A Wireless Sensor Network for Greenhouse Climate Control

Using a wireless sensor network, the authors developed an online microclimate monitoring and control system for greenhouses. They field-tested the system in a greenhouse in Punjab, India, evaluating its measurement capabilities and network performance in real time.

Roop Pahuja
National Institute of Technology Jalandhar

H.K. Verma
Sharda University, India

Moin Uddin
Delhi Technological University

Wireless sensor networks are an important pervasive computing technology invading our environment. Over the years, research into WSN technology has matured to the extent that the ZigBee, based on IEEE 802.15.4, has emerged as a communication and networking standard to cater to the unique needs of WSN. It's a low-power (a few μW), low-data-rate (250 kbps), fault-tolerant, easily scalable, short-range (100 m) wireless protocol for embedded electronic devices called *sensor nodes*.[1] ZigBee and ZigBee-like standard-based WSN products and systems are now available to suit a variety of applications, including environment monitoring, precision agriculture, home and building automation, healthcare, traffic management, and so on.[2–4] WSNs are also gaining importance in *controlled environmental agriculture* technology, especially in greenhouse horticulture, because they offer wireless and flexible installation and reliable operation. (See the "Related WSN Work in Greenhouse Horticulture" sidebar for more information.)

Motivated by the idea of integrating a WSN into a high-level programming language to develop a custom application of public interest, we developed and field-tested a novel system for greenhouse climate control. Our system provides microclimate monitoring of the greenhouse temperature and relative humidity and analyzes the greenhouse crops' vapor pressure deficit (VPD), an important climate parameter related to plant growth, health, and yield conditions. To enhance the monitoring network, we integrated into it a VPD-based MIMO (multiple input and multiple output) fuzzy climate controller and an RS-485 actuator network to automate the greenhouse climate-control operations. Here, we discuss the technical issues we faced in designing this greenhouse-specific WSN and in implementing its intelligent application software.

Material and Methods

First, we had to gather greenhouse domain knowledge to gain a better understanding of greenhouse crops, work activities, operations, and research trends.[1,2]

In particular, we needed to understand the microenvironment. A greenhouse is a complex, multivariable interactive system. Because of local weather fluctuations, the plant-growing process and its interaction with internal climatic conditions, and the use of different climate control equipment, the greenhouse environment is highly dynamic and varies spatially, thus creating

Published by the IEEE CS ■ 1536-1268/13/$31.00 © 2013 IEEE

Related WSN Work in Greenhouse Horticulture

Carlos Serodio and his colleagues—part of a multidisciplinary research group in Portugal—designed and implemented a networked platform using a wireless sensor network (WSN), controller area network (CAN), and Internet and email tools. Their platform offers computerized agriculture management systems in a greenhouse to support distributed data acquisition and control, helping growers make better decisions in carrying out agricultural practices in a greenhouse.[1]

Zhou Yiming and his colleagues discussed the hardware and software design of a ZigBee WSN node with temperature, relative humidity, and moisture sensors and proposed a star or mesh network architecture for a greenhouse WSN system.[2] Hui Liu and his colleagues designed the Crossbow WSN for measuring temperature, light intensity, and soil moisture using a terminal interface for logging and displaying data, along with experimental testing of antenna heights that effect radio range.[3]

Teemu Ahonen and colleagues developed a node using the Sensinode sensor platform fitted with temperature, relative-humidity, and light-intensity sensors based on the 6LoWPAN protocol. They tested its feasibility by deploying a simple sensor network into a greenhouse in Western Finland.[4] One-day experiment data was collected to evaluate the network reliability and its ability to detect the microclimate layers.

Dae Heon Park and his colleagues developed a WSN-based greenhouse environmental monitoring and dew point control system that prevents dew condensation phenomena on the crop's surface, helping to prevent diseases and infections.[5]

REFERENCES

1. C. Serodio et al., "A Network Platform for Agriculture Management System," *Computer and Electronics in Agriculture*, vol. 31, no.1, 2001, pp. 75–90.
2. Z. Yiming et al., "A Design of Greenhouse Monitoring and Control System Based on ZigBee WSN," *Proc. Int'l Conf. Wireless Comm. Networking and Mobile Computing*, WiCOM, 2007, pp. 2563–2567.
3. H. Liu, Z. Meng, and S. Cui, "A Wireless Sensor Network Prototype for Environmental Monitoring in Greenhouse," *Proc. Int'l Conf. Wireless Comm. Networking and Mobile Computing*, WiCOM, 2007, pp. 2344–2347.
4. T. Abhonen, R. Virrankoski, and M. Elmusrati, "Greenhouse Monitoring with Wireless Sensor Network," *Proc. IEEE/ASME Int'l Conf.: Mechtronics and Embedded Systems and Applications*, MESA, 2008, pp. 403–408.
5. D. Heon Park and J.-W. Park, "Wireless Sensor Network-Based Greenhouse Environment Monitoring and Automatic Control System for Dew Condensation Prevention," *Sensors (Basel)*, vol. 11, no. 4, 2011, pp. 3640–3651.

microclimate zones. Climatic conditions vary from the greenhouse center to its side walls, and from the canopy to the aerial levels.[5]

We also needed to automate various operations and decisions. We had to gather and analyze plant-related sensory data using proactive computing methodology[2] to obtain the actionable output decisions for the different plant-related operations driving the in-house actuating equipment (operations such as climate control, fertigation control, irrigation control, and integrated pest management).

Finally, we needed to provide online information. Sophisticated software must provide online connectivity to the greenhouse control system with GUIs to display microclimate data statistics, decision support, and control operations.[6]

The need for greenhouse micro-environment monitoring to get reliable climate measurements, with better spatial and temporal resolution, has caused a paradigm shift from single-point fixed sensing to multipoint, multivariable flexible sensing. This has given WSNs an edge over wired networks. Moreover, to help automate greenhouse operations, a WSN can be integrated with an actuator network and a high-level programming platform to implement an online information system that growers can easily access.

To address these issues, we implemented the WSN-based online microclimate monitoring and control system shown in Figure 1.

