Materials and Methods

2.1. Architecture of the IoT-based measurement system
A schematic of the system is shown in Figure 2. Several layers can be distinguished, responsible for:

- data acquisition,
- data transmission,
- data processing.

The hardware part of the system is based on Milesight products. The official distributor of Milesight devices in Poland is IoT Solution [20].

Data acquisition is based on a grid of battery-powered sensors. The EM500-PT100 devices are responsible for this. Temperature measurement is carried out using a Pt100 sensor in the range from −10°C to +40°C with an accuracy of 0.5°C. By using an external measuring probe, it can be placed directly in the canopy of the tree, e.g., at the bud. All the EM500 devices are the end nodes in our IoT system. They transmit the data to the UG67 gateway employing LoRaWAN protocol every 10 minutes. The gateway has been configured as a packet forwarder. The data from the gateway is sent using the MQTT protocol to the cloud server. We use ChirpStack open-source LoRaWAN Network Server as a
cloud. The main components of the cloud server are the gateway bridge, network server and application server. Gateway bridge is a service that converts the messages received from packet forwarder (i.e., UG67 gateway) to JSON data format. The data then passes through the network server where message authentication, among other things, is performed. Finally, the data reaches the application server, which is responsible for their aggregation in the database. The system architecture designed in this way gives great possibilities for communication with the user, e.g., the owner of the orchard, through various forms of end applications. At this stage, we are using the Blue Open Studio SCADA system by Schneider Electric running on a Microsoft Surface Go tablet.

2.2. Location and installation of the IoT-based measurement system

We installed the system in the orchard in the town of Pilica, postcode 05-660, Warka, Poland. In the tested area, there are two varieties of apple trees that grow in ten rows. The first variety is Gala, grown on M9 rootstock (six rows), and Ligol which grows on P60 rootstock (four rows). The trees of the Gala variety had an average height of 3.07 m and grew in rows every 1.03 m, with a row spacing of 3.51 m. The trees of the variety Ligol, on the other hand, were 3.26 m high and grew in rows every 1.70 m, with a row spacing of 3.79 m. According to the orchard owner’s experience, frost stagnation occurs on the selected plot.

We installed 31 of the EM500-PT100 sensors. The sensors were installed on rows I; IV; VII and X with a row spacing of 10.43 m. More sensors helped us to evaluate our proposed method of interpolating the results as well as to develop guidelines for mounting the sensors. Measurement sensors were mounted with cable ties on support poles for variety GALA and on tree shoots for variety LIGOL (Figure 3). Then the measuring probe was mounted with clamps. The sensors, irrespective of variety, were mounted at an average height of 1.41 m and the measuring probes at 1.61 m from the ground. In addition, three verification sensors were mounted in rows II, V and X at distances from the start of the row of 35.70 m, 47.13 and 15.20 m, respectively. The gateway was mounted on the storage wall at a height of 9.3 m (Figure 4). In addition, the gateway was placed on an angled mast to increase the data transmission capability in different directions.

Next, we performed GPS positioning of the sensors and the gateway. Figure 5 shows a satellite image with the positions marked. The average distance between the gateway and the sensors was 222 m, the distance to the nearest sensor was 187 m and to the furthest sensor was 262 m. The sensors marked in
yellow are verification sensors. The measurements of them served as a test dataset in the process of verifying the algorithm of interpolating the results.

2.3. Interpolation method for temperature measurement

Interpolation is a method of estimating the value of a feature for a place where it has not been physically measured. The value is calculated based on data from several points in the neighbourhood. Many interpolation methods use different algorithms. The most popular in spatial information systems are inverse distance weighting (IDW), spline, and kriging. Data interpolation for fields with very high spatial variability requires a sufficient number of samples and their location should not be random. The first step, however, should be to assess the quality of the surveyed feature on the basis of non-interpolated data, because the interpolation process itself smooths the map and makes it look reliable even if the data have very poor quality. The main goal of the system is to provide information about the local air temperature in the orchard. For economic reasons, the number of sensors should be minimal. To perform measurement interpolation, we used the IDW. The IDW method is supposed to make it possible to calculate the temperature value at any place in the orchard from the measurements of all the sensors corrected by suitable weights according to the equation:

\[
T(x, y) = \sum_{i=1}^{n} \frac{\left[ \left( \frac{(x-x_i)^2 + (y-y_i)^2}{k^2} \right)^{\frac{k}{2}} \right]}{\sum_{i=1}^{n} \left[ \left( \frac{(x-x_i)^2 + (y-y_i)^2}{k^2} \right)^{\frac{k}{2}} \right]} \cdot T(x_i, y_i)
\]  

(1)

where:
- \(T(x, y)\) – temperature calculated at a point with coordinates \((x, y)\),
- \((x, y)\) – longitude and latitude respectively,
- \(T(x_i, y_i)\) – temperature measured by the sensor with coordinates \((x_i, y_i)\),
• \( p \) – a natural number that \( p>0 \); the greater \( p \) the greater the impact on \( T(x, y) \) of sensors located closer to the point with coordinates \((x, y)\).

