SMART WIRELESS TIPPING-BUCKET RAIN GAUGE
Measurement and Automatic Dynamic Calibration

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Abstract: The paper presents the design and implementation of a smart tipping-bucket rain gauge that uses a universal frequency do digital converter characterised by period and impulse counting measuring capabilities with on-line accuracy control and a serial interface connected to a transmitter-receiver RF module that provides a wireless communication between the smart tipping-bucket rain gauge (TBR) and a host unit expressed by a FieldPoint real-time controller or a laptop PC associated with a weather monitoring network The TBR sensor tests in dynamic conditions are performed using a FieldPoint based system. The system consist in a submersible pump that works under the FieldPoint control and assure the accurate control of water flow rates delivered to the rain gauge funnel. The rain gauge calibration ensures precise conversion of bucket tip times to actual rainfall rates. The data acquired during the calibration is stored in FieldPoint system memory and used for an accurate rain fall measurement after an intelligent data processing based on designed and implemented neural network. Data logging and data communication are parts of the LabVIEW real time software developed for the present system.

1 INTRODUCTION

The measurement of the rain fall represents an important task associated with weather stations and environmental surveying stations. Different types of sensors are used to measure the quantity of rain water falling in time (Advanced Measurements, 2003). Tipping-bucket rain gauges (TBRs) have been used extensively for collecting rainfall intensity data ever since their inception and subsequent use in weather station starting form 1970 because they are simple and durable. Other advantages are that they can be installed in remote areas, can be connected to a variety of monitoring or recording devices, and are relatively inexpensive. Disadvantages are that measurement errors can be significant during heavy rainfall or light drizzle, losses from evaporation and wind effects can occur, and calibration is often difficult and time consuming (Nemec, 1967).
Referring to the calibration the TBR static and dynamic calibration methods it can be mentioned.
In the static calibration method, the rain gauge is levelled, and the stop under a bucket is adjusted until application of a specified volume of water (usually added to the bucket drop by drop using a pipette) causes the bucket to tip. This procedure is repeated several times for each bucket, and an average volume for both buckets is calculated. Measured bucket volumes can vary as much as 5% depending on factors such as the kind of water used (rainwater versus tap water), the buckets dry or wet initially state and the buckets surface quality (Marselek, 1981). An important weakness of the static calibration method is related to the assumption that the volume of water needed to cause the bucket to tip is independent of the rainfall intensity which can conduct to underestimation of the rainfall intensity (10 to 40%).
Dynamic calibration methods attempt to account for undercatchment by calibrating the TBR while the buckets are in motion and have been proven to be effective. Different dynamic calibration and system are reported in the literature (Humphrey, 1997). All of the preceding methods describing dynamic calibration of TBRs involve application of many

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flow rates and quantifying the response time of the tipping bucket.
In this conditions a controller water pump and accurate measurement of time periods associated with bucket movements during the rainfall measurement is required.

The article presents a smart wireless tipping-bucket rain gauge where the TBR is connected to the counter/period input of a universal frequency digital converter. An additional frequency measurement channel is used to acquire the information delivered by a temperature sensor associated with rainwater temperature measurement and frost conditions. The acquired information is wireless transmitted using a RF receiver-transmitter component to a host real-time controller that performs tasks such as the TBR tests and calibration control, data logging, fault detection and diagnosis, data communication and data publishing.

2 SMART SENSING SYSTEM

2.1 Rainfall and Temperature Sensing Unit

The rainfall sensor is represented by a classical architecture of tipping bucket rain gauge whose resolution is defined by:

$$\boldsymbol{r} = \frac{4\boldsymbol{V}}{\pi \cdot \boldsymbol{d}^2} \quad (1)$$

where V is the bucket volume, and d is the rain gauge diameter (of the outer funnel). It extracts the rainfall information based by the water running through the collectors funnel into one of the system twin buckets. When the water flows from one to other bucket based on the included magnetic reed switch (low cost proximity sensor) a voltage pulse is generated. Counting the pulses, N_{RW} for 1h time period the total amount of rainwater can be calculated using the following relation:

$$\boldsymbol{q}_{\boldsymbol{RW}}(1\boldsymbol{h}) = \boldsymbol{N}_{\boldsymbol{RW}} \cdot \boldsymbol{r} \quad (2)$$

which express the rainfall intensity level expressed in mm h^{-1}.