The Wireless Sensor Network

Our greenhouse WSN is a deterministic network based on IEEE 802.15.4 and XMesh.[7] Like ZigBee, it's a robust, full-featured multihop, ad-hoc, mesh networking protocol for embedded sensor devices for Crossbow motes. Network hardware comprises numerous battery-operated sensor nodes with embedded temperature and relative humidity sensors and a gateway node.[8,9] Each node is preprogrammed in TinyOS,[10] the component-based, event-driven embedded operating system that defines each node's sensing, computation, communication, and routing capabilities. To design a versatile, flexible, and robust WSN for greenhouse custom applications, we had to address the following technical issues.

Climate-control variables. The important climate-control variables we considered to evaluate the greenhouse-crop VDP were the temperature (ranging from –10 to 50° C) and relative humidity (from 0 to 100 percent) within the greenhouse canopy and aerial height levels. The crop VPD is defined as the difference between the saturated vapor pressure at the canopy level at a given temperature and the actual vapor pressure present in the air at that temperature and relative humidity. Saturated vapor

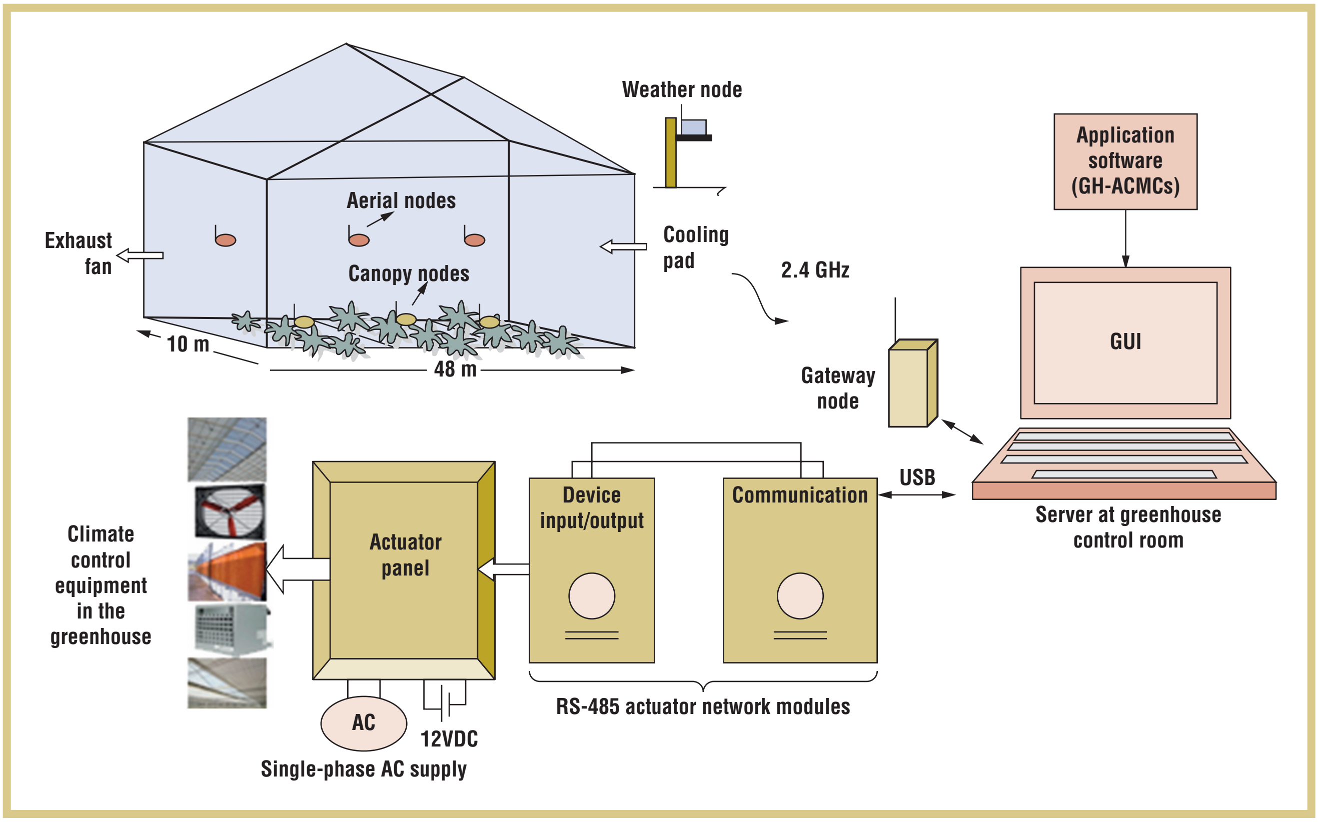


Figure 1. A typical architecture of an online microclimate monitoring and control system for greenhouses, based on a wireless sensor network. Wireless sensor nodes are deployed in the greenhouse at different grid and height locations, and one weather node resides outside the greenhouse.

pressure is a function of temperature and is calculated using the Arrhenius equation.[11]

The effect of having different temperatures at the canopy and aerial levels and relative humidity in a greenhouse is quantized as the greenhouse-crop VPD, which controls the transpiration rate and thus plant growth, health, and yield.[12] These climate variables fluctuate slowly and spatially within the greenhouse. A reporting-time interval of 15 minutes or so is recommended to extract dynamic statistics.[6]

Network deployment scheme. The greenhouse WSN comprises a few sensor nodes deployed inside the greenhouse at specific locations and a single node deployed outside to sense weather parameters. A gateway node is connected to the server in the control room to facilitate data communication. To calculate the crop VPD and measure spatial variability of parameters within the greenhouse, we used a grid- and height-based deterministic, site-specific, and uniform deployment scheme (see Figure 1).

In this scheme, the greenhouse floor area is virtually partitioned into grids of uniform size, with two height levels—one within the canopy and the other at aerial levels (1.5 m above the canopy). Each location has an ID label, g_ih_j, where i denotes the grid number (1 to n, where n is the maximum number of grids in the greenhouse), and j denotes the height number (1, 2). We placed at least one sensor node (preprogrammed with a relative location node ID) at each grid and height zone to measure the temperature and relative humidity. The grid size (200 to 500 m^2) characterizes the spatial variation of these parameters, keeping in mind that nodes are within radio range of each other (50 m).[8] There's a trade-off between the grid size, number of nodes (cost), and spatial resolution.

