2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation
DOI: https://doi.org/10.13031/aim.202000762
Paper Number: 2000762

Internet of Things (IoT)-based Precision Irrigation with LoRaWAN Technology Applied to High Tunnel Vegetable Production

Haozhe Zhang[1], Long He*[1,3], Francesco Di Gioia[2], Daeun Dana Choi[1], Paul Heinemann[1]

[1] *Department of Agricultural and Biological Engineering, Pennsylvania State University, University Park, PA 16802, USA;*

[2] *Department of Plant Science, Pennsylvania State University, University Park, PA 16802, USA;*

[3] *Penn State Fruit Research and Extension Center (FREC), Biglerville, PA 17307, USA*

**Written for presentation at the
2020 ASABE Annual International Meeting
Sponsored by ASABE
Omaha, Nebraska
July 12–15, 2020**

ABSTRACT. ***Precision irrigation with sensor-based decision-making system has proven to be effective for water saving in crop production. Internet of things (IoT) system is necessary for monitoring the real-time data from sensors as well as automatically applying water. LoRaWAN, a new low-power wide-range network technology, is low-cost and easy to be implemented in IoT systems that can be used for precision crop irrigation. In this study, an IoT-based precision drip irrigation system with LoRaWAN technology was developed and evaluated for a vegetable high tunnel production system. Four irrigation management systems were designed and tested, including one based on volumetric soil water content sensors (SWC), two based on soil water potential sensors set to irrigate at different moisture thresholds (SWP#1 -30kPa and SWP#2 -60kPa, respectively) and a simple pre-set timer-based irrigation management system as a reference. Treatments were arranged according to a randomized complete block design with three replications. Sensor data were recorded and uploaded to an IoT platform (AllThingsTalk) for monitoring and irrigation control. Thresholds were determined for each irrigation strategy to start and stop the irrigation. The results indicated that the developed IoT system worked properly for the irrigation task.***

***Keywords.* IoT, LoRaWAN, precision irrigation, vegetables.**

1. Introduction

In the United States, agriculture is a major consumer of ground and surface water, accounting for approximately 80% of the nation's consumptive water use, and this percentage can be higher in the western states characterized by dryer climate (USDA-ERS, 2019). As the global population continues to increase, food-crop production is expected to increase dramatically while water resources are increasingly limited (Howell, 2001; Di Gioia, 2018). Therefore, it is very important to use water efficiently, especially for crops such as vegetables, characterized by shallow roots and relatively high water content, and thus very sensitive in terms of yield and quality to any deficit or excess of water (Poh, 2011). Conventionally, irrigation is applied to vegetable crops by farm operators' decision based on their experiences and time availability, which often may not be optimal, causing inefficient water usage and crop yield and quality reduction either by over-irrigating or under-irrigating. Precision irrigation is defined as a modern irrigation management strategy to control plant water stress at critical growth stages by applying only the necessary amount of water directly to the crop, varying rate and duration as needed (Casadesus, 2012). By applying precision irrigation on agricultural crops, farmers are expected to benefit from lower cost of irrigation water and manpower, and improvement of crop yield and quality. Adoption of precision irrigation for crop production systems requires the development of integrated sensing, decision-making strategies, and control systems, eventually to precisely control the timing, rate and distribution of water as needed (Smith and Baillie, 2009).

The application of irrigation can be related to soil, plant or environment condition (Romero et al., 2012). Different sensor systems and technologies have been investigated and tested for precision irrigation, including evapotranspiration (ET)-based, plant-based, and soil moisture-based systems (Pardossi, 2011). ET-based irrigation requires a complete set of weather parameters from a nearby weather station to calculate ET rate (Allen et al., 1998). For the plant-based irrigation, canopy temperature is usually used as an indicator to schedule irrigation based on plant infrared thermal response to water status (Conaty et al., 2012). Among these methods, soil moisture sensor-based precision irrigation has been widely tested and used in vegetable field and protected culture systems. Soil water content (SWC) and soil water potential (SWP) are two indicators for available water in the soil which may be used to implement soil moisture-based irrigation systems (Osroosh et al., 2016). In our study, the soil moisture-based irrigation method was used throughout the experiments.

Wired or wireless sensor networks are one of the key technologies for precision and automated irrigation systems (Kim et al., 2008). Vellidis et al. (2008) developed and evaluated a prototype real-time, smart sensor array which measured soil moisture and temperature for scheduling cotton irrigation. In similar research, a microcontroller was used to provide real-time feedback control for a drip-irrigation system, toggling system control valves to apply water under the appropriate conditions (Prathyusha and Suman, 2012). Different embedded control technologies have been applied for automated irrigation systems, such as Xbee-PRO technology (Ramya and Palaniappan, 2012), GSM Bluetooth-based remote-control systems (Gautam and Reddy, 2012), and Dual Tone Multiple Frequency (DTMF) signaling (Dubey et al., 2011). Coates and Delwiche (2009) developed a mesh network system for wireless valve controllers and sensors to limit power consumption in addition to controlling water usage. Applications for mobile phones and wireless personal digital assistants (PDAs and "tablets") has been developed to enable access to remote sensor data and control over physical irrigation systems from a distance (Ahmed and Ladhake, 2011; Sumeetha and Sharmila, 2012).

