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A Systems Engineering Approach to Viticulture On-Farm Irrigation ⋆

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Abstract:
Water resources management presents an important research topic, because our planet is facing a serious water crisis. About 70% of all fresh water usage goes towards agriculture. Moreover, low water application efficiency are well reported in the literature. Improving on-farm irrigation efficiency can make a substantial contribution to a more sustainable utilization of the world's fresh water resources. It is argued that systems engineering principles can assist to realize the goal of improving water efficiency or produce quality in on-farm irrigation whilst maintaining productivity and quality of service. In approaching this resource management problem, wireless sensor network technologies and automation ideas are combined to improve economic productivity in dairy, horticulture and viticulture industries in such a way as to support continued growth in these major food industries in the face of a competitive water market. This paper reports the early progress of the project on smart irrigation system for viticulture and initial attempt in modeling the viticulture soil-water dynamics is briefly discussed. The results obtained are encouraging indicating that water automation is a promising technology.

Keywords: Information technologies in agriculture, Modeling and control of agriculture, Identification for control, Management of natural resources, Wireless sensor networks in agriculture, Sensor Networks

1. INTRODUCTION

UNESCO (United Nations Educational, Scientific and Cultural Organization) indicates that the world is heading for a water shortage under a no-change management scenario and median forecast population growth http://www.savewater.com.au (2003). Furthermore, the UN (United Nations) world water development report Water Report (2003) claims that at the beginning of the 21st century, planet earth is facing a serious water (management) crisis. Recently, in Water Report 2 (2006), it is estimated that our population requirements for water in agriculture will grow to 600km^3 by 2025. The world average efficiency of irrigation water use is estimated somewhere between 40% (Water Report (2003)) to 50% (http://www.unesco.org/water/wwap/) depending on the source; that is less than 40% to 50% of the water withdrawn for irrigation is effective in food production. Current work showed the potential of systems engineering principles in irrigation water management and this is an area which attracts increased attention, see e.g. Schuurmans et al. (1999), Weyer (2002), de Halleux et al. (2003), Weyer (2003), Litrico and Fromion (2003), Ooi and Weyer (2003), Mareels et al. (2003c), Mareels et al. (2003b), Mareels et al. (2003a), Dulhoste et al. (2004), Mareels et al. (2005b), Mareels et al. (2005a), Muñoz and Dukes and references therein, Weyer (2006), Cantoni et al. (2007), Ooi and Weyer (2007), Mareels et al. (2007) and Ooi and Weyer (2008).

The University of Melbourne, National Information and Communications Technology Australia Limited (NICTA) and Goulburn Murray Water (GMW), Australia embarked on a multidisciplinary research and development project: "Regional and Economic Benefits through Smarter Irrigation" sponsored by the Victoria State government under the Science Technology and Innovation initiative infrastructure grants program (see Dunn et al. (2006) and Dassanayake et al. (2007)). This project combines engineering at the University of Melbourne and NICTA a national centre of excellence in wireless sensor technology and the operational expertise of GMW, with an innovative irrigation community to develop and demonstrate smart water management systems in a range of agriculture enterprises in Victoria, Australia.

Irrigation management is a complex matter in most modern agricultural enterprises. For instance, a 200 hectare orchard in the Goulburn Valley, Australia could have up to 65 different blocks with different crops and different irrigation requirements a complex system to manage well. A modern vineyard is equally complex. The current practice of manual data acquisition and manual irrigation control is obviously labor intensive and expensive. It limits what can be achieved through water management. Automation based on wired sensor/actuator network systems is impractical. A reliable and cost effective wireless sensor/actuator network has substantial potential to

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increase product yields, quality and consistency while reducing labor costs of irrigation and achieving a better water efficiency on farm.