Node addressing scheme. We used an addressing scheme based on the relative location of the node (RLN) for location identification. The RLN ID tags have a four-digit number represented as GHNN, where G denotes the grid number (1 to 9), H (1, 2) denotes the height number, and NN (00–99) denotes the node ID (which uniquely identifies the node in the greenhouse). This scheme allows site-specific deployment of nodes at the identified locations in the greenhouse.

Based on this ID tag, we used location mapping to extract data from each node location at the server. In addition to providing location-aware sensing of greenhouse parameters, this mapping was more power efficient, simple, and straightforward to implement than a GPS-enabled, dynamic location-aware sensing scheme.[1]

Data acquisition and transmission. To continuously monitor the greenhouse signal dynamics for better precision control, we used a periodic sampling with averaged delayed transmission (PSDT) data-acquisition and transmission algorithm. Instead of periodically sampling the sensor signals and transmitting the acquired data at the same instant, the PSDT algorithm lets the node periodically sample the sensor signals at a faster sampling rate, collect a few samples, and periodically transmit the averaged sampled values at a higher transmission than sampling rate. Both temperature and relative humidity are sampled at two-minute time intervals, and the latest averaged sampled values of each within a 15-minute time frame are packetized and transmitted to the gateway node.

This technique improves the reliability with which signals are sampled and is power efficient. It supports high latency operation and averaging to compress data samples without sacrificing measurement accuracy and data integrity. The transmission rate is fixed and is appropriate for any crop.

Network topology and routing. Thick plantation and canopy coverage in a greenhouse can diminish the signal range of nodes forming the network, so packet losses can occur. To have a reliable and scalable network under such situations, a true mesh multihop network topology is preferred over a star- or hybrid-cluster-based topology.

All greenhouse nodes are full functional devices with both sensing and routing capabilities and one coordinator (gateway) node. Based on the XMesh routing algorithm, each node transmits its data packet to the coordinator node via the other parent node using multihops and the most efficient energy path. The node periodically updates its routing information (every six minutes) and dynamically creates new routes. As soon as a new node is added, it joins the network and starts transmitting data. The node remains in a low-power mode (with the transmitter in sleep mode and the receiver in a low-power listening mode) when there's no data or other message to receive or transmit.[7]

This topology extends the radio range of the devices with low-power consumption (a few μA), providing a field life of more than a month on a pair of AA standard cells (3 volts). Furthermore, it provides better coverage with self-healing and self-configuration capabilities, forming a fault-tolerant network well-suited for greenhouses.

The Actuator Network

To automate the greenhouse climate-control process, we used an actuator network from Advantech, based on the RS-485 industrial serial-networking standard. We connected greenhouse end devices (single-phase 220-volt AC motors, pumps, and starters) associated with climate-control equipment to the network module's relay ports (12 V DC 220 ohm). In response to the climate controller output, which decides the operating load and presents the status of climate-control equipment, the actuator network drive-layer program issues commands to RS-485 network devices to actuate particular relays, controlling the equipment by varying the load.

Application Software

We programmed the application software—the *greenhouse advance microclimate monitoring and control software* (GH-ACMCs)—for discrete packet acquisition and time-series analysis of network multivariate data. The GH-ACMCs lets us execute microclimate monitoring, climate control, and decision support functions, and it updates all vital greenhouse information on the GUI. Figure 2 shows the software's functional design model.

Packet acquisition, scanning, and deciphering. Packet acquisition is fundamental in providing connectivity to the greenhouse WSN. Using a point-by-point packet-acquisition and -collection method, network data packets interfacing with a PC port at the gateway node at any instant of time t are acquired and logged with a timestamp. Based on a variable timeframe-scanning algorithm, the logged data packets are scanned within the latest timeframe window t_w (with a typical value of 20 minutes). The timeframe window denotes the time during which the latest data from the node is available—in other words, during this timeframe, the node has (at least once) communicated its data to the central server system. The scanning starts with the current time. Then, by decrementing the time by one minute until the timeframe limit is met, the algorithm collects the packets transmitted from nodes within this timeframe.

From the scanned packets, each node ID is location mapped to separate the node packets for different locations. Corresponding to each location node ID, the latest packet available in the timeframe window is considered as the node packet from that location at that time instant. The raw data packets are deciphered and 16-bit digital data for node voltage, temperature, and humidity are converted to corresponding values in engineering units using sensor conversions.[13] An amplitude rejection-filtering technique filters out data packets that are undesirable due to a sensor malfunctioning. This method synchronizes the display of data from each node in the timeframe at each time instant and updates the information on the GUI as soon as a new packet from any node is detected. Without this method, it's difficult to coordinate all nodes and provide stable, reliable, and timely network information from an asynchronous, high-latency (15 minutes) network with an intermediate low-power mode of operation.

