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Chapter 9: Development and deployment of smart irrigation systems with automated controls

9.1. Introduction

The current study proposes a framework for the development and deployment of Smart Irrigation Systems (SIS) with automated control using Multiple-Criteria Decision-Making (MCDM) methods. The objective is to achieve efficient irrigation management with reduced capital and maintenance costs of the technologies used in the SIS. Water scarcity is among the key inciting parameters for the development of SIS. Climate change and rapid urbanization are projected to increase the risk of water scarcity and degraded water quality globally, particularly in developing countries. A potential solution is a shift from traditional irrigation towards modern water-efficient irrigation systems, which can improve yields and conserve water resources, especially during drought periods. These systems include Smart Irrigation Systems that have automated control components based on modern technologies that monitor, evaluate and control irrigation parameters and systems (Kim et al., 2008; Gutiérrez et al., 2014; Evett et al., 2021).

The advantages of using SIS stem from they provide the best in-field variable irrigation dose at the right time. Typically, SIS have simple design and are less costly than other modern irrigation infrastructures. However, traditional SIS implementation has low reliability, as they neglect several important factors related to the nature of the area and accompanied soils. Recent technologies using sensors and Precision Agricultural data promote the viability of deploying modern SIS with automated control. Automated decision-making regarding irrigation is advantageous as these solutions provide irrigation dose decision at the right time based on data, with no lag time and no possibility of human error (Ruiz-Garcia et al., 2009; Ramesh, 2014).

9.1.1. Overview of the Study's Objectives and Scope

Experience gathered over an extended period of developing and implementing proposed smart irrigation control has shown that a comprehensive intelligent control, based on intelligent agent technology employing a variety of organic and inorganic sensors, can provide many benefits and solutions to difficult irrigation problems. Algorithms incorporated in a combination of user-specified and autonomous, self-educating intelligent agents have provided cost-effective implementation of intelligent water flow control. Several low-cost sensors developed in the research can assist, not only incorporate intelligent control to verify and update control algorithms and settings, but also provide real-time measurement and control for surface and internal soil waters, and crop water usage and demands, in order to automatically re-calculate both long-term irrigation dynamic models and provide day-to-day intelligent control during the growing season. In the past, irrigation was controlled using sprinkler or furrow flow rates and schedules which did not account for the varying water usage of the different crops at different stages of their growth. The algorithms in the intelligent system are allowed to account for this. Utilization of portable pyrometers to ascertain variation of crop moisture usage, in order to verify crop needs, can only be used at specified request. Under intelligent control the system can execute the necessary process. Research has shown that through the control of underground lateral pipe hydraulic pressures and flows, the intelligent control system was able to detect, not only internal soil water conditions, but also variations in crop internal moisture contents, as well as crop above surface moisture needs. By this, the proposed intelligent soil-water sensors and control system can indicate or verify various crop surface condition needs, such as weed growth or disease indication. The outputs of these activities will be used to enhance intelligent crop health monitoring.

9.2. Background and Literature Review

Humans have been harnessing water to create agriculture for thousands of years. The ancient Egyptians built flood basins during the 3rd millennium BC to capture the Nile’s seasonal flooding and redirect the flow as needed to promote growth. In the 9th millennium BP, the inhabitants of Zargos built irrigation canals to allow crop growth in the mountainous regions of the region. The Romans used aqueducts to move water long distances, providing a reliable source of nutrient-rich water for wide swaths of land. As civilizations advanced, so did irrigation systems. These systems matured from large communities using brute force to modify nature each season - built canals, aqueducts, and troughs - to supply and manage water flow. This resulted in large fields using a variety of methods to distribute and recapture rain. The advancement of these systems allowed for increasingly larger tracts of land to be maximized for agricultural production, helping sustain increasingly larger populations.

As smart technology has found its way into modern life, it has found increasingly significant applications in agriculture. Over the past century, agriculture has been in a nearly constant state of advancement. The tractor replaced horses. Synthetic pesticides and herbicides replaced manual methods of pest control, forever changing the face of farming. As these techniques have continued, new advancements have began to make their way to farms. The previous advancements made farming easier, cheaper, and faster, but at the cost of over-stretching the environment and depleting once rich ecosystems. Modern agricultural technology is aimed at combatting these issues while still reducing cost and maximizing results. Current research into new developments has turned to yield mapping, precision agriculture, intelligent pest sensors, autonomous tractors, seed sensors – all pulling from smart technology. These developments have the goal of sustaining agriculture for future generations.

9.2.1. Historical Overview of Irrigation Systems

Irrigation is the practice wherein various artificial systems are utilized for the distribution of water to land for assisting in the growing of crops. This technique is applied to the growing of crops as well as to facilitate the growth of plants in dry environments by supplying them the requisite water that they are deprived of. The artificial supply of water through irrigation assists farmers in improving crop yield as irrigation makes it possible for them to grow crops in all seasons including dry seasons. Therefore, irrigation systems have been in existence for centuries and play a very major role in agricultural success across the globe.

The Egyptians are known to have developed one of the earliest types of irrigation systems around 4000 BCE with the construction of canals for the distribution of large volumes of river water across their fields of crops. Nowadays, irrigation is practiced in almost all countries of the world, with varying degrees of application methods having been developed in different countries. While the tube well irrigation system is very common in parts of Asia, such as India, the sprinkler irrigation system is heavily practiced in the arid regions of the USA or Africa. In addition to the aforementioned systems, the surface and drip irrigation systems are equally significant and common in regions that experience limited annual rainfall. Progress over the years has seen the development of overhead center pivot irrigation systems and gravity-driven plastic tubing water distribution systems, which are being heavily utilized in certain parts of Australia and India. The development of new and innovative irrigation systems has greatly influenced the overall upsurge in agricultural production, especially in the areas of crop and horticultural production. Advances in smart technology today have made it possible to automate irrigation systems, further pushing the boundaries of agriculture toward smarter solutions.