The used temperature transducer is based on a LM35 and conditioning circuits expressed by a voltage amplifier and voltage to frequency conversion stage (LM331). The nominal dependence of the frequency output versus temperature is given by:

$$\boldsymbol{f}_{\boldsymbol{T}} = \alpha_{\boldsymbol{T}} \cdot \boldsymbol{A} \cdot \delta \cdot \boldsymbol{T} \quad (3)$$

where T represents the temperature in ºC, α_T=0.01V/°C the temperature-to-voltage conversion coefficient, A=10 the gain of the used amplifier, and δ=980$V^{-1}s^{-1}$ the voltage to frequency converter internal parameter. Thus for the temperature included in the 2-20°C range the frequency signal will varies between 196 Hz and 1960 Hz.

2.2 Muti-channel Data Acquisition and Wireless Communication Unit

The signals associated to the rainfall and the temperature measurement channels expressed by voltage pulse and frequency variation are acquired by the multichannel universal frequency to digital converter (UFDC-01)(Pereira, 2005). It contains two input channel that are on-line configured to perform frequency, period or pulse counter measurement functions. The measurement values are sent through the wireless connection to the FieldPoint real-time controller (National Instruments, 2005) or to a host computer (PC). Referring the UFDC settings the channel 1 is used for rainfall intensity measurement based on TBR and set for pulse counter mode (MD) while the channel 2 is used for temperature measurement and set for frequency measurement mode (M0).
Main characteristics of the UFDC include programmable conversion accuracy than can vary between 1 % and 0.001 % of FS (full-scale) amplitude, an auto-calibration capability based on the 8 MHz quartz crystal oscillator signal and a RS232 communication port that is connected to the a wireless interface expressed by a easy Radio ER400TRS.
The ER400TRS is a complete sub-system that combines a high performance very low power RF transceiver, a microcontroller and a voltage regulator (LPRS,2006). Several characteristics can be mentioned: RF frequency 434MHz, RF power output +10dBm, FM deviation 64kHz.
In the present application the RF module Serial Data Input and Serial Data Output channels operate at the standard 9600 Baud and the RDY handshake line is connected to GND. The Easy-Radio transceiver can accept and transmit up to 180 bytes of data, which it buffers internally before transmitting in an efficient over-air code format. Thus the digital values associated with the number of pulses value (N_{RW}) that corresponds to UFDC channel 1 or the frequency value (f_T) corresponding to the UFDC

channel 2 are transmitted using the TXD line of the UART port to the serial data input line (SDI) of the ER1. Based on the low power RF connection the data is sent to the ER2.(Figure 1).

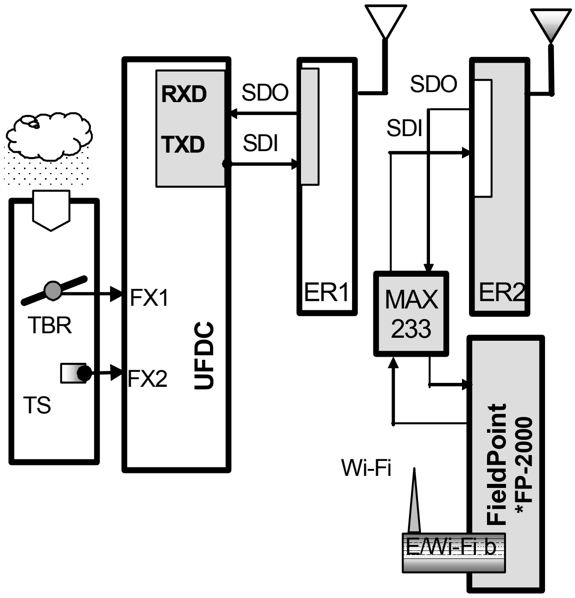

Figure 1: The block diagram rainfall & temperature smart sensing system.

The ER2 will decode the message and place the recovered data within a receive buffer that can then be unloaded to the receiving host (FieldPoint controller or host PC) for data processing. Transmission and reception are bi-directional half duplex i.e. transmit or receive but not simultaneously.