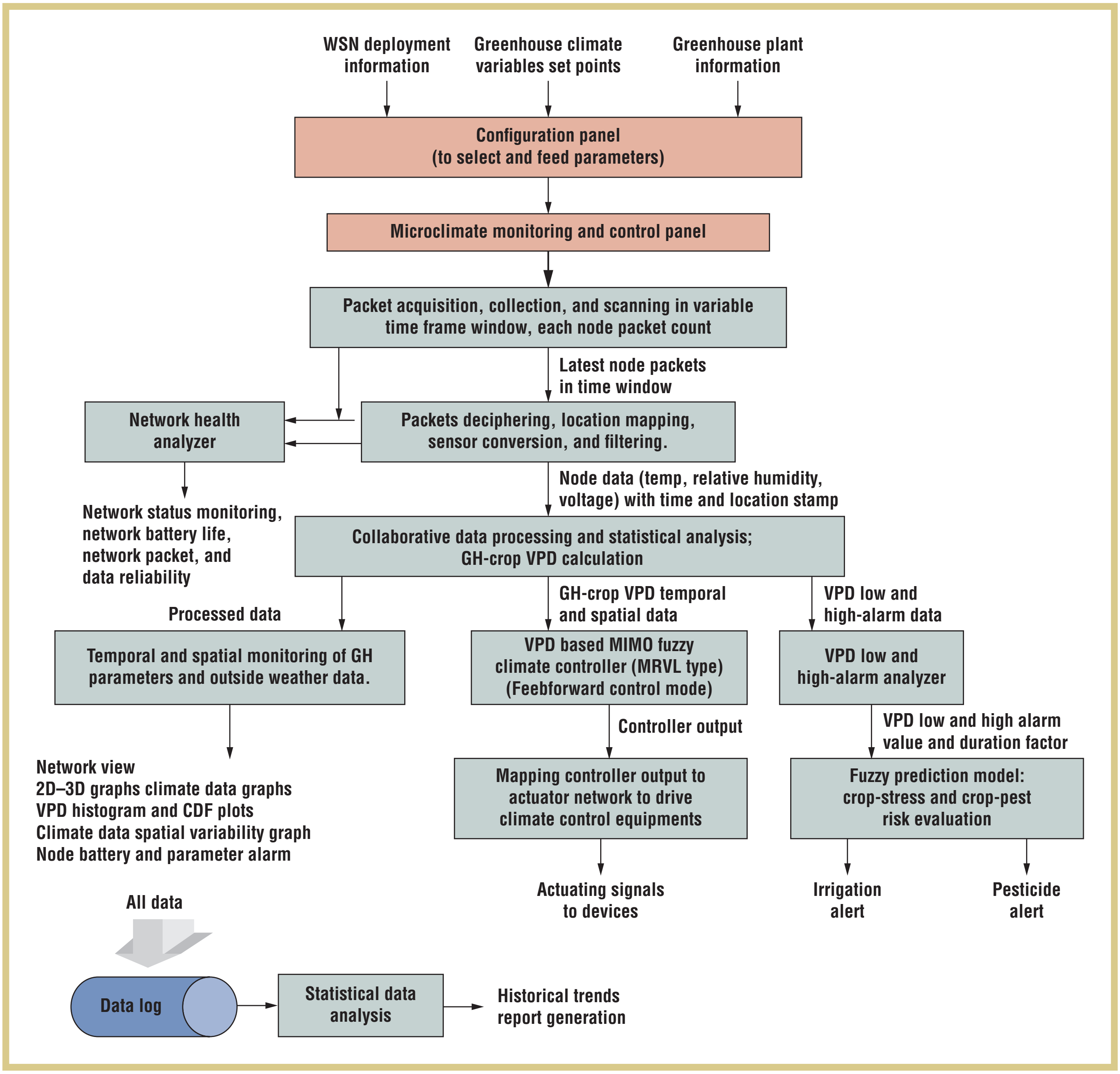
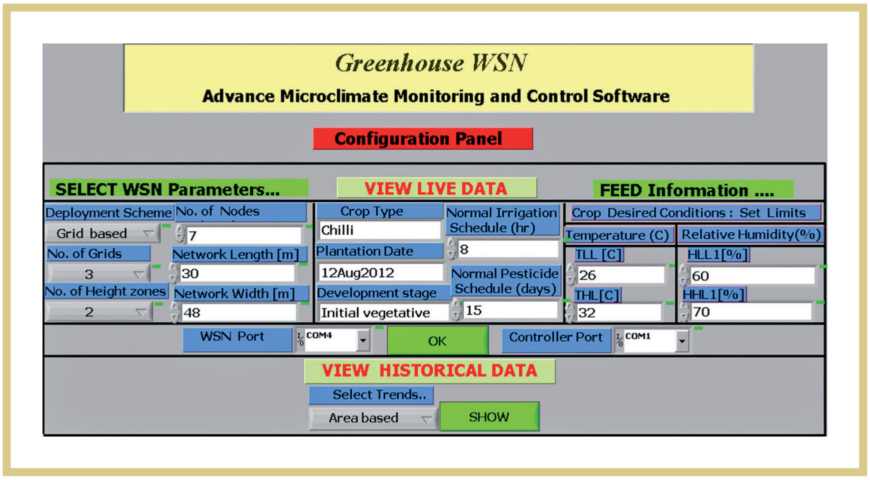


Figure 2. A functional flow chart of the application software—greenhouse advance microclimate monitoring and control software (GH-ACMCs).

Collaborative data processing and microclimate monitoring. The preprocessed time-instant values of temperature and relative humidity, as measured by nodes at different locations, are collaboratively processed to evaluate the crop VPD at each grid and provide reliable average values of climate variables.[11,12] Data from different nodes is statistically analyzed to project the spatial variation of climatic variables in the grids and at various height levels (3D plots). The spatial variability (standard deviation) value for each climate variable is calculated to estimate the data spread. VPD-histogram and cumulative frequency-distribution graphs are obtained to analyze the frequency of VPD variation in different ranges and the amount of time during which the VPD is less than a certain value.

Climate control. To regulate the greenhouse climatic conditions automatically, we implemented a VPD-based fuzzy climate controller,[14,15] operating under a feed-forward mode using a variable-load design method. With respect to the variations in the



Deployment Scheme: Grid based
No. of Nodes: 7
No. of Grids: 3
Network Length [m]: 30
No. of Height zones: 2
Network Width [m]: 48
Crop Type: Chilli
Normal Irrigation Schedule (hr): 8
Plantation Date: 12Aug2012
Normal Pesticide Schedule (days): 15
Development stage: Initial vegetative
TLL [C]: 26
HLL1[%]: 60
THL[C]: 32
HHL1[%]: 70
WSN Port: COM4
Controller Port: COM1
Select Trends..: Area based

Figure 3. The configuration panel GUI. This screenshot shows user-selected network deployment and crop-specific climatic parameters when the network system was deployed in a greenhouse for growing chilies.

outside-weather VPD, we calculated the VPD error and its rate of change. Corresponding to each error range (positive and negative) are different rule-based fuzzy controllers that issue signals to drive different climate-control equipment and regulate inside conditions. Controller inputs, the VPD error, and the VDP error's rate of change are normalized into seven linguistic terms, and 49 control rules for each actuating system (roof vents, exhaust fan, cooling pad, and heaters) are designed, taking into account how varying the operating load of each affects the inside climatic condition.

When the VPD error is positive, the greenhouse is humidified by controlling the operating load of ventilation and cooling equipment. When the VPD error is negative, the greenhouse is dehumidified by controlling the operating load of ventilation and heating equipment. We operate a shade screen to increase the efficiency of the cooling and heating system in extreme summer and winter conditions. When the outside temperature exceeds 35°C during the day and falls below 5°C at night, the shade screen is covered. The RS-485 actuator network driver-layer program maps the controller output to issue commands to drive the devices. Based on the user-specified temperature and relative humidity limits, suited for the crop during its growing phase, VPD set limits are calculated to drive controller inputs.