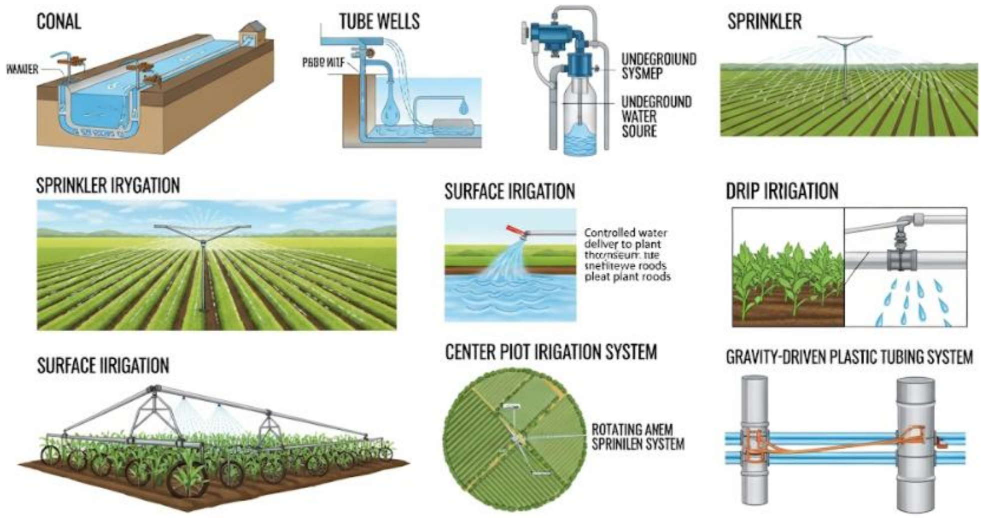

Fig 9 . 1 : Diverse Irrigation Techniques

9.2.2. Advancements in Smart Technology

Recent advancements made in smart technology fields such as mobile communications, sensor, embedded and network in those areas have vastly improved a variety of different applications, not only in the entertainment and marketing fields, but also in medicine, education and manufacturing. The global market for agriculture and farming is also shifting towards adoption of various advanced technologies for improved productivity as well as return on investment. In this regard, the wireless sensor networks, a new network paradigm, can be used to detect various phenomena or signals from the environment to monitor or control these physical parameters. In the domain of agriculture, various types of sensor nodes, solar-powered, low-cost and small equipment connecting to the wireless sensor networks, e.g., soil moisture sensor, temperature and humidity sensors, have been developed and deployed from days or weeks to a few years.

Several researchers have focused on increasing the lifetime of the sensor nodes on site by utilizing solar energy. The motivation is clear, if the lifetime of the sensor nodes can be increased, the operational cost of the wireless sensor networks is reduced significantly, as battery replacement can be an expensive process. All these sensor nodes can be freely deployed or randomly taken away and accomplish a variety of time consuming and tedious tasks, which lead to the demand for smarter sensor nodes with a capability of smart sensor network, and subsequently for unattended operations and deployment. These will eventually open the gates of new ways to improve water and chemical provide the technology for environmental research. Agro-environmental monitoring must be made possible and practical, for hazard warning, for precision irrigation and precision farming, and for autonomous controller behavior. To realize these new applications, the advances in smart technologies, and the smooth integration of sensors, networks and autonomous controls must be made. These in turn will create opportunities for new sustainable businesses and services while enhancing our quality of life.

9.2.3. Current Trends in Agriculture

As the world population continues to grow, projecting to reach over 9 billion by 2050, the agricultural sector will be faced with an increasing dilemma to satisfy food and water needs in a sustainable development framework. Agriculture is one of the largest consumers of freshwater, accounting for about 70% of our total water withdrawals, coupled with urbanization that will displace additional arable land into the cities. All factors which will increase pressure on agriculture. In addition, agriculture must also contend with the severe climate impacts such as rising sea levels, increased flooding and droughts, storm intensity, and frequency that are predicted. It is in the face of these massive challenges that a "New Revolution" in agriculture is needed. The primary goal is to optimize the use of natural resources, technology developments, and energy while seeking crop sector returns. Agriculture though is getting smart by adopting technology advances. For industry, precision irrigation can help reduce input costs, address regional variability, changing water availability, and take advantage of technologies to promote the profitability of agriculture and enhance and protect water resources. Reducing water loss also reduces nutrient discharge and saves transport costs.

A confluence of several factors favors a move in this direction. The technology development roadmap for communications technology shows application to agriculture. Communications technology is advancing rapidly in consumer-driven products for mobile applications. Solar technology provides power economically in remote areas. Control technology for managing remote equipment has a growing base in application such as technology. Finally, the demand for efficiency and accountability related to agricultural productivity is putting pressure on producers to minimize losses, make better decisions, and provide justification for actions. For agriculture, smart irrigation can help reduce input costs, address regional variability, changing water availability, and take advantage of technologies to promote the profitability of agriculture and enhance and protect water resources.

9.3. System Design

1. Requirements Analysis

The successful development of any system starts with the adequate definition of its requirements. In this particular case, this means to define what type of data will be collected from the irrigation field, in what conditions should the automatic control of the irrigation system be activated, and what actuators will be responsible for the automatic irrigation process. The types of data to be collected should refer both to the local weather conditions, such as real-time recorded precipitation values, temperature, air humidity, and sunlight intensity, and to the monitorization of the soil conditions such as real-time recorded soil moisture levels. Other soil conditions may be considered too, such as soil temperature and salinity. A non-exhaustive list of parameters to evaluate when making the decision to automatically irrigate is: weather prediction for the following five days; temperature from the previous days; soil moisture; accumulated precipitation from the previous days; registered global irradiation; relative humidity; anticipated crop evapotranspiration; panic and pre-flowering periods of the corn; and soil temperature. The actuators that should be considered for the irrigation process are pivots, drip irrigation, furrows and ditches, sprinklers, micro-sprinkling, and rain guns.

2. Hardware Components

Three different hardware architectures will be used in each farm to integrate distinct types of data. The first one is dedicated to the monitorization of the local weather conditions, the second one to the monitorization of the soil conditions, and the last one to the irrigation control via actuators. To accomplish the weather conditions monitorization, a meteorological station and a weather station are used. Their main limitations are high costs. These stations were installed across three agricultural experimental fields located at DIAM alone with its were used only to calibrate cheaper open-source solutions. The systems are based on Arduino boards, which are one microcontroller that can be used to develop this board with additional functionalities. The addresses of each one of these components are listed in Table 1.