Similarly, opportunities to improve irrigation based on current technologies and water delivery systems are limited in a dairy pasture context. However, if 'water on demand' can be achieved in the bulk supply (see e.g. Mareels et al. (2005a)) using wireless sensor/actuator networks will allow precision control even in flood irrigation. This combined with appropriate 'measure and control' software systems that exploit the real time measurements to deliver an irrigation management that is responsive to the pasture's needs may deliver significant efficiency gains.

A wireless sensor/actuator network with decision support software requires a considerable investment, which has to be economically viable. Does the productivity gain and water efficiency gain pay for the required infrastructure and its associated maintenance? The answer depends on the price of water, and the availability of a water market that enables a real time water trade. In Australia the pressure from climate change seems to make the deployment of wireless sensor and actuator networks almost a certainty, as soon as they become commercially available. At the other side of the ledger, the answer depends on what performance gains can be achieved through automation. It is difficult to estimate what water efficiency performance or produce quality improvement may be achieved by a wireless sensor/actuator network system. Especially when automation is considered for the first time as there is simply no experience with the behavior of the system under the automation regime. Even in the situation where manual operations are being mimicked through automation, the mere presence of automation always leads to new possibilities in operating or managing the system that more often than not were simply inconceivable before the automation was realized. Without a thorough understanding of this behavior, it is difficult if not impossible to ascertain what the economic impact will be. So typically, pilot studies are called for to quantify the impact automation can make. Pilot studies enable one to evaluate realistically the behavior realized under the automation regime, how it differs from the open-loop, manually managed system behavior and consequently one may confidently predict what impact automation has on the bottom line. Alternatively, simulation studies could be envisaged to predict the potential changes in behavior, with the aim of deducing or predicting what the (economic) impact can be. This requires that a good simulation model is available for the system under consideration, one that allows for the consideration of the automated behavior over time scales that enable economically valid conclusions. This is not a simple task in general as such simulations require information from very different realms of expertise, which are not easily integrated. Moreover, a model that captures the true dynamics to a sufficient degree is difficult to achieve without detailed measurements over a significant period of time (which in itself is perhaps a good reason to introduce a wireless sensor network).

This paper describes a pilot project of sensor/actuator network deployment in on-farm irrigation automation over the Aug 2006 to April 2007 irrigation season in Victoria, Australia. The objectives of the pilot trails are to build and test a wireless sensor/actuator network in a vineyard, orchard and dairy farm; to integrate the sensor/actuator network, software and user interface to create a water management system. More importantly, data are collected in order to understand and model the dynamic behavior. In this paper we focus on modeling the viticulture soil-water dynamics using system identification techniques (dairy pasture and horticulture and orchards were equally considered, but not discussed in detail).

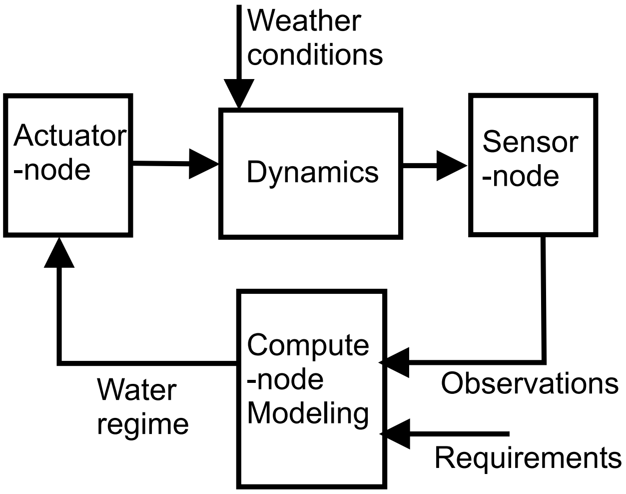

Fig. 1. Closed loop irrigation

The remainder of the paper is organized as follows. In the next section, the infrastructure is considered. In Section 3 follows a brief introduction to the Viticulture industry together with the description of the experimental site and the data that were collected. A simple modeling exercise of viticulture soil-water dynamics is carried out in Section 4. Finally, some concluding remarks are given in Section 5.