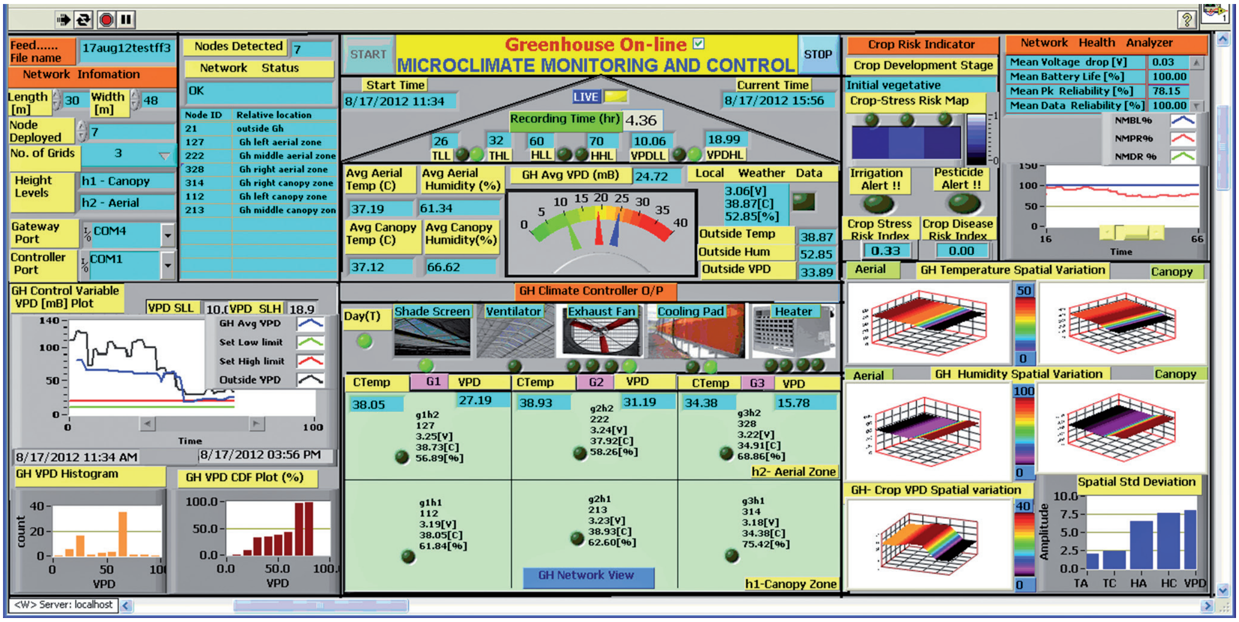
Crop-stress and -disease risk prediction. The quantitative analysis of alarming VPD conditions helps predict VPD's harmful effect on crops—that is, when the crop is under stress due to continuous high VPD conditions (high temperature and low humidity), or when there are chances of disease outbreak due to continuously low VPD (low temperature and high humidity), which can cause condensation on leaves. This functional module uses heuristic rule-based fuzzy controllers and a cumulative moving-average method to analyze VPD high and low alarm conditions (in terms of the grid and area), based on the VPD's alarm duration (during the normal irrigation and pesticide schedule) and the extent of the high and low VDP values to estimate a crop-stress and crop-disease risk index (0 to 1). After comparing these two indices to the threshold limit, irrigation and pesticide warning messages are issued for each grid and greenhouse area.[12,16]

Network performance monitoring. This functional module evaluates some of the important parameters related to a WSN's field performance in a greenhouse.[1] It tracks the number of nodes connected at each timeframe limit and displays the network connectivity status ("okay," "network initializing," or "detection or connection problem"). It has a low-battery alarm (2.3 V) and indicates the *network mean-battery life* and *network mean packet reliability* (as percentages). It also tracks data connectivity based on the display of vital information—the average crop VPD or outside VPD—and calculates *network data reliability* (as a percentage).

Implementation. All of the functional elements of the GH-ACMCs are implemented on the graphical dataflow programming platform, LabVIEW (8.5), from National Instruments.[17] It's a multipanel, modular, hierarchically designed software tool with an intuitive GUI that supports different levels of functionalities with intelligent, salient features. The configuration panel lets the user feed and select user-defined parameters related to greenhouse network deployment and plant-specific requirements, such as the temperature and relative humidity (see Figure 3). Based on these inputs, the microclimate monitoring and control program executes all the functional modules to perform online monitoring, control operations, and display vital information (see Figure 4).

Field Results

To test the system's feasibility and judge its measurement and network performance in a real-world field situation, we deployed it in a commercial chili-growing glasshouse, situated in a tropical region of northern India in the state of Punjab, near the city of Ludhiana. Greenhouse cultivation is a daunting task for the region's local growers during the summer season (May through August), when the outside VPD exceeds 70 millibars (mB) owing to high temperatures (above 40°C) and moderate relative humidity (20 to 60 percent). To evaluate the greenhouse climate dynamics and statistics under this harsh summer



Feed...... File name: 17aug12testff3

Network Infomation

Length [m]: 30

Width [m]: 48

Node Deployed: 7

No. of Grids: 3

Height Levels: h1 - Canopy; h2 - Aerial

Gateway Port: COM4

Controller Port: COM1

Nodes Detected: 7

Network Status: OK

Node ID	Relative location
21	outside Gh
127	Gh left aerial zone
222	Gh middle aerial zone
328	Gh right aerial zone
314	Gh right canopy zone
112	Gh left canopy zone
213	Gh middle canopy zon

Greenhouse On-line ☑

MICROCLIMATE MONITORING AND CONTROL

Start Time: 8/17/2012 11:34

Current Time: 8/17/2012 15:56

Recording Time (hr): 4.36

TLL: 26

THL: 32

HLL: 60

HHL: 70

VPDLL: 10.06

VPDHL: 18.99

Avg Aerial Temp (C): 37.19

Avg Aerial Humidity (%): 61.34

Avg Canopy Temp (C): 37.12

Avg Canopy Humidity(%): 66.62

GH Avg VPD (mB): 24.72

Local Weather Data: 3.06[V] 38.87[C] 52.85[%]