Internet of Things (IoT), which was coined in 1999 by Kevin Ashton, is a combination of networked sensors and machines for capturing, transmitting, managing, and analyzing data. The data from sensors are uploaded wirelessly to the server. Then data are available on the internet for analysis and computing. Finally, the server sends instructions wirelessly to actuators. A project called SWAMP tested the effect of their IoT-based irrigation system at four pilot locations in Brazil, Italy and Spain (Kamienski et al., 2019). Goap et al. (2018) developed an IoT-based smart irrigation management system which collected the data for machine learning to improve the algorithm of irrigation control.

There have been several applications of IoT in vegetable crop irrigation management based on Wi-Fi, cellular network (GPRS, LTE), ZigBee, etc. Gutierrez et al. (2014) developed a precision irrigation system using SWC and soil temperature sensors, whose data were transmitted to a gateway through a GPRS module. The gateway could process sensor data, trigger valves, and transmit data to a web application. Results showed the system conserved 90% of irrigation water compared with traditional irrigation in a sage crop field. Liu and Xu (2018) built a simple and low-cost precision irrigation system based on ZigBee for lettuce soilless cultivation. Results showed that the system improved water use efficiency by 68.03% and 98.61% and increased the production by 16.60% and 11.37% in spring and summer compared with manual irrigation control, respectively. These applications show IoT-based precision irrigation has been tested in several vegetable crop systems. However, there can be some improvement considering the network layer. In a recent research Zhao et al. (2017) compared the performance of Wi-Fi, ZigBee, GPRS and LoRaWAN. The results indicated that Wi-Fi and ZigBee had low coverage and only worked for the vegetable fields near to the gateway. GPRS is good for long-distance communication, but it has high-power consumption and high cost of maintenance and deployment. Instead, LoRaWAN has the maximum range of 10 km and low power consumption, and it is also low cost. This technology was originally used in 2015 and is not widely used in precision irrigation system for vegetables. For a vegetable field far away from the gateway, LoRaWAN could be a good choice for the network layer in IoT-based irrigation.

The primary goal of this preliminary study was to develop an effective IoT-based precision irrigation system using LoRaWAN technology in a high tunnel vegetable production system using cabbage as a test crop. Different irrigation treatments were established to evaluate the performance of the soil moisture-based irrigation strategies, and the functionality and robustness of the IoT system.

Specific objectives were:

1) Developing an IoT wireless sensing network system for precision irrigation of vegetable crops;
2) Investigating the applicability of SWC and SWP sensors in the developed IoT irrigation system; and

3) Conducting functionality evaluation on IoT-based irrigation system in terms of data communication and irrigation execution.

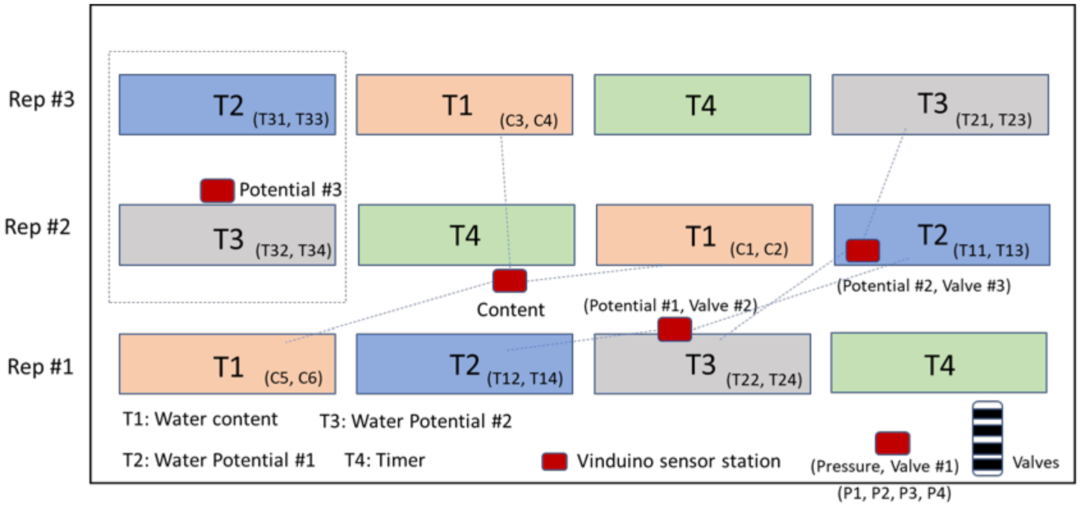
2. Materials and Methods

2.1 Experimental location and set up

To achieve the proposed goal and objectives, in the fall of 2019 a set of experiments were conducted at the high tunnel facility of the Penn State Russell E. Larson Agricultural Research Center (Furnace, PA) using cabbage as a test crop. An overview of the experimental setup and of the irrigation system is shown in Figure 1. The irrigation system was constituted by irrigation pipelines, solenoid valves, soil moisture sensors, pressure sensors and sensor boxes.