9.3.1. Requirements Analysis

A smart irrigation system should leverage the latest technology to enhance the process of irrigation, enabling easy access to irrigation activities with high precision, time and water-saving programming. The platform, mobile and desktop applications will allow users to easily control and monitor different aspects of their green assets' needs. The system should remotely monitor and control the irrigation systems, and help define the correct amount of water required for different plants in every season. Depending on data collected from sensors in real-time by an algorithm, the system should automatically calculate the amount of water needed and schedule irrigation in case of implementing an irrigation system with automatic control. On a larger scale, the system should monitor drone-based thermal and RGB image analysis to detect if a specific patch of grass is overwatered, underwatered, cooling, or burning. A drone or other aerial robotics system should be used to help define the most adequate areas using RGB color synthesis category. This data might also evaluate irrigation system performance across a football or any grass-based structure. The information gathered should help avoid watering when needed and show watering over-watering or under-watering imbalance.

Moreover, it is also important to highlight that the system will be used by a vast range of people with different instruction backgrounds and usage approaches. Because of this, the team will also pay special attention to both mobile and web user interfaces and their ergonomics, as well as how friendly the software is. Good ergonomics should include, among others, color contrast for people that have difficult seeing and usability for old people that would like to set their irrigation program but have problems with technology per se. This is especially important for older adults and less technological-savvy users, who might need to rely on the system over much longer periods or even their entire life.

9.3.2. Hardware Components

In the above system each irrigation zone will consist of one moisture sensor, two temperature sensors and one solenoid valve. The soil and air moisture is measured by the moisture sensor. We use two temperature sensors, one for measuring the outside air and the other for measuring the temperature of the inside irrigation zone. The outside air temperature sensor helps in detecting and giving alerts if there is any frost risk, whereas the inside air temperature sensor indicates the growth stage of the plants and thus the required irrigation schedules of zone. The solenoid valve is the actuation component which opens and closes the irrigation system. The communication between all the above components is established by using the microcontroller which controls the sensors and the solenoid.

The protocol that we use for communication between the devices has a long range compared to Wi-Fi and Bluetooth. The module has an operating voltage of 3.3V and is interfaced with both the microcontroller and the cloud server. The data fetched from the sensors is sent to the cloud and data received from cloud to control / automate the irrigation is received using the protocol. The communication technology that we use for sending alerts in the form of SMS whenever the need arises, that is, whenever there is frost risk or when the solenoid is not functioning as per schedule. The module is initially setup using the Wi-Fi and is done using AT Commands. It too has an operating voltage of 3.3V and is interfaced with both the microcontroller and the cloud server. The mobile app used in the system is an application which is built on a platform using built-in templates. The information from the cloud server is fetched to the application using a library.

9.3.3. Software Architecture

This project generally utilizes various Software Architectures which upholds the coding since some of the components can be created through a platform for our software which pushes updates and all the information needed for mobile and web applications. manages the communication code logic for the mobile application. In the mobile application that runs in the environment, the user needs to enter their log-in information to connect to the system. After a successful connection, there is a splash screen. The welcome screen and home screen display information and data such as current state sensors, last access, system events log, last data configuration backup, zone schedules, and selected zone status.

In the mobile app section, the users get feedback from the push notifications system of the device each time a defined function happens in the system. The functions done by the main server. The user can update everything from the web console interface, including the sensor and zone data but also download a configuration backup. It is important to highlight that all the information displayed is sent to and pulled from the main server. The web console application that resides on the server's side is a user interface for configuration management, and all the backend logic code is executed using a powerful script engine that provides several capabilities such as working with databases, file manipulation, system commands execution, etc. These code executions are purely data-driven and the data that drives the execution engine are stored in a database making the platform capable of executing and guiding a considerable set of complex operations being a suitable environment for a multi-user configuration management.

9.4. Automated Control Algorithms

Turning a smart irrigation system from a simple network of devices into a fully automated, autonomous unit requires the design of algorithms that control system operation based on their collected and processed data. It is important to consider in advance whether the system will operate autonomously or the farmers will require full control of the system. A nodal system architecture results in a situation where the system relies solely on the processing of localized data. A layer-level architecture allows cursory oversight of the entire system and enables the addition of protection protocols in specific, external areas.

Numerous irrigation controllers are readily available today for instant use. These devices have built-in solenoid control capabilities and time-based user-programmable irrigation cycles. With the introduction of new technology such as soil moisture sensors, some irrigation manufacturers have added sensor capabilities into their irrigation controllers. Such information can be internally used to temporarily hold off irrigation cycles for a certain amount of time until the soil has dried properly. These controllers mainly depend on cut-off points for soil moisture without any consideration for specific weather conditions. While these controllers are useful and perfect for their simplicity, there is a clear gap between their initial setup requirements and what is available today with added monitoring functionality and controllable via an open-source platform. This has encouraged teams of developers to create more intelligent protocols as they get bored waiting for an unexpected rainfall event to occur. Several outdoor projects have been implemented by different groups, yet very few have published their iterations and given advice on how to deploy or build one of their own while explaining what is happening behind the scenes. Automated control development for these devices is crucial. The focus of this discussion is mainly manipulating weather predictions for a point in time and using soil moisture levels to choose if irrigation control for the planted fields should be responded to.

9.4.1. Sensor Integration

The primary input for smart automatic irrigation controllers is the measurement of the variables that are indicative of plant health conditions, together with the required user data and/or local climatic conditions. Sensors can also be used to monitor the whole irrigation system performance, as they can be placed in the land, in the air, or in the hydraulic system. Research works identified pots with some type of substrates and plants inside, grown under fully controlled climatic conditions or soil moisture depletion rate conditions, as appropriate experimental scenarios for collecting information about the conditions leading to plant stresses.

Moisture, air temperature and humidity, and solar radiation are the most cited variables to predict plant stresses, but there is a considerable variation in the responses under similar conditions, as those stated above are not the only ones involved. Possible budgets for automatic irrigation in arid and semiarid regions rely on the parameters of the plant, the soil, and environmental conditions. Soil moisture sensors installed in pots and soil cover systems are more widely used. The information obtained under either of these two types of systems is the amount of irrigation needed to restore the desired moisture conditions and, therefore, the weekly irrigation calendar. The economic budgets would have associated the costs of irrigation, the environmental costs, and the savings and/or earnings obtained by harvesting.