Outside Temp: 38.87

Outside Hum: 52.85

Outside VPD: 33.89

Crop Development Stage: Initial vegetative

Crop Stress Risk Index: 0.33

Crop Disease Risk Index: 0.00

Network Health Analyzer

Mean Voltage drop [V]	0.03
Mean Battery Life [%]	100.00
Mean Pk Reliability [%]	78.15
Mean Data Reliability [%]	100.00

VPD SLL: 10.0

VPD SLH: 18.9

8/17/2012 11:34 AM

8/17/2012 03:56 PM

GH Climate Controller O/P

	CTemp	VPD	h2- Aerial Zone	h1-Canopy Zone
G1	38.05	27.19	g1h2 127 3.25[V] 38.73[C] 56.89[%]	g1h1 112 3.19[V] 38.05[C] 61.84[%]
G2	38.93	31.19	g2h2 222 3.24[V] 37.92[C] 58.26[%]	g2h1 213 3.23[V] 38.93[C] 62.60[%]
G3	34.38	15.78	g3h2 328 3.22[V] 34.91[C] 68.86[%]	g3h1 314 3.18[V] 34.38[C] 75.42[%]

<W> Server: localhost

Figure 4. The microclimate monitoring and control panel GUI. This screenshot indicates the state of the greenhouse at the current time instant, showing online network connectivity and displaying greenhouse climate-control dynamics and vital information.

weather, we conducted a short-term experiment during the peak day hours.

Preprogrammed wireless sensor nodes packed in PVC housings, equipped with a standard pair of AA cell batteries (3.0–3.2 V), were powered "on" and deployed at specific locations in the greenhouse (using the grid-height based deployment scheme explained earlier). As shown in Figure 1, the greenhouse section area (30 × 48 m^2, East to West direction) was divided into three grids—left (G1), middle (G2), and right (G3)—of size 30 × 16 m^2, and at the center of each grid, one node was placed in the canopy (the average crop size was initially 12 cm) to measure the canopy temperature and relative humidity. Another node was fixed at the aerial height level (1.5 m above the canopy) to measure the aerial temperature and relative humidity. The weather node was mounted outside the greenhouse, and the gateway node was interfaced to the server housed at the greenhouse control room (40 m from greenhouse site).

To automate the climate-control process, actuating device terminals were interfaced to an RS-485 actuator panel at the greenhouse site, and an RS-485 communication module was serially connected to the host PC. Depending on the availability of the devices at the greenhouse site, the climate controller was tuned to drive the cooling pad (0, 50, and 100 percent), exhaust fan (0, 25, 50, 75, and 100 percent), shade screen (0 to 100 percent), and roof ventilation (0 to 100 percent) with variable loads.

Before starting the monitoring and control operations, we configured the GH-ACMCs. We opened the configuration panel to feed input parameters (Figure 3). We entered the crop comfort zone ("set limits") of 26° C to 32° C, with a relative humidity of 60 to 70 percent, along with the crop normal-irrigation schedule (typically eight hours) and pesticide schedule (typically 15 days), as decided by the grower during the crop development cycle (initial vegetative growth period of chili). We also entered the network deployment information. As the configuration panel was executed, it linked the information to the microclimate monitoring and control panel GUI (Figure 4).

After the data-log file name was fed into the system, clicking the "start" button executed the program continuously with a start time of 11:34 a.m. on 17 August 2012. The information on the panel was updated as soon as a new network packet arrived within the 20-minute timeframe, with the scanning-time increment of one minute. At the start, there was an initial display lag (6 to 15 minutes) because of the network's high latency and low power mode operation.[7]

Results depicted the system state at the current time instant. At 3:56 p.m. on 17 August 2012, the network status was "OK." All seven nodes deployed were detected, and their node IDs and location information were displayed. None of the nodes were blinking (low battery alarm) or indicating a "malfunctioning." The weather node indicated a high outside temperature of 38.87° C and relative humidity of 52.85 percent, resulting in a high VPD (33.89 mB). Based on the user's set limits, the crop VPD set limits were calculated and displayed (10.06 mB to 18.99 mB).

