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Moving beyond manual software-supported precision irrigation to human-supervised adaptive automation

Peter George Raeth

Independent Consultant in Computational Science and Distributed Systems, Nova Southeastern University, Florida, USA.

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This paper “looks across the river” to explore computer engineering applied within agriculture, particularly precision irrigation. It begins with work by the United Nations Food and Agriculture Organization (FAO). They developed guidelines for estimating a crop’s water requirements. These guidelines describe a set of equations (Penman-Monteith form) drawn from the physics of evapotranspiration. The equations estimate water loss based on information specific to the crop, soil, terrain, and weather conditions. Many good papers have been published on applications of the hand-held calculator produced from those equations. This present paper addresses the gap between software-supported manual implementation of FAO’s equations and full automation. The project reported within transitions theory to practice by creating a proof-of-concept for an adaptive automation process that combines an embedded version of FAO’s equations with automated feeds of weather data and connectivity with irrigation controllers. The result is a prototype for an adaptive human-supervised fully-automatic approach to irrigation based on estimated crop moisture needs. With precision irrigation, farmers seek to cope with drought by minimizing water use without devaluing the crop. This present work is another effort in that vein..

Key words: Precision irrigation, distributed systems, water conservation, evapotranspiration, Penman-Monteith, adaptive automation, precision agriculture.

INTRODUCTION

The project described in this paper addresses the gap between software-supported manual implementation of Food and Agriculture Organization (FAO)’s evapotranspiration equations (Allen et al., 1998) and full automation in an adaptive human-supervised context. Precision irrigation is a component of precision agriculture (precision farming), a field of work that combines agricultural knowledge with other fields such as computer engineering, geographic information systems, remote sensing, and meteorology. The main point is to improve or, at least maintain, crop value while using fewer resources such as land, pesticides, water, and fertilizers. It does so while retaining nutrition and without resorting to the risks of genetic mutation.

Given the considerable literature in precision agriculture (Brase, 2006; Lal and Steward, 2016), it is clear that computer engineering can help create adaptive human-supervised automated-control of irrigation systems. Such

E-mail: peter_raeth@ameritech.net.

