Design and Implementation of Fuzzy Temperature Control System for WSN Applications

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Summary
Motivated by present day research trends that focus on application specific deployment and information processing in WSN, this paper presents, in general the design and implementation of rule based, simple, robust closed loop temperature control system using Virtual Instrumentation (VI) technology. It can be used for plethora of ZigBee WSN distributed measurement and control applications in areas like environmental monitoring and control, controlled-environment precision agriculture, building automation and process control. Using node based or zone - node based addressing scheme and double- averaging measuring technique, a ZigBee WSN, configured for periodic data transfer over adhoc multihop mesh network, transmits the measured value of zonal temperature as a feedback signal to the dual input, three-term fuzzy temperature controller. The controller software is designed to provide optimized output to drive a heating and cooling actuator network. The self-developed software (application program) with GUI, running on host PC, integrates and controls the operation of the hardware components to provide continuous temperature monitoring and control along with execution of add-on intelligent features. Looking into the practical aspects of deploying actuator network to drive FCEs that require external a.c / d.c power source along with low-power wireless sensor nodes, a novel ZigBee - RS485 HWSAN (heterogeneous wireless sensor-actuator network) is proposed and used as system hardware for low-rate deterministic small to medium control networks. Housed in a small greenhouse (GH) chamber and controlled by system software, this network fuzzy temperature control system provides uniform and precise ambient temperature control within an offset of ±1% over a wide temperature range of -10 to 70°C at a fast rate with information refresh rate as high as 2s. It provides high measurement and control performance and has flexible and versatile design to support not only single zone\ area base deployment but multi-zonal network deployment, where each zone is treated independently to meet same or different set point conditions. Moreover, the network has desirable level of security in terms of accurate, reliable and timely data transfer, fault tolerant configuration, alarm indication in case of node detection or network communication problem and low battery status indication to avoid battery-drained dead node situation

Key words:
ZigBee - RS485 Heterogeneous wireless sensor actuator network, Fuzzy temperature controller, Greenhouse automation, Virtual Instrumentation, GUI

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1. Introduction

WSN consists of spatially distributed embedded devices called sensor nodes, which form multi-hop adhoc mesh network, to cooperately measure the phenomenon of interest within the application domain [1] and communicate it to a sink node server system that is interfaced to backend communication wired\ wireless system for end user access [2] Before deployment each node is preprogrammed in embedded software to execute application specific sensor based data sampling and acquisition, simple computation and wireless multi-hop mesh communication to form a reliable, self configurable and self healing network. A sink node collects raw data packet from each node and interface it via USB or Ethernet to host PC\ server system. A suitable program running on host PC deciphers the packet and converts it into useful data for analysis, information processing and display on network user interface.

This network not only measures the phenomenon of interest with desired level of accuracy and data integrity, but also provides better spatial and temporal resolution to meet stringent requirements of complex and distributed measurement and control applications that are multi parametric, inaccessible, difficult, impractical and cost prohibitive to solve with wired networks [2][3]. Concentrating over the application domain of WSN, research review shows successful deployment of the network for data monitoring, event based detection, tracking, object classification, data collection for model building with less attention on control and automation [4][5].

Motivated by the concept of incorporating control in WSN, which is the need of some of the typical applications in the area of environmental monitoring and control, control environment agriculture [6], precision agriculture, building automation and process control [7], authors in this paper have projected a practical lookout of wireless sensor and control network and proposed the design and implementation of rule based simple, robust closed loop feedback fuzzy temperature control system using Virtual Instrumentation technology for such applications.

In today's WSN application scenarios, depending upon the practical feasibility and need base, different control strategies such as wired\ wireless, distributed\ centralized, single\ multi zone may be used to drive actuator nodes connected to FCEs, Combining control networks with sensor networks, henceforth broadly categories WSN as HWSAN (heterogeneous wireless sensor and actuator network) deploying wireless sensor network and wired actuator network and WSAN (wireless sensor and actuator network) deploying wireless sensor network and wireless actuator network with single zone\ multi zone controlling capabilities. As compared to WSANs, HWSANs offer more rugged and reliable actuation networks, compatible to drive power hungry actuator nodes but involve wiring overhead and limitation to remote access of controller. Moreover many FCEs (such as heaters, fans, valves, coolers, pumps) used in control applications require ac\dc power for their operation that is provided by wired power systems, hence purely wireless control networks at present are not realized unless new generation nodes facilitate onboard power generation using nanotechnology. T