2. EQUIPMENT/INFRASTRUCTURE

Closed loop irrigation management is based on real time information from the vinyard/orchard/pasture under consideration. Soil moisture, better still, fruit and canopy water requirements are to be measured and maintained within prescribed levels to match the desired water regime. The latter is informed by and adjusted according to (expected) weather conditions, and the typical growth cycle for the vines/fruit trees under consideration. Spatial sampling is necessarily sparse, and temporal sampling can be minimized using event based sampling. The idea is captured in Figure 1. The information gathered through such a sensor/actuator network enables, short and long term modeling, which in turn long term economic optimization of the agricultural enterprise.

2.1 Sensors

The right sensor technology is of critical importance, and despite significant advances, suitable sensor technology capable of measuring produce quality is not yet commercially available. Soil moisture measurement technology is more readily available and is used in the pilot project for automation in on-farm irrigation. Sensors used in this project are the Theta probe, Echo probe and Sentek's EnviroSCAN®, see Dassanayake et al. (2007) for details. The Theta probe is an impedance based dielectric soil moisture sensor (see http://www.mea.com.au/products/theta probe/), the Echo probe is a capacitance based measure of the dielectric permittivity of the soil to determine volumetric water content (see http://www.decagon.com/Ech2o/) and the Sentek's

EnviroSCAN® comprises multi-sensor capacitance probes able to profile soil moisture at different depths (see http://www.sentek.com.au/products/enviroscan.asp). These sensors were chosen partly because of their fast response, accuracy, simplicity and ease-of-use (easy to integrate into a real time monitoring system), low maintenance but most importantly because of the relatively low cost associated with ownership.

2.2 Actuators

Electromechanical actuators can be used to automatically start or stop an irrigation application. This technology is readily available across a wide range of irrigation technologies ranging from open channels to pressurized pipes.

2.3 Wireless Network

At the heart of a smart irrigation system is the information/data network that must link, sensors, actuators and compute nodes in order to deliver the automated irrigation. In this project, we utilize the NICTOR™ wireless sensor network platform developed by the Victoria Research Laboratory of NICTA, see Thoms et al. (2007). A Zigbee standard compliant wireless network client that easily interfaces with both actuators and sensors, and provides automated routing of data between compute nodes, sensor and actuator nodes as required. It has advanced security, plug and play networking, and advanced power management tools to ensure maximum network life. It provides a great level of flexibility and monitoring tools enabling remote management, diagnostics and (re)configuration of the entire network. A typical unit is solar powered, where the solar panel is dimensioned to meet both the communication and sensor/actuator requirements.

3. PILOT TRIALS FOR VITICULTURE

The viticulture pilot trial on Shiraz wine grapes is based at the Fosters commercial vineyard in Corop, Victoria, Australia. Much of Australia's grapevines (84%, totalling 7,020 vineyards) are grown with the aid of irrigation. The collective area of grapevines irrigated in Victoria was 149,960 hectares (from a total of 149,960ha Australia wide, 47.5%) in 2005. The average irrigation in Victoria was 5.1ML/ha which is more than the national average 3.76ML/ha, see ABS (2006).

Nationally the most commonly supply of water for irrigated grapevines was obtained from either state or private irrigation schemes (83,757ha). State or private irrigation schemes are the most common irrigation suppliers in Victoria accounting for 95.9% (25,156ha) of the total supply (note this does not include water from rainfall). A small supply of water was obtained from underground (31,694ha nationally) and other surface water supplies (26,945ha). In northern Victoria Water supply for irrigation is facing severe constraints.

A dramatic decline in flood irrigation has resulted in both drip and micro spray being the most common watering method (113,858ha or 75.9% of the total area irrigated). Spray irrigation excluding micro spray accounts for 29.5% (10,395ha) of total irrigated area in Victoria whereas flood or furrow irrigation accounts for less than 23%.