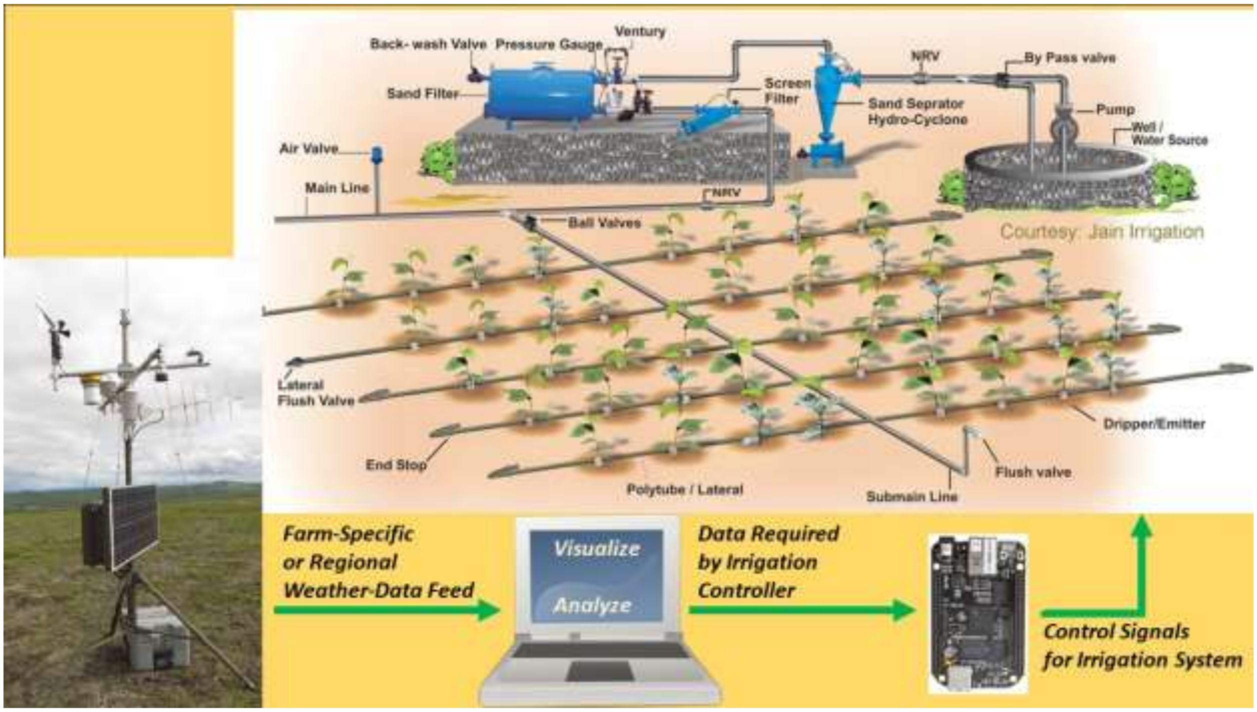

Figure 1. General vision for human-supervised fully-automated irrigation system[i].

control mechanisms have the potential to aid countries stricken by drought as they move beyond their dependence on direct-rain for watering crops. This could extend opportunities to grow crops outside the rainy season, while still not over-farming the land. Precision agriculture's positive impact on Africa has been noted in Shimeles et al. (2018), Ncube et al. (2018), and Jacobs et al. (2018).

Besides growing seasons limited by direct-rain irrigation, drought in many nations requires careful use of water. This leads naturally to control over irrigation so that crops are not over-watered or under-watered. Precision irrigation seeks to improve over methods that rely on fixed schedules and fixed volumes. Based on plant, soil, terrain, and ambient weather conditions, measures are taken to estimate a crop's water needs, and to irrigate on that basis. In the same way that crop health cannot always be estimated by visual observation, the same is true of a crop's water need. By the time the crop or land shows visual signs of dryness, the time when irrigation should have been applied is past. The project reported in this paper makes use of weather data and FAO's evapotranspiration equations to demonstrate an approach to limiting the amount of water drawn for irrigation. The author speaks to how the controller might be built, and discusses what this project has accomplished so far in that regard.

Figure 1 illustrates the general vision. Combining soil, terrain, and plant type, the plant's moisture needs, and actual rainfall, evapotranspiration calculations give an estimate of water loss and, thus, water needs. From there, a decision is made on activating the irrigator for some length of time at a given volume.

RELATED WORK

A number of good papers report on the use of evapotranspiration to reduce irrigation compared to standard schedule/volume watering. These make use of different manual controllers and a hand-held ETo (FAO, 2009). Proprietary irrigation controllers are generally designed for a particular crop, while supporting some variants. The UN's hand-held calculator yields variable-crop capabilities but is not designed to be integrated into an irrigation system so that a fully-automated mechanism can be realized.

Tolbert et al. (2016) worked with flatwood soils and sandy soils. They evaluated evapotranspiration (ET) control and soil-moisture control systems (SMS), with and without careful training of users. Turfgrass was the crop in question. The results were compared to cumulative irrigation with and without consideration of weather. They found that ET and SMS provided essentially equal results. Both were statistically beneficial when compared with conventional volume/schedule watering. A great deal of additional benefit was derived from careful training of users of SMS and ET controllers.

Goodman (2010) took an excellent step toward fully-automated human-supervised irrigation control based on evapotranspiration. He discussed and demonstrated the solution to myriad problems one should expect to encounter in the design and development of such systems. Like Tolbert et al. (2016), they addressed Turfgrass since landscaping is a major use of water in the USA. His evapotranspiration equation parameters are drawn from an online database provided by the State of California, USA. He showed that the target system can be developed using existing technology.