9.4.2. Data Processing Techniques

As seen from the data collection, noise present in the measured humidity can produce error in warning signal issuing at the controlled zones; especially affecting crops sensitive to soil humidity variations. Two mathematical techniques were tested to address this problem, a moving average and a polynomial curve adjustment over sliding windows. Both techniques have delivered noise free signals; being however the moving average the one that with least computational cost accomplishment the task of smoothing the data. It has to be mentioned that the time constant of both methods when smoothing the data was set by trial and error, thus the cubic polynomial adjustment of the data over sliding windows can be programmed; so that the polynomial co-efficients can be adjusted as modifying the fit error value. The fifth degree polynomial adjustment was able of recreating most of the data fluctuation of the humidity calculated values, but at the price of consuming a considerable computational cost.

Indoor and experimental field results showed that the microcontroller was capable of monitoring the humidity data and environmental variables and correctly longitudinally controlling the irrigation system for each planted crop, being able to effectively smooth the noise present in the measures. These preliminary tests shown also that the communication modules and the implemented algorithm allow not only managing the irrigation system, but also sending data about the crops conditions and precisely corresponding with alert issuing for extreme climatic phenomena; effectively answering the global criterion of management efficiency and system use.

9.4.3. Control Logic Development

First, the processing methods in these systems differ. The performance evidence of these systems will mainly depend on the control logic and the complexity of the decision architecture. A straightforward option would be to take the direct answer provided by the sensors and thus directly feed the actuators with the output of the sensors. However, this approach has several problems, especially in the case of external sensors. For example, the plant-environmental conditions may not be appropriate for acting at the particular moment in time, and there is an inherent delay in the response of the actuator that may change the efficiency of the final effect. For instance, looking at the sensor that detects the plant unevenness, even when it indicates that something is wrong, the robot only starts to act after that particular moment, losing the future contribution of the testing procedure that led to that possible problem.

Regarding the complex logic systems, on one hand, the more accurate responsiveness of the affectation, the higher the number of knowledge rules. The sophistication of the knowledge will give a realistic model of how a decision-making method possibly organises several procedural actions in a careful way and as a function of what the plant-environmental conditions are, and what the major consequences and effects are. There should be a scientific and experimental basis for both the observation rules, the mutual connections and the elaboration of the entire controlling logic. Statistical data processing may provide useful tools and methodologies to help develop more accurate conditions in the design of the automated irrigation systems. Machine learning and artificial intelligence will be indispensable technologies in these complicated decision procedures implemented in fully automated systems. They will be required to enhance and empower the autonomy feature of the decision procedure in fully automated and ICT systems applied in precision agriculture.

9.5. Implementation Strategies

Assuming the required knowledge is available to complete the deployment properly, implementing a smart control for irrigation management is a matter of 1) implementing pilot projects to guarantee that the technical solution is suitable, 2) testing the proposed control heuristics in a small selected region to validate its suitability and ease of use, and 3) training the end-users in practice.

1. Pilot Projects

A small-scale implementation of the required control system is needed to guarantee that the selected hardware and communications are enough for the whole system operation during the whole irrigating campaign. Recent advances in low-cost electronic systems, together with Bluetooth and Wi-Fi communications, allow the fast development of such prototype. In addition, due to the very small costs of the selected components, the objective is to be able to have a system that does not cost much in terms of the final price. The whole objective of this step is to validate the system should be running during a longer period or provide indications on which components of the deployment could fail in the meantime.

2. Field Testing

Once system requirements are established, it is possible to define the proposed heuristics. These results are obtained from previous simulations of the response of the system under any operational condition. The goal of this step is to guarantee that both the heuristics and the embedded system are installed and configured for the expected use. Once the control is in operation, the Special Control Software will modify the irrigation control strategy according to every crop's needs at every time, allowing the user to choose between following the intelligent strategy or switching back to a more common routine. The aim of this step is to prove the advantage of the Smart Sensor database.

3. User Training and Support

User training focuses on the human reasons behind the apparently strange results provided by the innovative control, and on the indirect advantages of following an intelligent protocol by the Smart Control Module. The aim of the training is to provide people with the appropriate knowledge to allow them to accept the Control Alerts and be able to derive advantages from the irrigation reports. After the test period, a final review will be made. If the Knowledge Transfer is satisfactorily completed, the sensors will be assigned to be used by the users.

9.5.1. Pilot Projects

Multiple pilot projects were created to demonstrate the merits of the system to potential customers. Some pilot sites were used for on-site data collection, site performance monitoring and system adjustment. The following pilot projects were developed during the project period.

1. CAL INVENTORY DEMONSTRATION PROJECT

The objective of this applied research demonstration project was to demonstrate the potential water savings by using a system for determining the irrigation requirements of residential landscape. This pilot project also showed how to integrate the system with a smart irrigation controller. The site covers approximately 4 acres, consisting of 15 different managed areas with different irrigation functions. The location is CAL-IPC’s San Jose Office. The pilot project selected a weather-based irrigation controller. It is interesting to note that the controller is manufactured in a region with a tropical climate different from that of California.

2. CAL INVENTORY IRRIGATION TECHNOLOGY DEMONSTRATION PROJECT

This applied research demonstration project was undertaken to demonstrate the benefits of smart irrigation controllers, including weather-based and formula-based controllers manufactured or assembled in California, and to compare the cost of such controllers with that of conventional controllers. Because water conservation needs to be pursued on a year-round basis, irrigation controllers should be made as accessible as conventional ones. The pilot project involved the installation of several controllers in a specific section of the CAl INVENTORY project. Researchers will compare the cost of these two types of controllers, among other indicators. The potential users of this pilot project are the landscape architects and contractors who develop the landscaping of this project.