Figure 1. An IoT-based irrigation setup in a high tunnel vegetable crop system

Four irrigation management systems were designed and tested, including one based on soil water content sensors (Treatment 1), two based on soil water potential set to irrigate at different soil water potential levels #1 -30kPa (Treatment 2), #2 -60kPa (Treatment 3) and timer-based irrigation system (Treatment 4). Treatments were arranged in a randomized complete block design with three replicates. Red cabbage (*Brassica oleracea* cultivar Omero F1) was selected as a test crop and was transplanted on October 4, 2019. The layout of the experiment field is shown in Figure 2. There were twelve sections. Five sensor boxes were used to connect all the sensors and valves in the test system, including the “Content” box for six SWC sensors; the “Pressure” box for four pressure sensors, one for each treatment, and one solenoid valve (valve #1); the “Potential #1” box for four SWP sensors in treatment 2 and one solenoid valve (valve #2); the “Potential #2” box for four SWP sensors in treatment 3 and one solenoid valve (valve #3); the “Potential #3” box for two SWP sensors in treatment 2 and two SWP sensors in treatment 3. The detail of sensor setup and the sensor boxes are introduced in the following sections.



Content: C1, C2, C3, C4, C5, C6 are water content sensors, odd numbers are at 15 cm, and even numbers are at 30 cm.
Pressure: P1, P2, P3, P4 are pressure sensors (psi) for treatment T1, T2, T3, T4 respectively. Valve #1 is in this box.
Potential #1: T11, T12, T13, T14 are tension sensors, T11, and T12 are at 15 cm, and T13 and T14 are at 30 cm. Valve #2 is in this box.
Potential #2: T21, T22, TS23, T24 are tension sensors, T21 and T22 are at 15 cm, and T23 and T24 are at 30 cm. Valve #3 is in this box.
Potential #3: T31, T32, T33, T34 are tension sensors, T31 and T32 are at 15 cm, and T33 and T34 are at 30 cm.

Figure 2. Treatments, sensors, and sensor box layout of four different treatments in the high tunnel

2.2 Irrigation system setup

Four main pipelines were set in the high tunnel, one for each irrigation management treatment. Treatments were arranged according to a randomized complete block design with three replicates. Each replicate was constituted by a raised bed 0.60 m wide, set 1.8 m apart center to center, and mulched with black polyethylene film. Each replicate was divided in four sections (4 m long), one per treatment, and for each section the drip tape placed underneath the mulch was connected to the main pipeline of the treatment for all three replicates. Figure 3 shows the layout of the irrigation system, including pipelines, valves/timer, pressure sensors, etc. The pressure was regulated to 15 psi. Valves #1 to #3 (PGV Series ¾ inch, Hunter Inc., San Marcos, CA) are on/off valves with DC solenoid. A timer (Orbit 1 output port digital hose end timer) was used for treatment 4. Pressure sensors P1 to P4 (G¼ inch 5V 0-1.2 MPa) were installed behind the solenoid valves and the timer to measure the water pressure in pipes. The pressure change indicates the connection or disconnection of the water.