Foster's Wine Estates (FWE) is a large company operating in Australian, which produces and sells wine to both international (Americas, Europe, Middle East, Africa and Asia) and domestic markets. FWE control about 50 individual brands of sparkling, table and fortified wines. Some of the premium wine brands include; Beringer, Lindemans, Wolf Blass, Penfolds, Rosemount, Matua Valley, Wynns Coonawarra Estate and Castello di Gabbiano. FWE manages over 15,000ha of vineyards and controls more than 20 wineries worldwide. The selected experimental site located at Corop in the Goulburn Valley, Victoria, Australia contains Shiraz wine grapes (see Wine Industry and Crop). Shiraz wine grapes have been selected as they represent significant contributions to both Australia's domestic and international wine markets (see Wine Industry for details). Shiraz vines at Corop are four years old on one root stock/clone combination with single wire trellis system. The potential experimental area is 8.64ha with the shortest row contains 111 vines. Drip irrigation method is used with a dripper spacing of 0.66m.

Most vineyards in the Goulburn Valley are irrigated with pressurized water delivery systems, being mainly drip (trickle). However, there is a great deal of variability in approaches to irrigation. These range from a basic approach, where the water delivered is based on an seasonal allocation, which is separated into a quantity to be delivered per irrigation event. To a more complicated approach, which would process the information obtained from the field; mainly manual labor, such as soil moisture, canopy size, soil type, etc, and then a scheduling timetable is compiled based on the operator's experience. On the whole, there are three decisions made routinely when scheduling irrigation; (1) how much water should be applied, (2) what time of day should this water be applied and (3) what should the duration be between irrigation events? See Goodwin (1995).

The Corop vineyard has been selected to represent a 'typical vineyard' and it is considered as one of the 'best practice' in the vineyard industry. The irrigation scheduling is based on regular assessments of soil moisture plus a good historical knowledge of the vineyard, such as a good understanding of the soil types, variation within blocks (the vineyard was separated into areas of soil type) and so on. Furthermore, in order to cut down the electricity cost of pumping as well as evaporative losses, irrigation events are usually occur at night time. The irrigation events are preprogrammed in the computerized irrigation system that will turn on and off the pump at the scheduled time. Note that there is no feedback and no real time measurement is used to make the irrigation decision, it is purely a heuristic time based scheduling strategy.

3.1 Experimental Layout

Soil survey's and an EM38 analysis were used to assess vineyard variation and an area consequently selected for the trial location. 20 multilevel Sentek EnviroScan® sensors (labelled as S1 to S20 respectively) were installed on the four rows of experimental vines with five sensors per row according to the experimental layout statistically designed by Dr L. Callinan. These sensors are measuring soil moisture at four different depths, 20cm, 40cm, 60cm and 80cm. The site is independently irrigated by four treatments. We named the treatments as Treatment 1 (T1), Treatment 2 (T2), Treatment 3 (T3) and Treatment 4 (T4), see Table 1 for the layout of the sensors and their corresponding irrigation treatments. Note that buffer rows and buffer spacing between replicates was implemented to minimize influence across treatments.

Plot	Row 74	Row 77	Row 80	Row 83
1	S1 (T2)	S6 (T4)	S11 (T3)	S16 (T1)
2	S2 (T3)	S7 (T1)	S12 (T2)	S17 (T4)
3	S3 (T4)	S8 (T2)	S13 (T1)	S18 (T3)
4	S4 (T3)	S9 (T2)	S14 (T1)	S19 (T4)
5	S5 (T2)	S10 (T1)	S15 (T4)	S20 (T3)

Table 1. Corop vineyard S1 to S20 sensors layout with their corresponding irrigation treatment.