Fig. 1 represents the main elements of the rainfall and temperature system with low power wireless transmission capabilities where ER1 and ER2 represents the RF wireless transmission modules, FX1 and FX2 the UFDC pulse counter and frequency acquisition channels, MAX233 interface chip performs the 0-5V (ER400TRS) to the RS232 voltage levels translation, SDO-serial data output, SDI serial data input and the E/Wi-Fi b represents the Ethernet-wireless bridge connected to the Ethernet port of the FieldPoint FP2000 real time controller. Based on implemented wireless communication systems the FP-2000 can work simultaneously in two wireless networks. The first one expressed by one or multiple smart rainfall measurement system or other weather sensors with RF low cost wireless interfaces and the second one (Wi-Fi - EE802.11g) that can include different PCs associated with advanced data processing and publishing.

2.3 TBR Dynamic Calibrator

In order to increase the accuracy of rainfall measurements a TBR automated calibrator was designed and implemented.

The calibration system consists of a FieldPoint system, voltage controlled submersible pump and a water reservoir.

The FieldPoint system is represented by NI FP-2000 controller interface that manages a node expressed by an analog output module NI FP-AO-V10. The output voltage of the analog output module is used to control the pump through a current buffer (CI). In this way, different values of water flow are automatically imposed to the measurement system. The common values obtained in the present application are between 20 and 1000 mL min^{-1}, that depends on the pump speed (through the imposed voltage), tubing diameter and tubing composition. The rain gauge to be calibrated (TBR) is connected to the UFDC-FX1 input that detects tip occurrence expressed by pulse signals (Figure 2) and count the number of pulses.

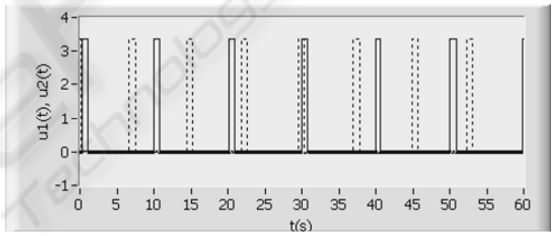

Figure 2: The TBR' magnetic reed switch output PR1(--) and PR2(-.-) pump rates.

The "brain" of calibrator (NI FP-2000) sent the start count (S) and read count (R) commands associated with Δt_c time intervals (Δt_c =1min). The read values N_{RW} are used to calculate the rainfall intensity.

The values of the rain flow intensity are imposed by the pump of the system that is previously calibrated.

Pump calibration procedure extracts the water volume versus pump control voltage characteristic. Thus for different values of the pump control voltage, V_c=[5; 9]V, different pump rates are obtained and used do deliver several water target volumes (e.g. 500mL, 1000mL, 2000mL). When the target volume for a given rate has been delivered to the collection flask, an optical level sensor (Honeywell), mounted on the flask, delivers a TTL signal that is acquired by the digital input module of the FieldPoint system, and the delivered time Δt_{di} is recorded together with the voltage value for the current pump rate. Using a digital channel of the

FieldPoint digital output module and a conditioning circuit the collection flask electro valve is opened for a time interval of $\Delta t_{oi}=\Delta t_{di}+\tau_i$, where the timing tolerance is expressed by τ defined as 10% of water delivery time $\Delta t_{di.}$
After the Δt_{oi} time interval the next pump rate is imposed and a new $\Delta t_{d(i+1)}$ is recorded. For the particular case of 1000mL water target volume the pump rates (PR) are calculated using the stored t_{di} values and are graphical represented in Figure 3.

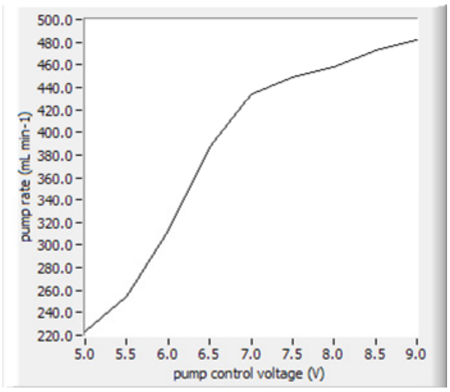

Figure 3: Pump calibration results.

All the pump calibrations were conducted within a water temperature range between 15°C and 17°C.
Based on the pump rate characteristics, obtained in the pump calibration phase, the rain gauge calibration was perfomed together with the TBR calibration, in the dynamic conditions, for different values of the pump rate (PR) associated to high level of rainfall intensity (PR=[446; 963] [mL min^{-1}].
Thus the pump was controlled for voltages in 5 V to 9V interval to inject water on the TBR level for different time intervals equivalent for 1000mL rainfall. During the Δt_{oi} time intervals the UFDC channel set as a counter was measured the number of pulses delivered by TBR for each interval. The results are presented in Figure 4.