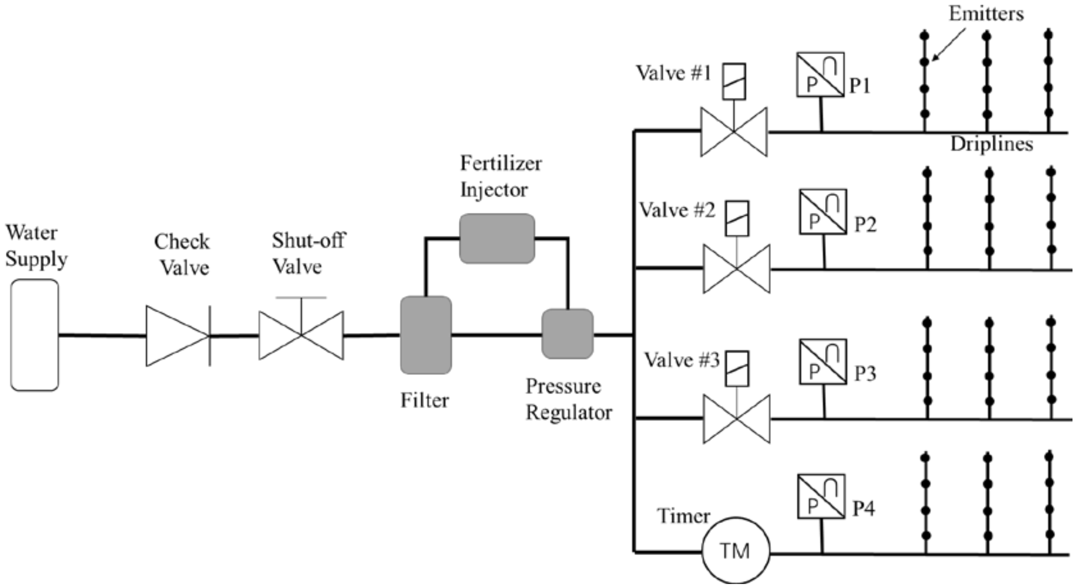


Figure 3. Overall irrigation system setup

2.3 Sensor system setup

In treatment 1 (SWC-based irrigation), two SWC sensors (TEROS 10, METER Group, Inc., Pullman, WA) were installed at two depths (15, 30 cm) for each section, with in total of six SWC sensors. The same installation was applied to treatments 2 and 3 with SWP-based irrigation, six SWP sensors were used for treatment 2 (Watermark 200SS-5, Irrometer company, Inc., Riverside, CA), and another six SWP sensors were used for treatment 3. For the timer-based irrigation treatment 4, there was no sensor installed at these sections. These sensors and the solenoid valves were connected to the sensor boxes. The major components of the sensor boxes included a base control board (Vinduino LLC, Temecula, CA) and a LoRaWAN wireless communication unit with antenna (LM130-H1, GlobalSat WorldCom Corp., New Taipei City, Taiwan). Each sensor box was powered with 3.7 V LiPo battery, and a solar panel was attached to charge the battery. Figure 4 shows the connection of SWC sensors and SWP sensors to a sensor box. In the “Content” box, there were six sensors connected, and in the “Potential” box, there were four sensors.

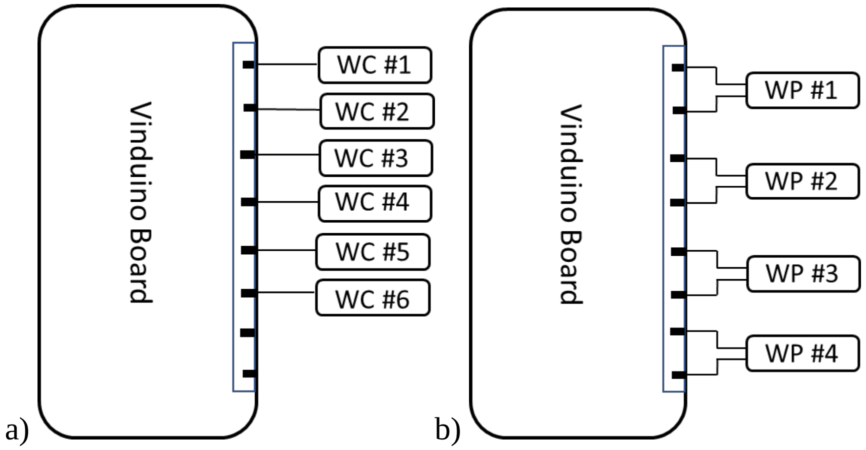


Figure 4. Connection of soil moisture sensors with the Vinduino board. a) SWC sensor, b) SWP sensor.

2.4 Irrigation valve control

For the sensor-based irrigation, solenoid valves were used to control irrigation. The Vinduino board sent signals to a relay to control the valve. Figure 5 shows the wire connection among these components. For the timer-based irrigation, a timer is used to control the irrigation. One sensor box could only control one valve. Therefore, three sensor boxes were used to connect valves. Four pressure sensors were connected to one sensor box. The pressure sensors were connected to the “Pressure” sensor box using the same way as the SWC sensors (in Figure 4a).

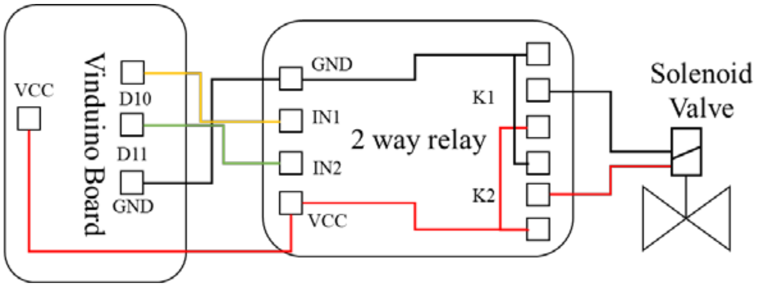


Figure 5. Connection of valve and relay with Vinduino board.

2.5 IoT system and data collection

An Internet of things (IoT) system was established to connect the sensors, valves, and sensor boxes in the test field. Figure 6 illustrates the procedure of the IoT system development. Besides the sensors, valves, and sensor boxes, a LoRaWAN gateway (LG308, Dragino Technology Co. Ltd, Shenzhen, China) was used in the system. The gateway and sensor boxes were configurated in a free IoT server named The Things Network. Then an IoT platform AllThingsTalk (AllThingsTalk NV, Mechelen, Belgium) was used to monitor, display, store the sensor data, and conduct the valve control.

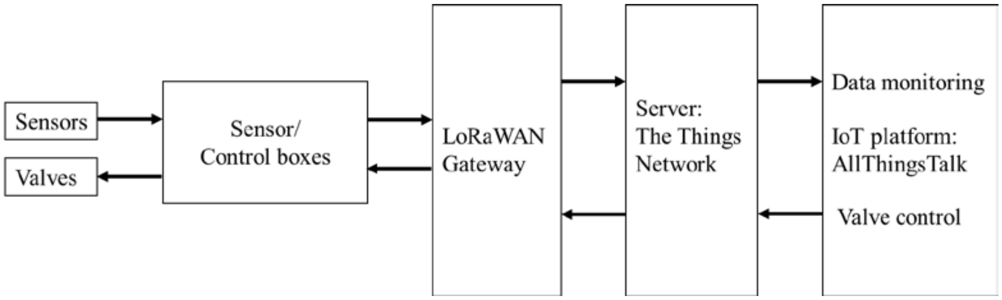


Figure 6. Structure for the IoT system.