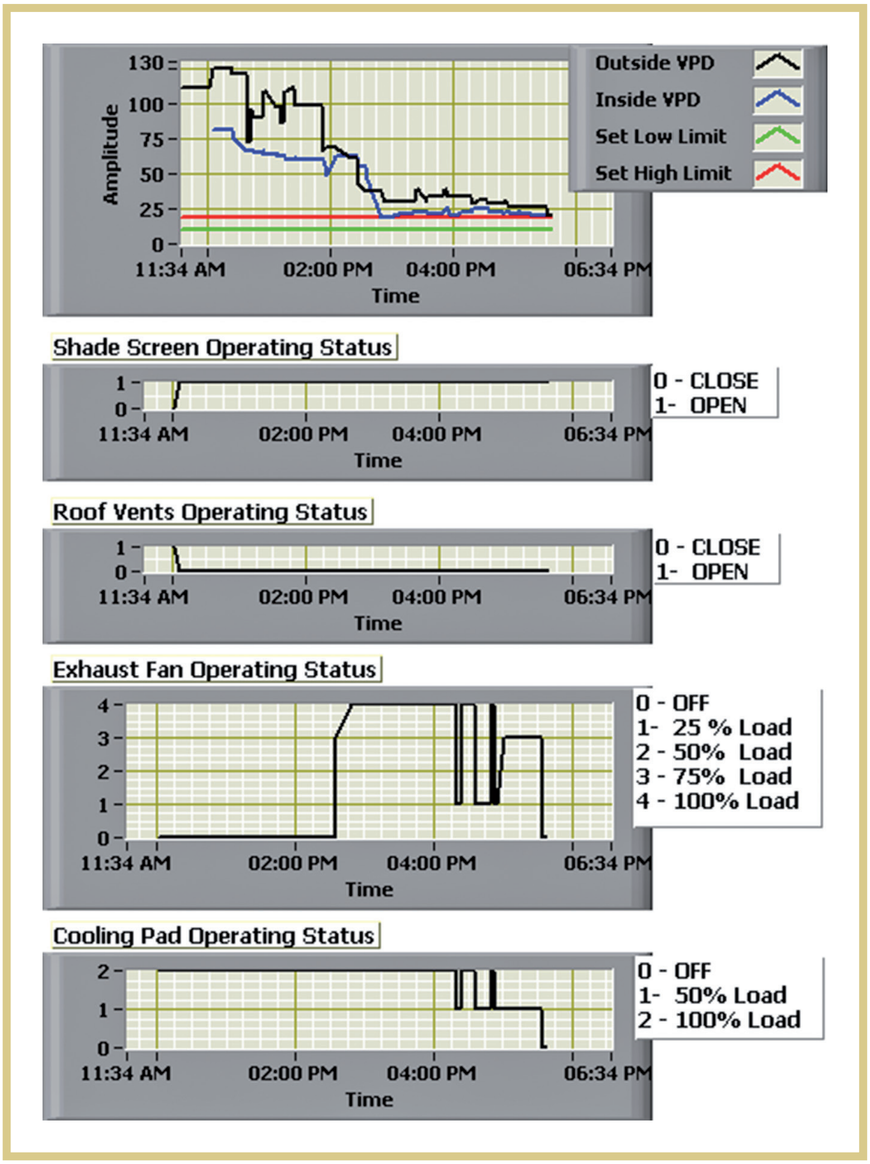


Figure 5. Time variation of average greenhouse-crop vapor pressure deficit (VPD) (inside VPD) under climate-control operation, along with outside VPD and set limits and corresponding variations in the operating status of climate-control equipment over the recorded period of six hours.

With respect to the current VPD error (14.9 mB), the climate controller output actuated the RS-485 network to drive the equipment with the appropriate load/operating status to humidify the greenhouse to minimize the VPD error. As indicated, the shade screen was "open" (covered), the roof vents were "closed," and the cooling pad and exhaust fan were operating under a "full" load. The network view graphically showed the nodes at the respective grid locations, indicating the local measured value of voltage, temperature, and relative humidity. The VPD value at each grid was calculated and displayed, along with the display of average values of the climate variables at the respective indicators. The greenhouse's average canopy temperature (37.12° C) and aerial temperature (37.19° C) remained high, with moderate aerial humidity (61.34 percent), resulting in the high average value of crop VPD (24.72 mB). The VPD time plot indicated that because of the climate-control operation, the greenhouse VPD decreased with time and was lower than outside, but it remained higher than the set limit.

Owing to the high average VPD, the crop was under stress, and the estimated value of the crop-stress index (area) increased 0.33 over time (after 4.36 hours) but was lower than the threshold (0.5) to initiate the irrigation alert alarm for the area. Also, the crop-stress risk-intensity map showed the spatial variation of the crop-stress risk index at the respective grids, based on grid VPD alarm analysis using prediction model and the corresponding grid irrigation alarm status. 3D plots indicated instantaneous spatial variation of the microclimate variables at different grid locations, and the bar graph plotted the spatial standard deviation of each, indicating the extent of variability of each from its average value. The greenhouse-crop grid VPD varied in the range (15.78 mB to 31.19 mB), with a spatial variability value of 7.5mB. Histogram and cumulative distribution frequency (CDF) plots indicated the crop VPD distribution pattern. For more than half of the time, the VPD was very high (greater than 50 mB) and then remained within 20 to 30 mB.

As indicated by the network health analyzer, the network's mean battery life at the current time instant was highest (100 percent), because all nodes had a voltage greater than 3.0 V, with a network mean voltage drop of 0.03 V. Due to packet losses, the network mean packet reliability remained between 75 and 100 percent, but the data reliability was very high (100 percent). Data was simultaneously recorded and logged in the respective files for historical display and trend analysis.

Figure 5 shows variations in the average value of the greenhouse-crop VPD under climate-control operation, as well as variations in the outside VPD

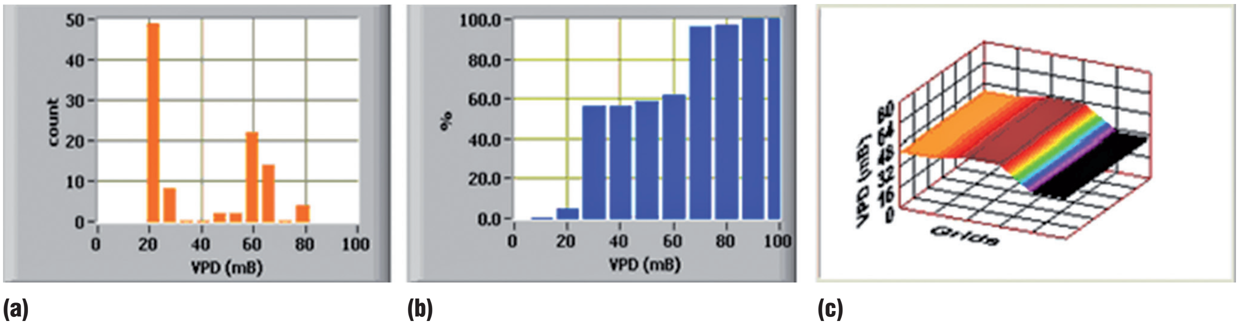


Figure 6. Greenhouse-crop VPD distribution patterns: (a) histogram, (b) cumulative distribution frequency (CDF) plot, and (c) mean VPD spatial plot over the recorded period of six hours.

and set limits and the corresponding variations in the actuating status and load of the climate-control equipment over the recorded period of six hours. Because the outside temperature was higher than 35°C, the shade screen was opened (covered) and the roof vents remained off. Under the extreme weather conditions, during the initial hours—when the outside VPD was extremely high (VPD error above 50 mB)—the greenhouse was humidified with the maximum cooling rate with exhaust fan ventilation turned off, resulting in a decrease of the average value of greenhouse-crop VPD, from 81.6 to 55 mB.

When the outside VPD dropped below 60 mB, the exhaust fan operating load increased from 75 percent to 100 percent. Increasing the ventilation rate with cooling further reduced the VPD (from 25 mB to 20 mB). When the outside VPD error dropped below 10 mB, the cooling pad and ventilation were switched to lower rates, which decreased the inside VPD to a minimum value of 18.18 mB. When the outside error was less than 1 mB and its rate of change was also negative, all the actuating devices were switched off (to the low-power mode).