Chin and Auda (2017) introduced Internet of Things (IoT) technology to support a general ability to monitor and affect crops. Their work greatly expands one's vision of what can be accomplished using cloud-based technology and appropriate sensors. Their paper also addresses interfaces that support human supervision so that, while full automation is achieved, computer systems are not totally autonomous.

Yihun (2015) showed that diverted-water irrigation enables Teff production beyond the rainy season (An important point since most Teff production in Ethiopia depends on rainfall). He also developed values for Kc, an important parameter in evapotranspiration calculations. He focused on fine-textured and clay-loam soils, and showed how these values change as the crop grows.

Although beyond the scope of this paper, use of diverted-water irrigation by Yihun (2015) leads one to wonder if the land available for planting outside the rainy season could be expanded if water could be retained instead of being allowed to run off. Bladders developed by Yitbarek (2019) are an option, as are the rain-catch barrels of Munyaradzi et al. (2013a). One must be concerned with how to keep water containers full during the dry season. In Zimbabwe, it is common for trucks to deliver water. Water sources are an issue as well, especially in land-locked nations such as Ethiopia and Zimbabwe. One option is water desalination. Desalinated water could be imported from coastal nations. Technological development of desalination may be reaching the point of affordability, as suggested by Colagrossi (2019). Such matters are worth mentioning since irrigation requires water from somewhere and should not necessarily be limited to diverted natural sources or to rain, whenever rain happens to fall.

Araya et al. (2010) also developed values for Kc but employed a simpler approach than Yihun (2015). Similar to Tolbert et al. (2016), they found that trained users yield statistically significant benefit. In the case of the project reported by this paper, Kc values reported by Yihun (2015) and Araya et al. (2010) were employed to calibrate the FAO's evapotranspiration equations.

Precision irrigation has been found to be very beneficial for Ethiopian Teff crops (Yihun, 2015; Hilemicael and Alamirew, 2017). The thrusts in irrigation mentioned in this section are important since, currently, farming in Ethiopia is heavily dependent on direct rainfall (Kubo et al., 2012). With dependable irrigation and dependable water sources beyond direct rainfall, it may be possible to extend the time during which Teff can be grown, without over-farming the land. This has been demonstrated already in Ethiopia by a project that is collecting rainwater in bladders for use during periods of no-rain (Yitbarek, 2019). Literature found by the author on precision irrigation applied to Teff does not employ a fully-automated approach. By closing the gap between manual software-supported and fully-automated irrigation approaches it is possible that additional water savings could be achieved. This is something that would be beneficial to Africa and supportive of small farmers, thus adding to food security, especially if small farmers collaborate as part of a cooperative.

MATERIALS AND METHODS

Teff originated in Ethiopia and is that country's major crop and where most of the world's Teff is produced (Mottaleb and Rahut, 2018). As this research began, the author was a visiting Assistant Professor of Computer Science teaching at University of Gondar, Ethiopia, ICT Directorate (Information and Communication Technology). This led to the use of that crop as a means of discussing the broader issue of adaptive human-supervised fully-automated precision irrigation. Thus, evapotranspiration equations were calibrated for Teff. There have been several successful precision irrigation applications in Ethiopia for Teff. These rely on evapotranspiration calculations using equations developed by FAO (Allen et al., 1998). The projects cited earlier performed calculations using an international-standard manual calculator produced by FAO (Raes, 2009). Such projects demonstrate the value of applying evapotranspiration considerations to Teff production in Ethiopia.

A problem with FAO's hand-held evapotranspiration calculator is that it does not lend itself to insertion within embedded systems. It would be difficult to employ within a broader range of standard industrial equipment. Therefore, the author began with the 375-page document produced by Allen et al. (1998) and cast evapotranspiration equations in an industrial-standard computer language, C++. This language, employed according to language standards, has proven to be fully portable across Windows and Linux operating systems.