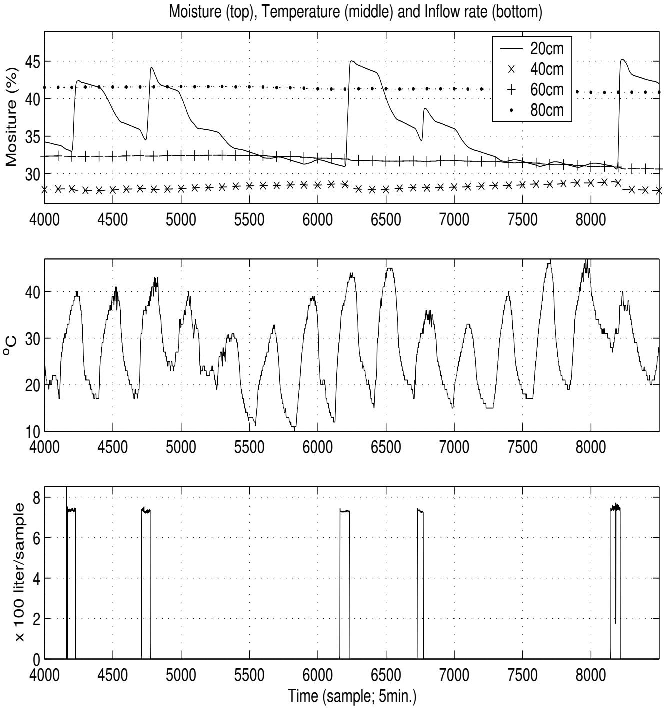

Fig. 2. Soil moisture of sensor S4, temperature inside NICTOR™ box and inflow rate of treatment T3.

3.2 Data

Due to the space limit, in this paper we focus on the results from Sensor S4. Figure 2 show soil moisture at 20, 40, 60 and 80cm depth from sensors S4, see Table 1 collected in January 2007 together with the temperature inside the NICTOR™ box and the inflow rate of the corresponding irrigation treatment T3. Note that the inflow rate is the total for treatment T3, but not for individual drip hole/sensor. These data are uniformly sampled with a period of 5min.

Note that the Sentek EnviroScan® sensors have only been calibrated against saturation (that is in water and air). Hence, the soil moisture readings are only a rough indication of the water content in the soil but not the actual soil water content, i.e. readings from two different sensors from two different locations are not directly comparable. We are in the progress of calibrating against the soil type of the experimental site, once this is completed, they will then reflect the actual soil water content. However, for the study carried out in this paper, calibration against soil type is unnecessary.

Discussion From Figure 2 it is clear that saturation occurs. For example, between samples 6000 to 6200 and again from 7500 to 8200. This needs to be taken into account during the modeling process.

From Figures 2, there is a time delay between the start of an irrigation and the soil moisture response. The time delay depends on the irrigation and ranges from 33 to 44 samples (165min to 200min). Experience suggests that this is a longer than expected delay, perhaps due to the extreme drought conditions during the particular irrigation season. Experience, under more normal seasonal conditions suggests that the infiltration response should be noticeable in about 60min. This delay is however readily derived from the data, and hence the automated system can *learn* under what conditions to operate; a clear benefit of using real time field data, rather than expectations.

The unexpected time delay between water application and soil moisture response measured can be explained by an unusual micro-topography of the soil near the sensors. Uneven ground preparation around the sensors, may force the water to flow away from the sensors rather than straight into the ground near where the sensors are. It is more likely that the longer delay and uneven micro-topography is due to very dry conditions throughout the pilot trials (and not the soil preparation). This is further supported by Figures 2 where saturation events are recorded. Saturation should not occur under normal irrigation circumstances. However, under extreme dry conditions, soil dries out to the extent that cracking occurs. This causes the water to move down in strange patterns, occasionally missing some sensors, occasionally flooding a sensor. Furthermore very dry soil conditions, also lead to slow water movement because of absorption.

Better preparation of the soil around the sensors is now being carried out to eliminate soil micro topography problems over the next season. In addition, a soil mechanics investigation is under way to better study the wetting patterns.

4. MODELING

As a starting point, modeling of a very simple relationship between soil moisture at a single point, applied water, temperature as well as usage by plant and distribution of water to the surrounding is considered. From Figure 2 it is clear that virtually no change in soil moisture is measured at 40, 60 and 80cm depth. Hence, the soil moisture measured at 20cm is considered.