The first step was to configure the gateway and the sensor boxes. The LoRaWAN gateway was first connected to a computer with wired ethernet cable for matching the parameters, including using "The Things Network" as server and "915MHz" as band frequency. The gateway could be setup as Wi-Fi mode after the configuration. In the server interface, a gateway was created with the recorded gateway ID. Then an "Application" was built in the gateway to represent the proposed high tunnel vegetable irrigation system. An Application EUI and App Key of the application were generated automatically by the server. Five devices were created under the "Application" to connect the five sensor boxes, respectively. Algorithms were developed for these sensor boxes with different functions, including soil moisture recording, valve control, and pressure sensor recording. The Application EUI and App Key were used for the sensor boxes to be connected to the gateway for uploading data (sensor data) and downloading data (control signal) to the gateway. Once the sensor boxes were turned on, they were connected to the server after a few seconds.

The next step was to connect the configured sensor boxes to the IoT platform AllThingsTalk. In the web-based interface, integration "AllThingsTalk" was added to the application. Then the IoT platform was linked to the gateway server. Sensor data was uploaded to and stored by the IoT platform for monitoring and irrigation control. In the platform, five devices were added as corresponding to the five sensor boxes. Then the assets were created to represent the corresponding sensors and/or valves in each device (sensor box). The communication was applied with a pre-set time interval, depending on the settings in the sensor boxes, which was 10 minutes in this research. The sensor data (uplink) and valve control (downlink) was communicated as binary payload. A battery voltage or sensor reading was parsed from a byte between 0 ~ 255. They were converted to actual values by editing the payload format in the device interface. When controlling valves, the platform sent a byte as 0 or 255 to close or open the valves.

For each device in the AllThingsTalk, the real-time sensor readings and battery voltage were shown. The platform also provided the history of sensor readings over the time, and these data could be exported in an excel file. The status of all assets of five devices could be displayed to a pinboard (Figure 7). The status of the solenoid valves was presented by a big circle in real time with black color for close and green color for open. The valves could be controlled either manually by toggling the switches on the pinboard or automatically through the rules set in the platform by comparing the sensor data with setting thresholds.

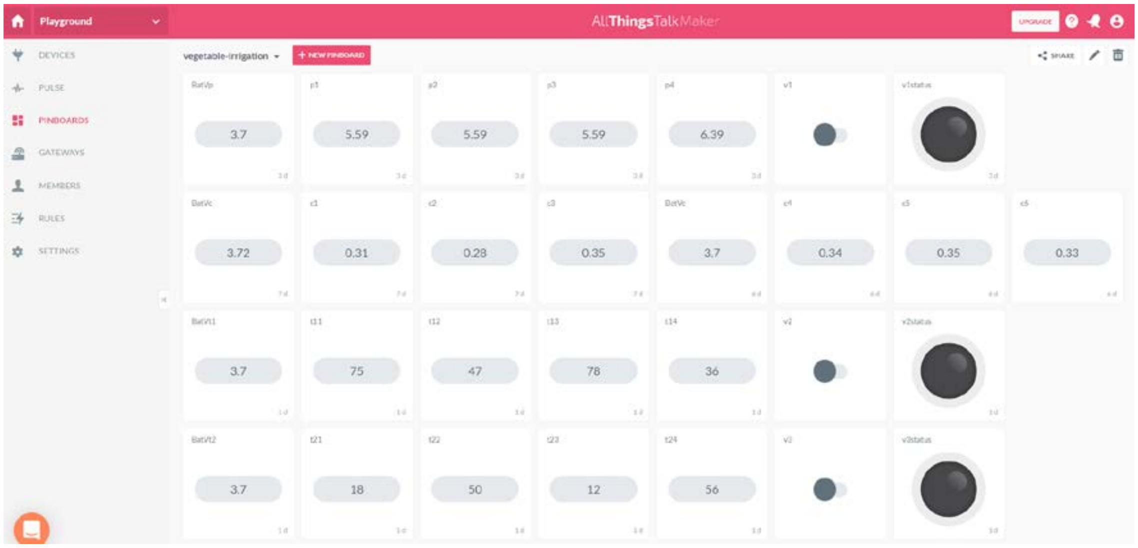


Figure 7. The IoT platform for sensor data display and irrigation valve control

3. Results and Discussion

The developed Internet of Thing system was tested and evaluated, including the feasibility of the system, the recorded sensor data, and the status of the valve control. However, the results on the water use efficiency and crop yield on different irrigation strategies were not available for this experiment because the water supply was terminated due to the cold weather condition.

3.1 Feasibility of the IoT system

The sensor data was uploaded to the IoT platform as expected, and the developed IoT system worked properly for opening/closing the valves by manually toggling the switch. The gateway was located at an indoor office 300 m away from the high tunnel. We observed that there were some data loss during the time, which was approximately 4.3% packet loss. The packet loss may be caused by the block of walls of office and high tunnel, the long distance, and the performance of the gateway. Most sensor boxes, charged by a solar panel, worked throughout the season without changing batteries. However, the battery often went dead in the "Content" box. A 10000 mAh LiPo battery can only lasted for about 7 days. A possible reason could be that power was supplied to the sensors continuously instead of intermittent power. These issues will be considered to resolve in our future studies.