The evapotranspiration equations for ETo and ETc have several parameters. Each parameter is calculated by its own sub-equation, or looked up in a table relative to the crop, soil, and terrain. The work by Allen et al. (1998) is replete with examples, calibration tables, and discussion. These were all employed during design and testing, parameter by parameter and equation by equation, to develop and test new software. Each sub-equation has its own example. These examples were used to assist in creating and testing software in a modular approach. The flow of calculations were were guided in Allen et al. (1998). The result is software that works exactly as specified for whatever calibration or weather input.

ETc is calculated as a modification to ETo for translation from the reference crop to a specific crop. In a study, Allen et al. (1998) give Kc values for numerous crops during various growth phases. These values were produced from various studies under different conditions. There are equations for modifying Kc values for specific conditions that can be applied under standard conditions. However, those equations were not applied in the present phase of the project reported here since Kc is not tabulated for Teff and the papers giving Kc values resulted from specific conditions. The author assumed those conditions so that Kc was used directly, as reported.

Historical weather data was obtained from America's National Oceanic and Atmospheric Administration – National Center for

Environmental Information (https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&countryabbv&georegionabbv). However, weather data for Ethiopia is not complete. So, a test set for Gondar was constructed for one growing season from what data is available. This gives weather data for testing. If the project goes beyond proof-of-concept, it offers encouragement for producing reliable quality weather data.

For this prototype, physical implementation used a common Windows laptop and a BeagleBoneBlack-Industrial embeddable computer (https://beagleboard.org/black). The laptop, along with the community version of VisualStudio was used for writing and testing of all software, including that installed on the BeagleBoneBlack. The BeagleBone runs the Debian version of Linux and was the only thing purchased for this project, at a cost of $100US. It was chosen because it is a full-up Linux-based computer, contrary to other popular devices that are only microcontrollers. Microcontrollers are limited compared to computers but they do have their place in automation. The BeagleBone is open-source hardware, as are many microcontrollers. That means all construction plans for the hardware are freely available without license. In this case, the project purchased a ready-made industrial version. VisualStudio-Community is free, as is the Debian-Linux operating system. Windows is not free but that is normally a part of common laptops. It is interesting to note that the Windows side of the software could run on an inexpensive Linux computer. There are many ways to architect the hardware. In this case, Windows was chosen since that type of machine was already on hand. Plus, VisualStudio-Community is free and is an excellent software development environment. Generally, there are possibilities for moving to less expensive hardware as the transition from proof-of-concept to implementation proceeds.

Referring back to Figure 1, historical weather data takes the place of the weather station. The BeagleBone is the embedded computer, and the laptop is the laptop in the figure. This prototype did not connect to an irrigation system since that was not available. Instead, the laptop sends a message to the embedded computer, which then activates an LED to show that the signal was received. The LED remains on for as long as the message from the laptop indicates. How long the irrigator operates depends on the amount of water required and the amount of water the irrigator produces per unit of time. The program initializes an amount of moisture available to the crop based on documented crop-moisture needs (It was assumed that the field was appropriately water upon planting). As the days progressed, calculated ETc was subtracted from the moisture available. Rain on that day was added. The difference between needed and actual moisture was made up by the irrigation message.

Kc was derived from a study by Araya et al. (2010). They give their measures of ETo and ETc. ETc = Kc × ETo, so Kc was not difficult to derive. Since that research was conducted under specific circumstances, the derived values for Kc were used without modification. Based on the Kc values relative to growth phase and growth phase determined relative to number of days after planting, an interpolation procedure calculates Kc.

General Kc values in Araya et al. (2010) do require modification for the situation at hand. That software is currently in production.

RESULTS AND DISCUSSION

ETo calculation results were compared to those produced by CropWat (http://www.fao.org/land-water/databases-and-software/cropwat/en). That tool appears to be using a simplified version of the calculations described by Allen et al. (1998). For instance, CropWat seems to use incoming solar radiation instead of net radiation. The result is that this project's software delivers results that are 2 to 4% lower than CropWat. This is expected since incoming solar radiation is always greater than net solar radiation (net = incoming – reflected).