Fig 9 . 2 : Smart Irrigation Pilot Projects

9.5.2. Field Testing

This section describes the many field testing sessions of the smart irrigation system, starting with an overview of important variables that were assessed, major findings, and professional and commercial perspectives of the results. The guidelines to be presented say which type of item was observed and at what stage of the overall development and deployment, as well as for how long. Five field testing sessions were performed: During system development; on the nursery phase of crop growth; on the crop growth stage; on crop post-harvest stage; on test module automation functionality. The field testing phases and item observations were adapted. The field testing of the developed smart irrigation system was of paramount importance because these sessions were used to assess: i) the performance of the smart irrigation control logic algorithms, these are commands implemented on the intelligent microcontroller that control sensor readings, valves actuation, pumps actuation, error log generation, internal battery charging and reading, remote data communication, and configuration; ii) reliability of the hardware and network communications – several power loss, hardware, wireless network connectivity, and cloud platform issues were detected in the different field tests. After the series of systematic tests of different modules for specific items on different stages of crop growth, the entire smart irrigation system worked. Its hardware and the developed mobile application for system monitoring and control interface application – the last two months of operation were used mainly for the user to get familiar with the mobile application. It is not only time-consuming, but also expensive for family farming.

9.5.3. User Training and Support

All users of the smart irrigation system need to be trained on how to operate the system properly to ensure the effective use of the system and achieve the expected results. The channel of user training could be face-to-face or video-based live training. The operation of the system requires that the users know how to log in to the system, create Control Logic and Operation Schedule, how to check the status of the system properly, and how to force control the irrigation zones. The Control Logic contains all of the logic-based rules that the users want to set to control the actions of the system and monitors the conditions in which the system is active and the operations performed by the automated system. The Operation Schedule contains the schedule-based rules that the users want to set to control the actions of the system and monitors the conditions in which the system is active and the operations performed by the automated system.

Complete instructions to navigate the system will be provided in detail. Support will be in the form of tutorials, PDFs, videos, messages, email, and possibly telephone support. For many users, there will be little or no experience with creating logic statements for sensor control. To combat confusion and ease the user experience, default control logic rules will be added for common scenarios. Control Logic and Operation Schedule must be modified regularly, as this is a user-defined system for dynamic weather conditions and planting schedules. Users will sign a contract stating that they are responsible for modifying the Control Logic and Operation Schedule, and that the Smart Irrigation System is being governed under their terms. All users will be trained and informed when irrigation, whether automatic or manual, must occur for certain periods of time for vegetative, flowering, fruiting, and cutting sections.

9.6. Performance Evaluation

Performance evaluation is essential to verify and validate that the smart irrigation system is performing as intended. Commercially available smart irrigation solutions, however, do not contribute to the research community because they do not publish their data online. Without common methodologies or datasets, other researchers cannot reproduce the results presented in prior publications. Without the ability to conduct reproducible research, the validity of the data used in prior research works is questionable. Our work, EasySpin, a popular system architecture in a commercial product aligns with prior research studies in terms of system characteristics but comes with many available network resources, which require careful implementations to use and evaluate. The dataset of sweeper and one newspaper delivery robot is also available for public sharing. Careful evaluations of commercial products based on prior research methods and approaches would hence benefit from carefully designed experiments using long-term, larger-scale case studies on suburbs and other environments. Most other products apply over-simplified experimental approaches. In vitro testbed approaches which gather performance data in entirety or in parts using closed-loop and manual operator conditions. Their comparison sources also lack analytics or common metrics and rely on manual observations. As mentioned, our in-field datasets gathered random operations and manually-defined routes for the sweeper, and for one newspaper delivery robot, present extensive metadata for open data analyses. We suggest that multi-method data would provide a compelling case for the problems for which the robot system is utilized. To our knowledge, the evaluation of a commercial product with prior research works such as ambient lighting, sensor fusion, environmental boundary conditions, and run-time verification have not been conducted previously except those informal manual assessments by recruiters, photographers, or opportunistic users in some existing realistic environments. By accumulating the analytical information collected in our work, we encourage other researchers to conduct a range of open analyses by comparing performance results of differing robot systems and utilization problems.

9.6.1. Metrics for Success

To evaluate the performance of a Smart Irrigation System, we need to find a number of success metrics. The discussion in this section focuses on two evaluation aspects. The first evaluation aspect relates to the power consumption of the entire system including soil humidity, temperature, gas, and light sensors, as well as the WiFi module for the data upload to the cloud. The second aspect relates to the quality of the data uploaded to the cloud, and the main question we are investigating here is: what is a minimum time gap between data uploads to avoid a significant watering delay?

Power Consumption

Different types of sensors can be powered either by built-in batteries, solar panels, wireless power transfer, or be wired to a power grid. The most convenient option for a Smart Irrigation System is a battery power supply. In that case, the power consumption becomes essential for the design of the entire SI prototype. The geo-location of our testbed is such that there are long periods of poor sun illumination during winter months. Hence the sensor-to-cloud data upload should be provided at least every few hours, while in summertime potentially data upload can be done every minute or two.

To estimate the battery life of our prototype, we perform measurements of the power consumed by each element of the system while it is in a working state. Power consumption of the sensors was measured with a multimeter, and power consumption of the WiFi module with a power monitor. We discovered that the module consumes from 0.15 mA in the sleeping mode, to up to 2.2 mA while actively uploading data to the cloud. We provide a summary of our experiment, as well as a histogram of the power monitoring.

9.6.2. Case Studies

This chapter presents two case studies: the development and deployment of Smart-Irrigation systems in a university campus in Canada, and the design and deployment of a similar system in a desert region in Mexico. These case studies describe our experiences with the development and deployment of Smart-Irrigation systems, including hardware and software components, as well as protocols for designing, deploying, and maintaining a Smart-Irrigation system. Additionally, we report irrigation water savings while comparing the Smart-Irrigation to a traditional wall-timer-based irrigation system. We observed water savings ranging from 20% to 80% during different months of the growing season. We conclude our case studies with a discussion on the challenges and lessons learned while deploying and maintaining Smart-Irrigation systems. Deploying Smart Agriculture systems in real-world settings introduces new challenges and logistics. Here we describe two examples to stress our lessons learned. The first case study discusses the design and deployment of Smart-Irrigation over a university campus in Canada, while the second case study examines a Smart-Irrigation system over a desert region in Mexico. Both examples are publicly accessible for future research and private interests. Case Study 1: The Smart-Irrigation project is offered via an online application. Figure 3 shows a location map of the present sensors on the Mackenzie Campus grounds. Mackenzie campus has over 56 species of trees and over 1393 trees. These trees are tentatively divided into the categories of Flowering Trees, Coniferous trees, and Nonflowering Trees.