Figure 3 shows water balance components of an irrigation system, see e.g. Allen et al. (1998) for more details. From Figure 3, the soil moisture θ at a point will increase in a response to irrigation (no rainfall events across the entire season), and θ will decrease as water is extracted by the plant, evaporation or due to deep percolation. Hence, a simple volume balance leads to change in $\theta, \dot{\theta} \propto \text{inflow} - \text{usage}$.

Obviously, (ignoring elusive rainfall) water is supplied from the surface/dripper lines, and is removed by plants and deep percolation. The flow measurement from the dripper line, I, represents the inflow term. The water usage by plants, (under unsaturated conditions) is correlated with the plant temperature, for which the NICTOR™ box temperature T_e is used as a substitute measurements (no clear canopy temperature was available, but is under investigation). As for the deep percolation, it clearly depends on θ, when θ is high, more water will flow to other points due to differential pressure, and vice-versa. (Given the drought conditions, it is reasonable to assume that the soil is not saturated.) This leads to a model of the form:

$$\dot{\theta} \propto I - T_e - \theta \quad \Rightarrow \dot{\theta}(t) = c_1' I(t) - c_2' T_e(t) - c_3' \theta(t) \quad (1)$$

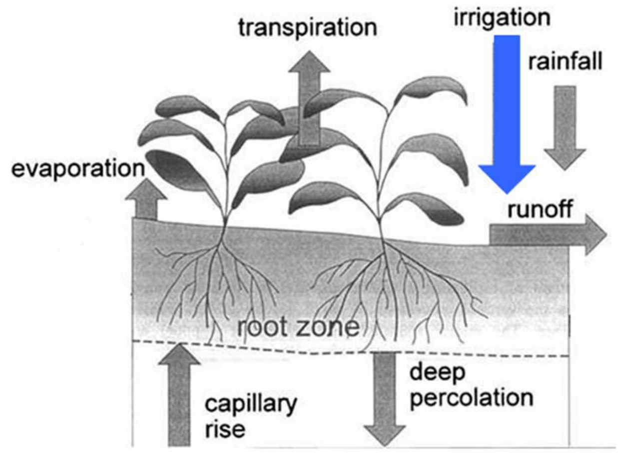

Fig. 3. Components of water balance in an irrigated field (modified from the figure in Allen et al. (1998)).

where c_1, c_2 and c_3 are three unknowns to be estimated. This equation (1) is discretised using a simple Euler method with sampling interval T min:

$$\theta(k+1) = c_1 I(k-\tau) - c_2 T_e(k) - c_3 \theta(k) \qquad (2)$$

where k indicates the sample time corresponding to T, $2T$, $3T$, $\ldots$, and $c_1 = Tc'_1$, $c_2 = Tc'_2$ and $c_3 = Tc'_3 - 1$ are the three parameters to be estimated from the measurement. τ is an integer representing the delay between the application start time and the first response at the sensor.

The predictor considered is the OE (output error) type:

$$\hat{\theta}(k+1, C) = c_1 I(k-\tau) - c_2 T_e(k) - c_3 \hat{\theta}(k, C) \qquad (3)$$

where $C = [c_1, c_2, c_3]$. The OE predictor using the previously predicted soil moisture $\hat{\theta}(k)$ to predict θ at time $k+1$, i.e. a simulation model. It is known that the OE predictor better capture the low frequency region of the system (see e.g. Ljung (1999)) which is the region where we are interested in.