ETc gives an estimate of moisture loss. There may be circumstances where some level of confirmation is needed. Munyaradzi et al. (2013a, b) and Marimbi et al. (2012) have demonstrated the use of inexpensive soil-moisture sensors in outdoor and greenhouse farms. Their results show that the amount of water can be lowered while avoiding over and under watering, and while maintaining or even improving the crop’s value. A concern is not only the cost of sufficient numbers of sensors but also the cost of communicating each sensor’s data. However, there is much potential for improving the economics of farming using their methods. In fact, many of the attributes considered in irrigation scheduling via soil-moisture sensing are the same as those considered in evapotranspiration. Thus, one easily sees the opportunity for a merger of technologies and approaches for precision irrigation.

A great deal of difficulty with weather data was encountered. While a historical database could be accessed, the data for Ethiopia is incomplete and spotty. This was overcome by constructing a dataset for a single planting season. However, this approach serves only for software testing. A reliable source of quality weather data is needed.

In the test case for the present prototype, ETc and that-day rain was employed to calculate the amount of water needing to be delivered by the irrigator. This may well cause overwatering if it were to rain within the next 24 h. But, without reliable and accurate weather data, how does one come to a useful prediction of rain? This is another encouragement for national weather services to produce the required observations. Once the data is in hand, physics-based or statistics-based next-day-rain predictions can be had. If the predictions are accurate, then one would not necessarily water immediately but only if no rain is predicted, or if predicted rain did not occur. This could lead to further water savings. For the project reported here, it is possible that a statistical prediction model could be created from historical weather data. The model could be updated as new data arrives.

As this is a data-driven application, the scalability of data gathering, processing, distribution, and storage is of concern. A preliminary review of the matter indicates that it is possible to set up an expandable highly-reliable system using respected open-source software.

Where reliable and accurate weather data is not available, the installation of a weather station is necessary. Other sources of weather data could be explored. A useful farm-specific weather station costs up to $1500US. There are other sources of weather data that are freely available, besides the one used by this project. Those should be explored and evaluated. Any installed weather station should become a feed into databases that are freely accessible. Should remotely-accessible public systems be necessary, companies such as RackSpace (https://www.rackspace.com) and DigitalOcean (https://www.digitalocean.com) provide hosting for portable software systems. Respected open-source cloud software and other tools can be readily installed and operated. It is not necessary to use restrictive hosting services that prevent portability from one system to another.

Although mentioned last, of greatest importance is collaboration and testing with agriculturalists who are actively dealing with issues of drought. Computers are enabling tools but they are no substitute for experience in the topic area to which they are applied. For example, in the case of precision irrigation, tables of Kc assume the crop is in a given growth phase at a given number of days after planting. But, what growth stage is the crop actually in at any particular time? That is something that an agriculturist must answer. Computers and simulations, even given hordes of real-time plant images and data can only offer an estimate, a best-guess. They are not intelligent. They are just boxes filled with on/off switches. The intelligence lies between the ears of agriculturalists.

Conclusions

By combining research in agriculture and computer engineering, it is possible to embark on a new thread in precision irrigation that goes beyond manual software-supported methods. This thread holds great promise of creating an open-source hardware/software capability that is implementable by small farmers and farming communities if reliable and complete weather data can be achieved. Results in this project to date demonstrate that the technology exists for transitioning research into practical application. There are also possibilities in Controlled Environment Agriculture, an effort to bypass the issues of seemingly random rain and other environmental issues. Bethke and Lieth (2020) provide a broad introduction to that topic.

Water is an essential resource for farming and food security. Drought, or at least insufficient water, is common in Africa and other parts of the world. This project represents another thrust in minimizing water use while still maintaining or even improving crop value. It builds on previous results achieved in Africa and elsewhere. There is much encouragement to continue in this vein.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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