Figure 6 shows the frequency (Figure 6a) and CDF distribution pattern (Figure 6b) of the crop VPD, indicating that for more than half the time, during the initial hours, the crop VPD remained higher than 50 mB. Also during that time, 30 percent of the values fell between 60 and 70 mB. During the later time, the crop VPD remained lower than 40 mB, and 50 percent of the values fell between 20 and 30 mB. Figure 6c shows the mean spatial variation pattern of the VPD at grids, which ranged from 47.0 mB to 30.14 mB, with a mean standard deviation of 8.78 mB. Crop VPD was lowest at the right grid (which was near the cooling pad), followed by left grid (near the exhaust fans), and it was highest at the middle grid (at the center of the greenhouse).

For six hours, our WSN monitored and controlled a greenhouse climate with high data and packet reliability (85 to 100 percent) and low battery drop (0.03 V). The climate controller tracked the initially high inside VPD and lowered the value to meet optimal conditions by operating the devices as needed. Furthermore, the real-time display of greenhouse climate-control statistics helped the grower make better decisions in executing greenhouse operations, eventually leading to healthy crop growth and better yields. Improving greenhouse climate control under such extreme weather conditions will require more efficient cooling systems (with variable loads) or grid-based humidifiers that could quickly decrease the initial rise of greenhouse-crop VPD during peak hours to obtain more uniform and optimum VPD control.

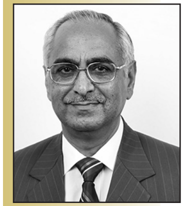
We plan to perform long-term system testing under different weather conditions with further improvement in control strategies and hope to implement irrigation, light-intensity, and carbon-dioxide monitoring modules to enhance the capabilities and performance of our automatic greenhouse climate controller. **P**

REFERENCES

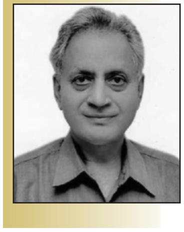
1. K . Sohraby, D. Minoli, and T. Znati, *Wireless Sensor Networks—Technology, Protocols and Applications*, Wiley Interscience, 2007.
2. J. Burel, T. Brooke, and R. Beckwith, “Vineyard Computing: Sensor Networks in Agricultural Production,” *IEEE Pervasive Computing*, vol. 3, no. 1, 2004, pp. 38–45.
3. Accenture, “Remote Sensor Network Accenture Prototype Helps Pick Berry Vineyard Improve Crop Management,” tech. report, 2005; www.accenture.com/SiteCollectionDocuments/PDF/pickberry.pdf.
4. S. Shanmuganthan, A. Ghobakhlou, and P. Sallis, “Sensor Data Acquisition for Climate Change Modeling,” *WSEAS Trans. Circuit and Systems*, vol. 7, no. 11, 2008, pp. 942–952.
5. H. Liu, Z. Meng, and S. Cui, “A Wireless Sensor Network Prototype for Environmental Monitoring in Greenhouse,” *Proc. Int’l Conf. Wireless Comm. Networking and Mobile Computing*, WiCOM, 2007, pp. 2344–2347.
6. G.J. Timmerman and P.G.H Kamp, *Computerized Environmental Control in Greenhouses*, Ede, the Netherland PTC, 2003.

the AUTHORS

Roop Pahuja is an associate professor and a PhD student in the Department of Instrumentation and Control Engineering at the National Institute of Technology Jalandhar, India. Her research interests include sensors, sensor networks, virtual instrumentation and graphical system design, the development of intelligent PC-based measurement and control systems, and WSN applications. Pahuja received her M.Tech in measurement and instrumentation from the Indian Institute of Technology, Roorkee, India. Contact her at pahujar@nitj.ac.in.



H.K. Verma is a distinguished professor in the Department of Electrical and Electronics Engineering at Sharda University, India. His research interests include smart sensors and sensor networks, embedded systems, digital relays and power system protection, hydraulic measurement and hydro-electric power development, and intelligent and energy-efficient buildings. Verma received his PhD in power system instrumentation and protection from the University of Roorkee, India. He is a member of the Institution of Engineers (India), Institution of Electronics and Telecommunication Engineers, and International Society of Automation. Contact him at hkvfee@gmail.com.



Moin Uddin is the pro vice–chancellor at Delhi Technological University, India. His research interests include computer networking, AI and soft computing, wireless communication and networks, and robotics. Uddin received his PhD in electronics and computer engineering from the University of Roorkee, India. He is a member of All India Council for Technical Education, the Ministry of Human Resource Development, India, and the India Society for Technical Education. Contact him at prof_moin@yahoo.comemail.

7. *XMesh User Manual*, Crossbow Technology, 2007.
8. *MTS/MDA Sensor Board User Manual*, Crossbow Technology, 2007.
9. *MPR/MIB User Manual*, Crossbow Technology, 2007.
10. P. Levis and D. Gay, *TinyOS Programming*, Cambridge Univ. Press, 2009.
11. J.J. Prenger and P.P. Ling, “Greenhouse Condensation Control,” Fact Sheet (Series) AEX-800, Ohio State Univ. Extension, 2000.
12. “Understanding Humidity Control in Greenhouse,” Fact Sheet no. 400-5, BC Ministry of Agriculture, Fisheries and Food, 1994.
13. *Xserve User Manual*, Crossbow Technology, 2007.
14. A. Errahmani, M. Benyakhlef, and I. Noumhidi, “Decentralized Fuzzy Control Applied in a Greenhouse,” *ICGST-ACSE J.*, vol. 9, no. II, 2008, pp. 35–40.
15. K. Gottschalk, L. Nagy, and I. Farkas, “Improved Climate Control for Potato Stores by Fuzzy Controllers,” *Computers and Electronics in Agriculture*, vol. 40, nos. 1–3, 2003, pp. 127–140.
16. E. Turban, J.E. Aronson, and T.-P. Liang, *Decision Support Systems and Intelligent Systems*, Prentice Hall, 2006.
17. S. Sumathi and P. Surekha, *LabVIEW Based Advanced Instrumentation Systems*, Springer, 2007.