As mentioned from Figure 2 it is clearly seen that there are saturation effects. The saturation effects are catered for by considering a very simple method. First, the soil moisture saturation lower limit, $\underline{\theta}$ is approximated from the data set, and then the final model becomes:

$$\begin{aligned} &\hat{\theta}(k+1, C) = c_1 I(k-\tau) - c_2 T_e(k) - c_3 \hat{\theta}(k, C) \\ &\text{if } \hat{\theta}(k+1, C) <= \underline{\theta}\,; \qquad \text{set } \hat{\theta}(k+1, C) = \underline{\theta} \qquad (4) \end{aligned}$$

4.1 Parameter Estimation

Using the first 2000 points of the data set, the parameter vector $C = [c_1, c_2, c_3]$ is estimated based on a prediction error method with a quadratic criterion, i.e. the criterion to be minimized (see e.g. Ljung (1999)) is $\frac{1}{2000}\sum_{k=1}^{2000}(\theta(k) - \hat{\theta}(k, C))^2$, where $\hat{\theta}_2(k, C)$ is given by (4). From Figure 2, $\underline{\theta}$ =31% is estimated. τ is set to vary between 30 and 45 samples, by inspection from Figures 2, the time delay ranges from 33 to 44 samples. The averaged sum squared prediction error (SSE) on the validation data set is used as a quality measure of the model. SSE is calculated as SSE $= \frac{1}{N}\sum_{k=1}^{N}(\theta(k) - \hat{\theta}(k, \hat{C}))^2$. N is the number of data points used in the validation. The estimates, $\hat{C}$ with the smallest and largest SSE (with τ considered) are shown in Table 2.

τ (samples)	$\hat{c}_1$	$\hat{c}_2$	$\hat{c}_3$	SSE
30	0.000263	0.000800	-1.000128	3.931329
45	0.000260	0.000767	-1.000111	5.169497

Table 2. Parameter estimates for Sensor S4

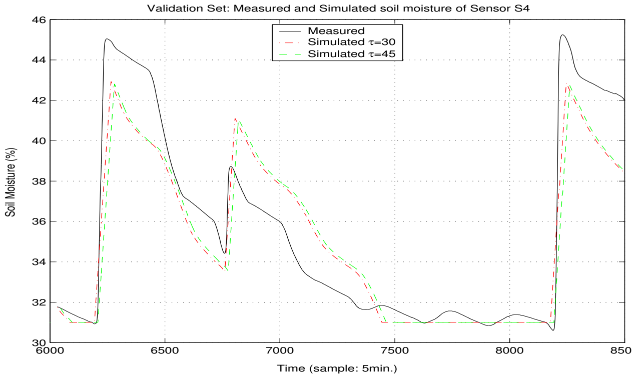

Fig. 4. Measured and simulated soil moisture of the validation data set using model with $\tau = 30$ and 45 samples.

The measured and simulated soil moisture of the validation data set using the models obtained in Table 2 are plotted in Figure 4. Only the first 30 (or 45) data points of the measured soil moisture are used (depending on the time delay), but all the temperature and inflow data are used for the simulation.

Discussion From the system identification results, it is clear that a simple model is able to describe the dynamics between soil, water and temperature. The model is able to capture the main trends in the soil moisture, with an offset error. However, the offset error is less than 2.5%, and is entirely acceptable. The model is sufficient to produce a 2h ahead prediction. The time delay in the dynamics is due to the soil micro topography and is aversely affected by the unusual operational conditions over the irrigation season caused by the extreme drought conditions.

The system identification results are limited by the data quality (see Ljung (1999)), suggestions for improved data collection include: use temperature measurements derived from a weather station rather than the NICTOR$^{\text{TM}}$ main board, which will be well above the environment temperature; irrigate over a large(r) range of operational conditions (dry and wet).

5. CONCLUSIONS

The first results from the pilot systems indicate that automation in irrigation can provide substantial economic benefit, through improved produce quality and/or significant water savings. Basic system identification and control engineering ideas based on relatively simple models that link the applied water regime with produce quality are key. The NICTOR$^{\text{TM}}$ wireless network platform is well suited to the task. Surprisingly, simple linear models are able to capture the essential dynamics between soil, water (inflow) and temperature, sufficient for short term irrigation management.

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