9.6.3. Comparative Analysis

The integrated smart irrigation system semi-automated smart irrigation system using Microcontroller, Automated Control for Irrigation Synthesizer, Smart Wi-Fi Plant Watering System, Automated Smart Irrigation System, Smart Irrigation And Weatherstation Automation System have been presented. However, no known work incorporates all of the using features mentioned above. The comparative analysis helps in identifying the differences in the features used by previous works. Automated Smart Irrigation System with Long-Range Control Distance is similar in concept but the automated smart irrigation system is not flexible as this system because by use of a Bluetooth controlled relay switch, we can set the distance to any desired length. Other systems are not similar in containing an Ethernet module for connection to the internet that helps to send/receive the irrigation timings over the internet whenever required. This helps a lot for long-term monitoring of the irrigation system used in large fields. Additionally, the automated smart irrigation system also consists of a real-time location tracker. It sends the location information to the server every 1 minute. If the farmer is living away from the field, he can track on his family members tend to frequently try to visit his field. The composite of these features mentioned previously have required a larger microcontroller like GPIO enabled and L293D Bridge IC for driving the relay modules. To our knowledge, there is no such complex autonomous smart irrigation system in existing works that uses satellite or physical location for gardening purposes. This system would favorably help long working hour duty personnel and farmers who are distant from the farming field.

9.7. Challenges and Limitations

Modern smart irrigation systems have been designed to provide a precise amount of water and nutrients to crops at the right time and in the right place during the growing season. Automated systems are expected to reduce labor requirements, eliminate the need for difficult decisions for the grower, irrigate when conditions are optimal for the plant, minimize nonproductive water loss in the environment, improve nutrient management, and demonstrate improved environmental stewardship. The aim of an accurate smart system response covers a problem – many external factors such as climate and weather changes may not be taken into account in the same way by all existing commercial applications. This section describes some of the major challenges and limitations of smart irrigation technology, stressed the need to validate the results from data and also the implications of detailed methodology design.

Given the limited knowledge and experience on the part of growers, research is needed to develop more highly automated systems that build on existing systems. The advance requires appropriate combinations of available new communication technologies, sensors, and devices developed for environmental sensing. It is also unclear if these new methods and devices provide better results than systems designed for the lowest possible errors. In addition, more research is needed to provide a complete roadmap and toolboxes for growers in implementing various smart irrigation methods. Growers, especially smaller ones, need help in validating the advantages and disadvantages of each proposed system and methodology to best address their unique objectives and circumstances. In this context, only occasional data on the performance of alternative systems are available to support decision-making, integrated with the best available technology.

Experimental findings indicate that the use of wireless sensor networks for moisture monitoring in a broad area is a feasible and promising option, but also suggests that the current technology has both technical and economic limitations. The technology has limitations, particularly for larger and more complex systems. It is also less reliable than farmer experiences. How farmers would be compensated for providing the high reliability necessary is a largely unexplored area. Budgetary limits mean that the sampling set criteria should be carefully selected. Prices of elementary components are declining.

9.7.1. Technical Challenges

Although the use of automated controls with smart irrigation systems touches off a new era of efficient operation, many challenges will determine the final implementation or not of the commercially available smart controllers. Here we show only the most important ones. Focusing on the economic aspects, further discusses some of these issues discussing the economic viability of proposed methods.

One of the primary and most obvious development challenges is the accurate sensor reading for estimating several soil characteristics. Many of these sensors are relatively new, their deployment in the field for long periods may not have proven results nor enough extensive field data analysis. For example, salt can impact dielectric and electrical measurements that can affect the interpolation equations normally used to obtain the soil moisture content from a measured dielectric/susceptibility coefficient. Further, water phase transition due to freezing may affect soil dielectric/susceptibility readings and, in general, sensors with capacitance mechanisms when put in contact with water. Some sensors also suffer from sensor drift which will decrease their measuring reliability over time or need moister calibration to achieve accurate results. Using more than one sensor type for measuring the same physical property can be beneficial in solving some of these issues.

Next is how much to measure at which frequency to produce an accurate model with both accuracy and resolution required to avoid over- or under-irrigation when obtaining the control actions. The location of the sensors directly impacts the control action obtained from the controller. A third challenge that might arise is the delirium problem in the estimate of the soil's properties either due to fluctuation of sensor readings, lack of readings, etc. This can happen whether using filtration techniques to reduce the noise in the readings or machine learning algorithms implemented to optimize the actuation logic.

9.7.2. Economic Considerations

Despite the benefits offered by automated irrigation systems with smart controls, there are several factors that make widespread deployment unlikely. To begin with, the ability of automation to reduce water consumption and the demand of farmers in economic terms are important initial drivers. However, it should be noted that this type of study is not entirely conclusive since the survey was conducted with farmers who already have some form of automated irrigation. Other studies that do not focus specifically on remnant samples indicate that although monitoring soil moisture sensors reduce the costs associated with irrigation, in general, farmers do not see the technology as a "necessary" improvement for their irrigation systems, especially for those who have been using them for years. Therefore, the use is not guaranteed, by mid-sized farmers with older systems, nor by new farmers.

In this sense, it is common for on-demand commercialization of agricultural products to lead to reductions in the use of irrigation, a behavior that is not observed in agricultural production systems in which the supply of products is considered to be regulated. Unfortunately, the former type of agricultural production development is not productive for the establishment of attractive industrial complexes, and although initial developments strongly affect growth, the latter describes the tendency towards the spontaneous development of agricultural products. In particular, at the investment level, it was estimated that avoiding flooding technology would be used mainly for those exporters who demand high quality products since they pay premiums. Demand benefits would be strongly associated with exports, prices, and irrigation policies.