3. Results and discussion

3.1. Sensor battery life calculation

In terms of sensor power consumption, the key components are the battery (Figure 6B) and the LoRa communication module (indicated by the red box in Figure 6A). The sensor is powered by a lithium chloride-thionyl (Li-SoCl2) battery with a capacity of 19 000 mAh. The battery is easy to remove and is available from many electronics retailers under the trade code ER34615. The sensor uses a LoRa radio communication module marked as E22-900M22S from Ebyte. The current consumption declared by the manufacturer depending on the module’s operating state is shown in Table 1.

![Figure 6. Overview of the PCB of the temperature sensor: A) from the battery fixing side, B) from the LoRa communication module side.](image)

| Operation         | Minimum value | Mean value | Maximum value |
|-------------------|---------------|------------|---------------|
| transmitting data | 114 mA        | 119 mA     | 124 mA        |
| receiving data    | 4.8 mA        | 5.0 mA     | 5.9 mA        |
| deep sleep mode   | 150 nA        | 185 nA     | 200 nA        |

Table 1. Current consumption value of LoRa radio communication module declared by the producer.

In order to estimate the possible battery life, several assumptions about the sensor duty cycle have been made:

• the sensor performs periodically two operations, i.e., sending measurement data and sending a diagnostic query,
• measurement data are sent without acknowledgement, data transmission is carried out through an uplink message,
• a diagnostic query consists of two actions, i.e., sending a join message to the network server and receiving an acknowledgement from the server in a form of a downlink message,
• a diagnostic query is carried out every 30 minutes,
• measurement data are sent every 10 minutes, it is called sampling period and it can be modified by the user,
• to send a data packet, regardless of the type of the message, as well as to receive it, the communication module needs to be powered up at least for 10 s [11],
• sensor enters deep sleep mode whenever it is not sending measurement data or executing a diagnostic query.

According to the assumptions and data provided by the manufacturer of the communication module, we can estimate the hourly energy consumption of the sensor as:

\[
Q_h = \frac{t_t \cdot I_t + t_r \cdot I_r + t_s \cdot I_s}{3600}
\]

\[
t_s = 10 \cdot \left( \frac{60}{T_t} + 2 \right)
\]

\[
t_r = 3600 - t_r - t_t
\]

where:
• \(Q_h\) – hourly energy consumption (mAh),
• \(t_t, t_r, t_s\) – accumulated operating time of the sensor expressed in seconds in the mode of transmitting, receiving or sleeping, respectively, for 1 hour, where the time \(t_t\) depends on the sampling period \(T_t\); the time \(t_r\) is fixed at 20 s,
• \(T_t\) – sampling period expressed in minutes,
• \(I_t, I_r, I_s\) – sensor current consumption in transmit, receive or sleep mode express in mA.

Assuming maximum current consumption values declared by the manufacturer and a sampling period of 10 minutes, the hourly energy consumption is \(Q_h = 3.48\) mAh. With a battery capacity of 19 000 mAh, we obtain a battery life of more than 5 460 h, which corresponds to more than 220 days. If we reduce the sampling period to 1 minute, the hourly energy consumption will be equal to 22.1 mAh. Therefore, the battery life will then be approximately 870 h, meaning over 35 days. For comparison, in the paper [11] obtained 398 h of battery life for the measurement system with 10-minute sampling powered by a 6 000 mAh battery. If a similar battery were used in our system, the battery life would be over 1 720 h.