3.2 Soil moisture monitoring with IoT system

Figure 8 shows the SWP change in treatment 2 and 3 in 20 consecutive days since November 20th, 2019. These were the daily average of the water potential readings. During this period, a 30-minute irrigation test was applied at 11:50 am on day 6. As we can see, the SWP were at different levels initially, and were gradually decreasing to lower values before the irrigation. Once the irrigation was applied, the numbers were increasing to higher values. Then as the day went, the SWP started to gradually decrease again as the soil starting to lose water. These drier locations (with initial lower values) were drying faster than other locations. Therefore, a longer irrigation period may be needed for these drier locations. The sensor readings at the first section of treatment 3 was always high values (wet) and did not change much during the whole period. We found that this section was a bit lower than other sections, which may cause water accumulation from other sections or outside of the high tunnel.

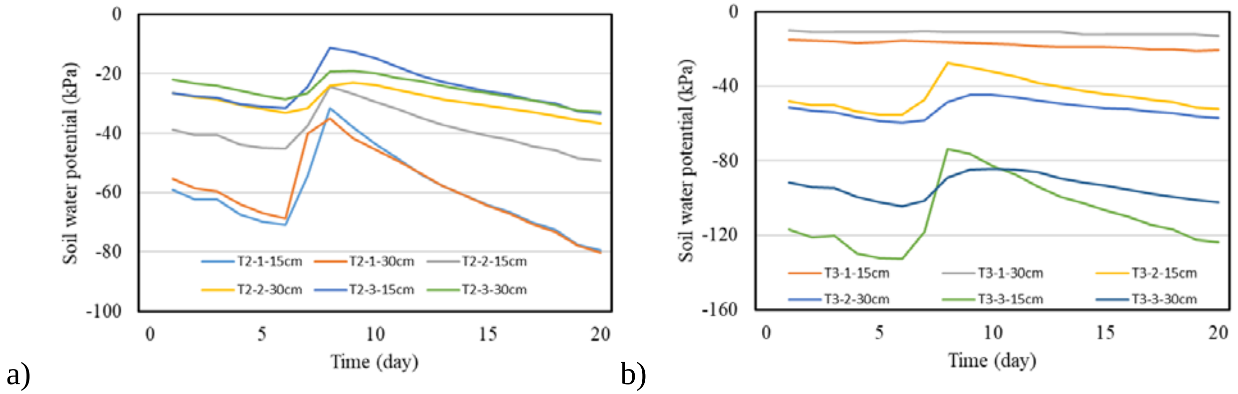


Figure 8. Part of SWP change of treatment 2 (a) and 3 (b) since Nov 20th, 2019.

The detailed changes of soil water potential in the day 6 (irrigation day) were also analyzed. Figure 9 shows the water potential changes for all the sensors in treatment 2 and 3 in the 24 hours range. Before the irrigation, there were big differences among these sensor readings. Section 3 in treatment 3 was drier at both depths, while section 1 in the same treatment was wetter from the beginning. With the irrigation, the SWP at different section at both depths changed quickly. In treatment 2, at the end of day 6, the readings from all the sensors were down to around -20 kPa. However, when we look back to longer period in Figure 8, these locations with lower values were getting to dry faster than others. That could be attributed to less water being contained at the root zone, and it would take less time for the water potential sensor to react as dry. In treatment 3, the section 3 was much drier, and the SWP were above -80 kPa after the irrigation. Therefore, longer irrigation at these locations should be considered if it is expected to contain the water longer. There are a few other important observations from the study. First, as the figures show, the SWP were continuing to increase for a few hours after the irrigation. Also, the installation location of SWP sensors is critical to represent the water status in the crop root zones. Therefore, it would be important to conduct more studies in terms of sensor location and irrigation duration to provide guide for future automatic irrigation system.

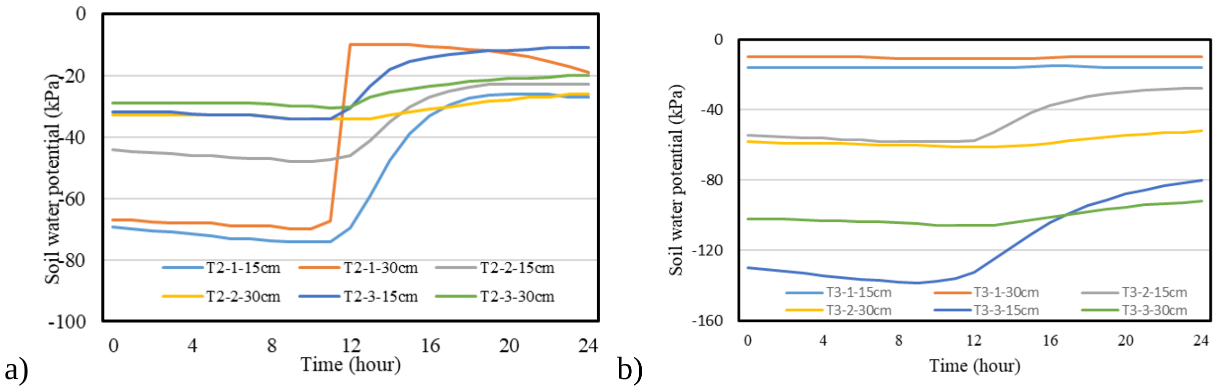


Figure 9. SWP change of treatment 2 and 3 in day 6 (24 hours) when the irrigation was applied