9.7.3. Environmental Impact

Due to the drastic modifications in environmental factors, the inhabitants of this earth are now in fear of environmental catastrophes. A large portion of the world's population is mainly dependent on agriculture for basic food consumption. Water plays a crucial role in the agricultural sector's growth. Water-supply irregularities have an enormous influence on crop output as well as quality. Smart irrigation systems have enabled high-quality and yielding crop production, and hence the amount of yield loss can be minimized. Additionally, with water conservation techniques, these systems also greatly assist in maintaining the water table. Uncontrolled mixing in irrigation, processing, and managed wet-dry cycles also leaves a significant impact on surface water and groundwater systems with an influence on pollution.

Smart irrigation systems not only help with reducing water use but also the energy consumed by pumping and conserving water. The agricultural sector is known to be a major contributor to greenhouse gas emissions. Excessive applications of fertilizers create an excessive generation of nitrous oxide from soils. However, with smart irrigation systems utilizing the characteristics of both sole irrigation requirements as well as the sensor utilization for direct measurements, nitrogen use is maximally optimized, resulting in a reduction of fertilizer applications and reducing the generation of nitrous oxide. An increase in nitrogen use efficiency has positive climate and economic benefits by reducing nitrous oxide emissions with possible reductions in fertilizer expense for the farmers. These systems can also contribute to extending growing seasons through improved control over the root zone environment. These systems help significantly contribute to the atmospheric carbon dioxide levels associated with climate change mitigation, thus, enabling the sustainable and environmental-friendly economic factor.

9.8. Future Directions

1. Emerging Technologies

The impact of emerging technologies in smart irrigation design is significant. Blockchain simplifies the trust in automation within smart irrigation systems. Contract smart irrigation systems could autonomously control water transfers in space and time for execution by a third party, since the rules of engagement are preagreed with the owner of the irrigation system. Other emerging technologies further increasing automation are artificial intelligence and the Internet of Things. Machine Learning personalizes irrigation scheduling by comparing predicted vegetation health with observed crop evapotranspiration. Communication networks found in drone-based wireless sensor networks could simplify the installation and maintenance processes of smart irrigation designs by rapidly deploying large amounts of small sensors.

Cyberphysical systems further increase the autonomy of smart irrigation systems. In such systems, the watering decision is not taken by the human owner or a smart irrigation algorithm but by the crop itself. The crop network must be made measurable. To achieve this, noninvasive techniques predict the plant signal by monitoring its satellite, for instance using multispectral or thermal imagery. Then, this predicted signal would be integrated with the irrigation decision via a feedback loop strategy or synchronized to the watering cycles.

2. Scalability of Systems

Many of the current smart irrigation systems have been tested only on certain crops for a limited time and with reduced sensor placement density. Thus, establishing the generalizability and scalability of designs to other crops, different latitudes, altitudes, and soil types, as well as different installation configurations, is still of high demand. Furthermore, validation efforts cannot be limited to systems deployed in a research field. Validation would be strengthened if collaboration efforts are increased to provide a smooth transition from research labs to farmer's fields of mature concepts. Such partners often have access to farms of bigger size that are needed to properly assess the return of investment of complete smart irrigation systems under different growing conditions for the various crops grown.

3. Integration with Smart Cities

Another aspect of research is the role of these autonomous irrigation systems in the Smart City. Urban growth with the introduction of new irrigation districts and the need for collaboration between farmers and the city for a sustainable future should be discussed in terms of the digital twins. Digital twins of crops communicate with the twin of the city to prevent excessive water outfluxes into the canal network during precipitation episodes.

9.8.1. Emerging Technologies

The Internet of Things (IoT) is making tremendous developments toward the creating of smart homes and industries that communicate big data, images, and videos. Within the concept of smart homes, the appliances have the capacity to communicate with users and with the cloud to deliver the services required. Irrigation systems can easily be integrated into this smart home environment due with the availability today of platforms that support the management of several other appliances, equipment, and sensors that use an easy to learn and easy to program user interface. The smart irrigation controller can be programmed to perform several tasks, including the possibility to trigger commands to several irrigation valves, activate smart plugs, which can drive pumps or auxiliary fans, and communicate with sensors, switches and probes. Some devices even offer video streams of the gardens under their responsibility, which helps the homeowner to visualize the healthiness of the plants.

Recently appeared on the market a complete sensor node that communicate using short-range low-energy Bluetooth or ZigBee, facilitate the cost and energy involved in the acquisition and sending of data to the node. These nodes can be integrated into integrated solutions with other companies' product that offer irrigation management. Another technology that arrived to be used in smart irrigation applications was the low power Wide Area Network. These networks provide the necessary coverage and range for the construction of solutions far from the office campus, or that have very dispersed sensors in open fields, offering an intriguing advantage over solutions that use LoRa technology, based on integrated chipsets that simplify the integration or power management. Currently, these technologies face the challenge of power supply for a long time, mainly when used feeding actuators.

9.8.2. Scalability of Systems

Scalability is one of the important features of IoT systems. The system must utilize distributed intelligence to allow seamless integration of new control nodes into the system. This requirement is dictated by smart irrigation systems that are deployed over large areas, such as agricultural fields. In addition to environmental conditions, soil conditions will also vary over the field; therefore, different locations may require different water control laws. For example, in row irrigation fields where crops such as corn are planted, in the early stages of development, most of the water should go to the row between the crops, and the amount of irrigation water applied to the individual crop rows is small. Each row of drip irrigation can use its own control laws. When planting other crops in which water should be supplied to stimulate growth evenly, such as the early stages of agricultural development, there will be a need for continual irrigation in every row of crop growth. In this case, control laws may need to be reassessed several times depending on the growth stage of the crops. Without the extension of functionality, even when applied to control all rows uniformly, the system can be executed in a centralized manner.

Currently, most high-profile IoT systems are capable of executing centralized control. The irrigation system is using centralized control to communicate commands to each device over the wireless network. The control center has a preassigned time scheme for all zones. After executing the individual zone, it waits for the prechosen time interval and transmits the specific duration command to each zone for the next run. But due to the cost incurred when running the centralized system, some questions are being raised. Apart from reduced flexibility and increasing unpredictability, this may result in fuel wastage. This functionality, however, requires extensive hardware development and has creation costs. Adding more nodes of the same type will create additional templates that can make system updates in the future extremely costly.