3.2. Interpolation of air temperature measurements

The IDW interpolation method uses equation 1 to determine the calculated temperature. The formula takes into account the temperatures read by the individual sensors and their position relative to the calculated point. For the calculation, it is required to determine the value of the power exponent \(p\). The greater \(p\) the greater the impact on the calculated temperature of sensors located closer to the point of calculation. We determined the value of \(p\) experimentally, using the verification sensors (marked in yellow in Figure 5). Taking different values of \(p\) from the range \(<1; 10>\), we calculated the temperature values for the coordinates of the verification sensors, treating their measurements as an element of the testing dataset. Then we calculated the mean square error MSE for the complete testing dataset according to equation 3. The smallest value of the MSE error (i.e., 0.59) was obtained for \(p = 1\) and this value was adopted for further research.

\[
MSE = \frac{\|T_m - T_c\|_2^2}{N}
\]

where:
• \(T_m, T_c\) – temperature measured by the sensor and calculated through the interpolation method,
• \(N\) – number of measurements,
• \(\|\|_2\) – Euclidean norm.
The calculations were performed for the period of data collected on 14-15.06.2021 between 21:00 and 04:10. The choice of the time window was not accidental. Analysing the measurement data, we have noticed a relationship between the value of the mean square error MSE and the scatter of the measurement data (Figure 7). Smaller values of MSE occurred in the periods of smaller data scatter, i.e., the difference between the maximum and minimum value of the measured temperature. Typically, these periods occurred during night-time hours. During the day, some of the measurement probes were strongly affected by sunlight, thus overestimating the indications. In extreme cases the scatter exceeded even 10°C. At the turn of 14 and 15 June, sunset and sunrise fell on hours 20:55 and 04:16. In the night hours, the scattering of measurement values has smaller variations, which is also reflected in the accuracy of the interpolation method. Taking into account the fact that frosts also occur in a similar period of the day, we have decided that further analysis of the interpolation method will be performed just for the night hours. In the time interval from 21:00 to 04:10, the scatter of measured values ranged from 1.9°C to 4.1°C and its average value was 2.7°C.

![Figure 7. Comparison of the measurement scatters in the 24 hours with the mean square error for the interpolation method.](image)

The next stage of testing the method of interpolating the measurements was an attempt to minimise the number of sensors. The system in its present configuration consists of 31 sensors, of which three are used as verification sensors. The following scenarios for reducing the number of sensors were analysed (Figure 8):

- the present arrangement of 28 sensors, (93 units/ha),
- the orthogonal arrangement of 16 sensors, (53 units/ha),
- the triangular arrangement of 14 sensors, (47 units/ha),
- the orthogonal arrangement of 12 sensors, (47 units/ha),
- the triangular arrangement of 10 sensors, (40 units/ha),
- the orthogonal arrangement of 8 sensors, (27 units/ha),
- the triangular arrangement of 8 sensors, (27 units/ha),
- the orthogonal arrangement of 6 sensors, (20 units/ha),
- the triangular arrangement of 6 sensors, (20 units/ha).

Figure 8. The scenarios of sensors arrangement (sensors marked green are active, red inactive): A) the present arrangement of 28 sensors, B) the orthogonal arrangement of 16 sensors, C) the triangular arrangement of 14 sensors, D) the orthogonal arrangement of 12 sensors, E) the triangular arrangement of 10 sensors, F) the orthogonal arrangement of 8 sensors, G) the triangular arrangement of 8 sensors, H) the orthogonal arrangement of 6 sensors, G) the triangular arrangement of 6 sensors.

For each scenario, we calculated the MSE error in the time interval from 21:00 14.06.2021 to 04:10 15.16.2021 for all three verifications points. The relationship between MSE and sensor arrangement shows Figure 9.
Figure 9. Impact of the number of sensors and their arrangement on the MSE.

The dashed line indicates the error we obtained using all 28 sensors for the calculations. A comparable MSE value was obtained for two variants: 10 sensors triangularly arranged and 16 sensors orthogonal arranged. In two variants, i.e., 6 and 8 sensors arranged triangularly, the reduction in the number of sensors resulted in a decrease in MSE to the value of approx. 0.39. This means that the target number of sensors per ha could be reduced by 78% (from 90 units/ha to 20 units/ha). Other arrangements resulted in an increase in the value of the error of the interpolation method.

4. Conclusions
Poland’s location in a temperate climate zone causes those orchards are exposed to the damage of flowers and fruit buds as a result of spring frosts. At the same time, frost is one of the main sources of serious losses in orchards, particularly in apple orchards. The most vulnerable are the flowers from the pink bud stage until the end of flowering and the fruit buds. During this period, temperatures of $-2^\circ C$ to $-4^\circ C$ can cause the loss of between 10% and 90% of apple blossoms respectively, which has a significant impact on yield. The way to reduce losses is to choose the right protection against frost, such as a mobile air heater.

The article describes the concept of using Internet of Things technology as a system supporting the operation of a mobile air heater. The system is primarily intended to monitor the air temperature and, through the end application, inform the heater operator or orchard owner about the current situation. By using a method of interpolating the results, it will be possible to plot a temperature map of the orchard air at a later stage of the project. In a preliminary study, optimisation of the number of sensors per hectare was performed. Different scenarios with different numbers of sensors in the orthogonal and triangular arrangement were tested. For the triangular arrangement, a more accurate mapping of the verification sensor indications was obtained.