2.4 Neural Network for Field Data Correction

Considering the experimental values that express the non-linear dependence of the measured rain-gauge rate versus an imposed PR an intelligent TBR data correction algorithm based on single input single output (SISO) neural network [8] is designed in MATLAB and implemented for on-line processing at the FP-2000 level using LabVIEW real-time. The input of NN is expressed by the normalized values of measured raingauge rate while the output represent the underestimating corrected values the considered true rainfall interval. The raingauge rate was previously calculated sing the number of pulses measured by the UFDC and wireless transmitted data.

3 RESULTS AND DISCUSSIONS

The experimental results obtained from TBR based measurements in dynamic conditions are presented in Figure 4.

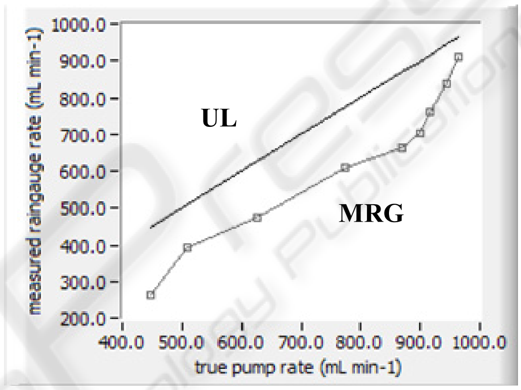

Figure 4: Departure of measured rain gauge rate (MRG) from true pump rate along 1:1 line (UL).

The underestimation maximum level for considered rainfall intensities was about 205 mL min^{-1} which requires the application of data correction using the implemented NN.
Using designed MLP neural network characterized by 2 to 5 hidden neurons with tansignoid activation function the underestimation rainfall error decrease according with the designed neural network architecture (Table 1).

Table 1: Underestimation errors with and without correction.

U error without NN corr. (mL min^{-1})	Underestimation error with NN based correction(mL min^{-1})			
	Number of neurons			
	2	3	4	5
205.5	14.7	9.1	9.2	12.1

Analyzing the Table 1 can be observed that good results are obtained for 3 or 4 hidden neurons. For the particular case of 3 hidden neuron neural network the TBR rainfall intensity measurement error, with correction (err_{TBR+NN}) and without correction (err_{TBR}) underestimation error, with and without compensation, associated with tested TBR in dynamic conditions are presented in Section 3.

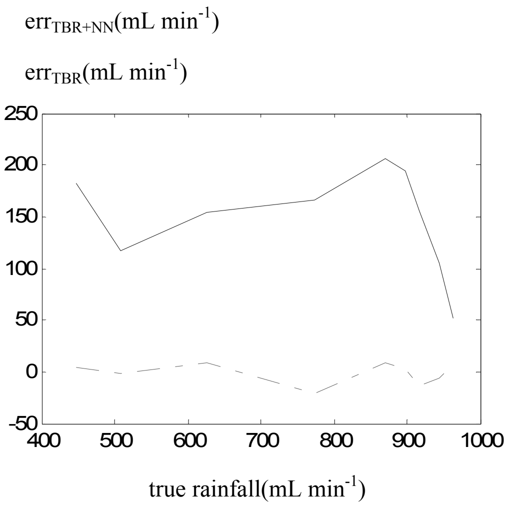

Figure 5: TBR measurement error with and without correction based on neural network.

4 CONCLUSIONS

A smart wireless tipping-bucket rain gauge was designed and implemented. The proposed solution combines the flexibility and the measurement accuracy of the universal frequency to digital converter with the low cost RF RS232-wireless bridge in order to perform the weather parameter monitoring in a wireless network.

Based on the fact that the tipping-bucket rain gauges suffer from serious non-linear underestimation errors, especially when rainfall is characterized by high rates, a real-time system based on FieldPoint technology for TBR test and calibration was designed and implemented. Using the experimental data associated with high rainfall rates an intelligent algorithm based on Multilayer Perceptron architecture was designed in order to decrease the TBR underestimation errors. Several simulation and experimental results express the capabilities of the implemented solution.

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