Figure 10 shows the SWC change in treatment 1 from day 1 to day 15 since Nov 20th. Irrigation was applied for a 30-minute period at 11:50 on day 6. However, there was no dramatic SWC change for all the sensors after the irrigation, while the readings increased slowly for more than one week after irrigation at day 6. At the end of this period before the battery went dead, there was a big increase for all the sensor readings. There were a few possible reasons for this result, one was that the supply voltage from the battery was not enough, and the other reason could be that the solenoid valve malfunctioned when we remotely controlled the valve to open. The water content sensors consumed much power due to the continuous sending signal mode in our program. In the future, we will improve our algorithm to only connect the sensors to the power when the data recording is required.

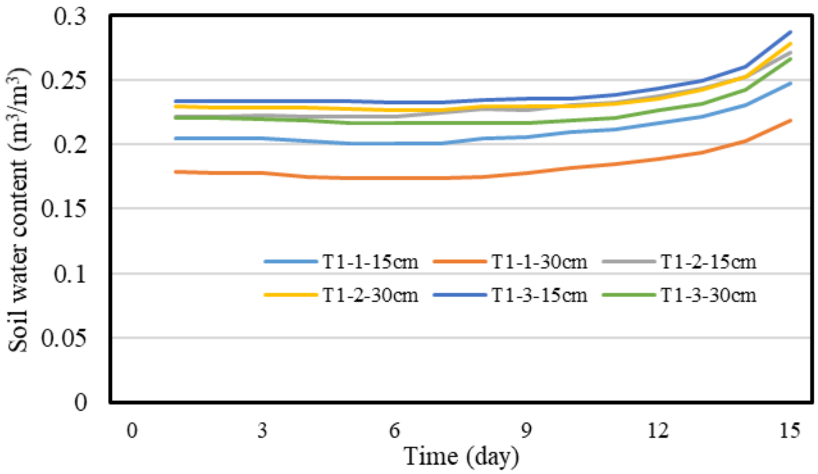


Figure 10. Part of SWC change for treatment 1 since Nov 20th

3.3 Valve control with the IoT system

The irrigation was applied successfully with the implemented IoT system. The IoT platform was available as a mobile application. When the switch was toggled to on in the AllThingsTalk app, the valve was opened. At the next communication, valve status showed open, and the pressure sensor showed a positive reading. When the switch was toggled to off, the valve was closed. At the next communication, valve status showed close, and the pressure sensor reading became 0. When the switch was not moved, there was no action on the valve, and the valve status and pressure sensor reading kept the same as last time.

4 Conclusion

An IoT-based precision irrigation was developed and evaluated with function test. The IoT-based precision irrigation system displayed and recorded the data from the soil moisture sensors and pressure sensors and executed the on/off of the solenoid valves successfully. The LoRaWAN communication has a 4.3% packet loss at 300 m distance, which may cause by the office wall obstacle, long distance, and gateway performance. The system can work without changing batteries for two months except the soil water content sensor box. More studies on accurately recording soil water content sensors and associated battery issues will be conducted in the future. This study provided some preliminary information on using IoT-based precision irrigation system to monitor the soil moisture status of a vegetable field and control the irrigation remotely through mobile application or website.

Acknowledgement

This research was supported in part by the United States Department of Agriculture's (USDA) National Institute of Food and Agriculture Federal Appropriations (Project PEN04547; Accession No. 1001036), the State Horticultural Association of Pennsylvania (SHAP), the USDA Northeast SARE Research and Extension Grant Project (Grant No. 19-378-33243).

References

Ahmed, V., Ladhake, S. A. (2011). Innovative cost effective approach for cell phone based remote controlled embedded system for irrigation. In *Communication Systems and Network Technologies (CSNT), 2011 International Conference* on (pp. 419-422). IEEE. https://doi.org/10.2135/cropsci2011.11.0581

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome, 300(9), D05109.

Casadesús, J., Mata, M., Marsal, J., Girona, J. (2012). A general algorithm for automated scheduling of drip irrigation in tree crops. *Computers and Electronics in Agriculture*, 83, 11-20. https://doi.org/10.1016/j.compag.2012.01.005

Coates, R. W., & Delwiche, M. J. (2009). Wireless mesh network for irrigation control and sensing. *Transactions of the ASABE*, 52(3), 971–981.