Maximum battery life of more than 5460 h (about 220 days) was estimated for a sampling period of 10 minutes. If sampling increased to 1 minute, the estimated battery backup time would decrease to 870 h (approximately 35 days). Such a battery life is sufficient to monitor the temperature in the orchard during the key period of potential frost occurrence.
5. Acknowledgements
The research was financed in the framework of the project „Innovative frost protection technologies for fruit and horticultural crops” co-financed from the European Union funds under Measure 16 – Cooperation of the Rural Development Programme for 2014–2020.

References
[1] Doroszewski A, Wroblewska E, Jozwicki T and Mizak K 2013 Evaluation of damage to fruit and horticultural plants caused by frosts in May 2011 Acta Agrophysica 20 (in Polish)
[2] Latocha P 2008 Frost resistance and spring frost sensibility of a few cultivars of Actinidia grown in Central Poland Annals of Warsaw University of Life Sciences - SGGW. Horticulture and Landscape Architecture
[3] Koźmiński C and Michalska B 2011 Variability in the numbers of cold, cool, warm, hot, and very hot days in Poland in the April–September period Prz. Geogr. 83 91–107 (in Polish)
[4] Rodrigo J 2000 Spring frosts in deciduous fruit trees — morphological damage and flower hardiness Scientia Horticulturae 85 155–73
[5] Radzka E, Jankowska J and Markowska M 2014 Intensity and frequency of occurrence of ground and air frosts at the Zawady Experimental Station Annales Universitatis Mariae Curie-Skłodowska. Sectio E. Agricultura 69 (in Polish)
[6] Sulikowska A, Wypych A, Ustrnul Z and Czekierda D 2016 Variability of thermal resources in Poland as a result of ongoing climate change Acta Sci.Pol. Form. Cir. 15 127–39 (in Polish)
[7] Dudek S, Ćwikły J and Kuśmiercz-Tomaszewska R 2012 Trends in the occurrence of ground frosts in the region of Bydgoszcz Woda-Środowisko-Obszary Wiejskie 12 93–106 (in Polish)
[8] Boksztzanin K, Wrona D and Przybyłko S 2021 Influence of an alternative soil management system to herbicide use on tree vigor, yield, and quality of apple fruit Agronomy 11
[9] Rabcewicz J, Białkowski P and Konopacki P 2011 Efficiency of air heating trailed machine for protection against spring frost in apple orchard Zeszyty Naukowe Instytutu Sadownictwa i Kwiatarstwa w Skierniewicach 20 (in Polish)
[10] MCMS Warka Products catalogue available at www.mcms.pl
[11] Kuo Y-W, Wen W-L, Hu X-F, Shen Y-T and Miao S-Y 2021 A LoRa-Based Multisensor IoT Platform for Agriculture Monitoring and Submersible Pump Control in a Water Bamboo Field Processes 9 813
[12] Ojo M O, Adami D and Giordano S 2021 Experimental Evaluation of a LoRa Wildlife Monitoring Network in a Forest Vegetation Area Future Internet 13 115
[13] Nord J, Koohang A and Paliszkiewicz J 2019 The Internet of Things: Review and theoretical framework Expert Systems with Applications 133
[14] Woźniakowski T and Orlowski A 2020 Hybrid Reality on the Internet of Things as an Environment for Transferring Knowledge International Journal of Research in E-learning 6
[15] Pizoń J, Klosowski G and Lipski J 2019 Key role and potential of Industrial Internet of Things (IIoT) in modern production monitoring applications MATEC Web Conf. 252 09003
[16] Czerwinski D and Milosz M 2017 An inexpensive environmental monitoring system with IoT agents ITM Web Conf. 15 01001
[17] Tan Z A, Rahman M T A, Rahman A, Hamid A F A, Amin N A M, Munir H A and Zabidi M M 2019 Analysis on LoRa RSSI in Urban, Suburban, and Rural Area for Handover Signal Strength-Based Algorithm. IOP Conf. Ser.: Mater. Sci. Eng. 705 012012
[18] Bojanowska A 2019 Customer data collection with Internet of Things MATEC Web Conf. 252 03002
[19] Pizoń J, Kulisz M and Lipski J 2021 Matrix profile implementation perspective in Industrial Internet of Things production maintenance application J. Phys.: Conf. Ser. 1736 012036
[20] iOTSolutions Products catalogue available at www.iotsolution.pl