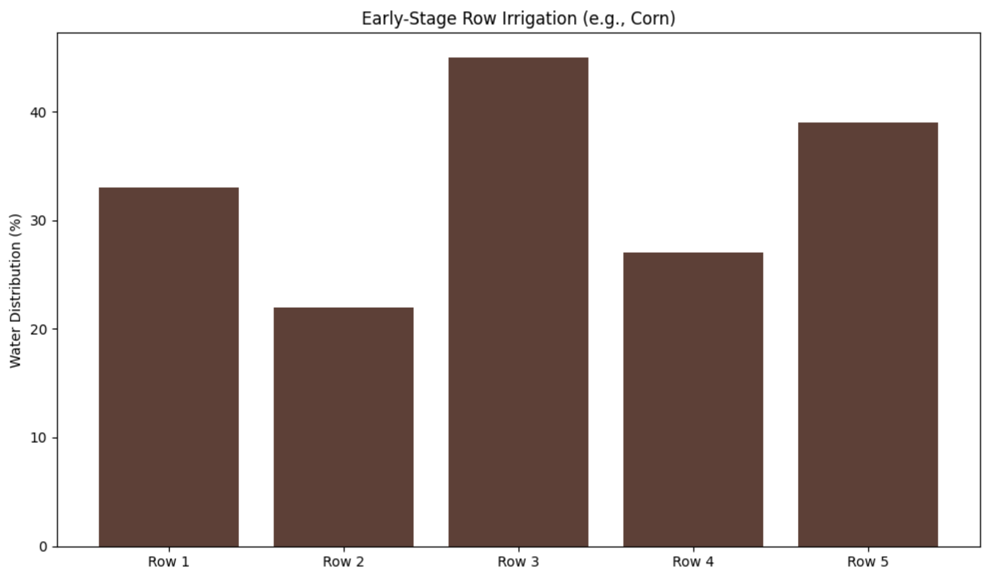

Fig 9 . 3 : Early-Stage Row Irrigation (e.g., Corn)

9.8.3. Integration with Smart Cities

A smart irrigation system is becoming an integral part and a bare necessity of a smart city. Conventional irrigation has been associated with 60% of the world fresh-water consumption. By integrating the other smart city technologies in agriculture and irrigation sector, the fresh-water consumption can be reduced significantly. Integration solutions within the dimension of smart irrigation include, but are not limited to, what is listed in the following.

Advanced Transport Systems, Electric Vehicles & CO2 Infrastructure: Provision of CO2 for use during the transportation of goods to the farm – use of electrified transportation means, enhancement of the CO2 transport transition by coordinating with the transportation centre: Use of electric transport for CO2 transportation, but also for cooling and other processes – charging of electric vehicles by photovoltaic panels installed on top of the product lying on the field.

Farms with Energy Architectures: Innovation of self-seeding – photovoltaic panels on piling structures over the crops – photovoltaic panels projection daylight to the crops in order to enhance their growth – photovoltaic panels keeping the product in required temperature for better and improved preservation.

Farms and Districts with Atmospheric Monitoring Systems: Monitoring of meteorological conditions – use of environmental service to report possible weather disturbance, pollen monitoring.

Farms with Water Management Architectures: Support of water availability and purity by evaporation and distilled technology – re-assuring water purity in the farmland by monitoring (bio)indicators.

Farm Marketplaces: Empirical and scientific-based requests distributed throughout the smart-city community about the product requirements (demand): notification about the newly arrived products to local users – peer-to-peer marketplace for redistributing the product between the farmers on demand and supply basis.

9.9. Conclusion

While population growth has been increasing rapidly and forecasts predict that at least 10 billion people will inhabit the planet in 2050, shrinking arable land is increasingly creating problems in providing sufficient food. At the same time, climate change and pollution are having significant effects on both crop production and water resources. To ensure food security, agricultural innovation is crucial. Digital technologies can help minimize input costs in agriculture while maximizing profits at the same time. New technologies, including new breeds, precision crop farming, automation, and robots; also including agricultural-robotic systems, precision irrigation, and strategic water resources, create opportunities for water saving, precision irrigation, and minimized environmental impacts. The irrigation systems have also developed air- or pressure-driven systems requiring little water with high efficiencies.

Moreover, socio-economic conditions drive the increasing investment in automated irrigation systems. The increasing demand for fresh vegetables and fruits, together with an increasing focus on health, has led to significant imports, which has equalized changes in the agro-food trade balance, creating a need for more food grown in greenhouse systems at the domestic level. To optimize the effectiveness of the systems as well as reduce costs, research must focus on automation and control issues, especially with respect to temperature and humidity; as well as soil moisture requirements. The solution proposed allows for the monitoring of environmental data, taking full control of the irrigation system using affordable sensors. The control commands are sent to the irrigation system in the case of needed actions, accomplished by using low-cost contact relays. The monitoring is performed via technology and user-friendly pages of the application dedicated to monitoring.

9.9.1. Summary of Findings and Future Implications

This work presents several potential benefits of employing a smart irrigation system under remote monitoring and control along with the practicalities that are taken into consideration over the iterative process of development, deployment, observation, and adjustment. This is not merely a development effort to mount a gadget on a plant and couple it with an app to survey its wellbeing. Developing and using a smart irrigation system is a continuous and iterative process through which we employ both new technology to simplify and enhance irrigation decision making as well as physical plant, soil, and climate systems understanding to contextualize and refine the use of the new technology. These lessons learned, beginning with one plant and culminating in two fields of basil and tomato, have been collected through the use of voltage and commercial sensors to monitor moisture levels in soil, observed the response of basil and tomato plants in avocados full of water deficit stress, and enhanced the associated automated controllers to adaptively regulate soil moisture in association with anticipated plant responses and rid the negative impact of excesses or deficiencies of soil water levels. This is not merely a deployment of a sensing network. This is the use of real-time observations of plant, soil, and environmental conditions to make and deliver better informed management decisions about plant irrigation requirements. This iterative process of new technology and real-world observation to enhance understanding, remove uncertainty, and provide better recommendations on how to meet plant water requirements will enable greater exploitation of smart irrigation systems for additional crops of other plants as well as other crops of related species.

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