Conaty, W. C., Burke, J. J., Mahan, J. R., Neilsen, J. E., Sutton, B. G. (2012). Determining the optimum plant temperature of cotton physiology and yield to improve plant-based irrigation scheduling. *Crop Science*, 52(4), 1828–1836. https://doi.org/10.2135/cropsci2011.11.0581

Di Gioia, F., Rosskopf, E. N., Leonardi, C., Giuffrida, F. (2018). Effects of application timing of saline irrigation water on broccoli production and quality. *Agricultural Water Management*, 203, 97–104. https://doi.org/10.1016/j.agwat.2018.01.004

Dubey, V., Dubey, N., Chouhan, S. S. (2011). Wireless sensor network based remote irrigation control system and automation using DTMF code. In Proceedings - *2011 International Conference on Communication Systems and Network Technologies*, CSNT 2011 (pp. 34–37). https://doi.org/10.1109/CSNT.2011.14

Gautam, I., Reddy, S. R. N. (2012). Innovative GSM Bluetooth based remote controlled embedded system for irrigation. *International Journal of Computer Applications*, 47(13), 1–7. https://doi.org/10.5120/7245-0043

Goap, A., Sharma, D., Shukla, A. K., Rama Krishna, C. (2018). An IoT based smart irrigation management system using Machine learning and open source technologies. *Computers and Electronics in Agriculture*, 155(September), 41–49. https://doi.org/10.1016/j.compag.2018.09.040

Gutierrez, J., Villa-Medina, J. F., Nieto-Garibay, A., Porta-Gandara, M. A. (2014). Automated irrigation system using a wireless sensor network and GPRS module. *IEEE Transactions on Instrumentation and Measurement*, 63(1), 166–176. https://doi.org/10.1109/TIM.2013.2276487

Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. In *Agronomy Journal* (Vol. 93, pp. 281–289). https://doi.org/10.2134/agronj2001.932281x

Kamienski, C., Soininen, J.-P., Taumberger, M., Dantas, R., Toscano, A., Salmon Cinotti, T., … Torre Neto, A. (2019). Smart water management platform: IoT-based precision irrigation for agriculture. *Sensors*, 19(2), 276. https://doi.org/10.3390/s19020276

Kim, Y., Evans, R. G., Iversen, W. M. (2008). Remote sensing and control of an irrigation system using a distributed wireless sensor network. *IEEE Transactions on Instrumentation and Measurement*, 57(7), 1379–1387. https://doi.org/10.1109/TIM.2008.917198

Liu, Z., Xu, Q. (2018). An automatic irrigation control system for soilless culture of lettuce. *Water (Switzerland)*, 10(11), 1–9. https://doi.org/10.3390/w10111692

Osroosh, Y., Peters, R. T., Campbell, C. S., Zhang, Q. (2016). Comparison of irrigation automation algorithms for drip-irrigated apple trees. *Computers and Electronics in Agriculture*, 128, 87–99. https://doi.org/10.1016/j.compag.2016.08.013

Pardossi, A., Incrocci, L. (2011). Traditional and new approaches to irrigation scheduling in vegetable crops. *HortTechnology*, 21(3), 309–313. https://doi.org/10.21273/horttech.21.3.309

Poh, B. L., Gazula, A., Simonne, E. H., di Gioia, F., Hochmuth, R. C., Alligood, M. R. (2011). Use of reduced irrigation operating pressure in irrigation scheduling. I. Effect of operating pressure, irrigation rate, and nitrogen rate on drip-irrigated fresh-market tomato nutritional status and yields: Implications on irrigation and fertilization management. *HortTechnology*, 21(1), 14–21. https://doi.org/10.21273/horttech.21.1.14

Prathyusha, K., Chaitanya Suman, M. (2012). Design of embedded systems for the automation of drip irrigation. *International Journal of Application or Innovation in Engineering & Management*, 1(2), 254–258. Retrieved from www.ijaiem.org

Ramya, V., Palaniappan, B., George, B. (2012). Embedded system for automatic irrigation of cardamom field using XBee-PRO technology. *International Journal of Computer Applications*, 53(14), 36–43. https://doi.org/10.5120/8491-2439

Romero, R., Muriel, J. L., García, I., Muñoz de la Peña, D. (2012). Research on automatic irrigation control: state of the art and recent results. *Agricultural Water Management*, 114, 59–66. https://doi.org/10.1016/j.agwat.2012.06.026

Smith, R. J., Baillie, J. N. (2009). Defining precision irrigation: A new approach to irrigation management. *Irrigation and Drainage Conference*, 1–6.

Sumeetha, S., Sharmila, D. (2012). Embedded based remote control application using mobile phone in irrigation. Bannari Amman Institute of Technology, Sathyamangalam, Tamil Nadu, INDIA.

USDA-ERS. (2019). Irrigation and water use. Available at: https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/. Accessed on May 1, 2020.

Vellidis, G., Tucker, M., Perry, C., Kvien, C., Bednarz, C. (2008). A real-time wireless smart sensor array for scheduling irrigation. *Computers and Electronics in Agriculture*, 61(1), 44–50. https://doi.org/10.1016/j.compag.2007.05.009

Zhao, W., Lin, S., Han, J., Xu, R., Hou, L. (2017). Design and implementation of smart irrigation system based on LoRa. In *2017 IEEE Globecom Workshops (GC Wkshps)* (Vol. 2018-Janua, pp. 1–6). IEEE. https://doi.org/10.1109/GLOCOMW.2017.8269115