To meet such stringent control requirements it is suggested to have small to medium scale deterministic network deployment with area or zone based addressing scheme. In this case the entire network area to be monitored and controlled is partitioned into small number of manageable zones. 'Zone' here is introduced to refer to an entity identified by a ID number. that represents certain grid area within application domain of the network that has a few number of wireless sensor nodes placed in adhoc manner for effective measurement of the parameters and fixed number\s of actuator node\s to initiate control action in response to the real time parametric information provided by sensor nodes. To address such a zone based sensor and control network a simpler and more efficient zone - node based addressing scheme, a variant to node based addressing, is proposed as a method to uniquely address and identify the node in the network zone. It uses 16 bits zone-node ID addressing code with higher and lower byte specifying zone ID and node ID respectively. This is rather simpler and more power efficient relative location based addressing scheme as compared to GPS enabled location based addressing method but requires careful deployment of nodes designed for particular zones. For small areas where spatial variation in parameters is very small, single zone\ area based network deployment strategy is preferred, where entire network area is considered as a single entity with sufficient number of sensor nodes and actuator nodes paced in adhoc\uniform manner. It uses node based addressing scheme with 16 bit node ID to address and identify the nodes.

Fig. 1 shows the schematics of general WSN based closed loop feedback control system. WSN is a new generation sensor data acquisition and collection network. Distributed within application zone wireless sensor nodes, transmit the sensor data packets to gateway node system. It collects the raw data packets, disseminate and preprocess the packets to retrieve meaningful sensor information to provide precise real

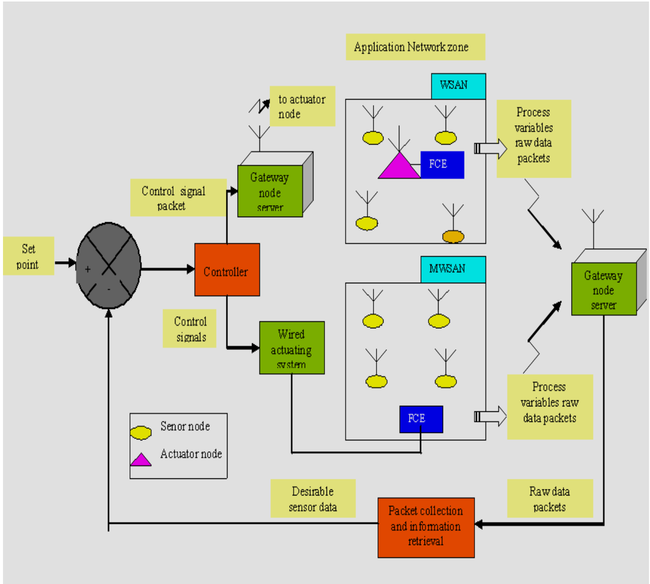

Fig1. Schematics of general WSN based closed loop feedback control system

time value of control variable as a negative feedback signal to the controller. Based on the error and is variants controller generates the output using conventional or AI analog\ digital control techniques to drive the actuator systems. Control signals are coupled to actuator nodes using either wired networks or control signal packets are wirelessly transmitted to wireless actuator nodes which in turn drive FCEs with the aim to minimize error. In case of multi-zone wireless sensor and control networks, the controller is time shared between sensor network information from various zones to drive corresponding actuator nodes [8].

Based on the concept, following sections of the paper discusses in short (i) Design background using VI that explains the techniques used to define functionality of the components and system as a whole (ii) System architecture that provides in general the requirement of hardware components with system layout and implementation of system software (iii) Experimental work that involves field deployment of novel ZigBee-RS485 MWSAN system for ambient temperature control in a small GH chamber with test results, conclusions and future scope.

2. Design Background

Based on VI the overall system design concentrates in developing a single\ multi-zone PC based sampled, point by point temperature network packets acquisition, analysis and actuating system [9] in which a control loop iterates at each sample of temperature information from WSN from each zone to generate fuzzy controller o\p signals sequentially to drive heating and cooling actuator nodes all zones for uniform and precise temperature control within error band of ±1% FSR. The underlying data acquisition, analysis and control methods and techniques decide the design of hardware and software components to define the functionality of the system. The section below discusses the design methods of important components.

(i) Data acquisition and analysis: For deterministic multi-zone WSN, zone-node based addressing scheme is proposed as a method to deploy sensor nodes in zones and report the best measured zonal temperature with minimization of error in sensing as a feedback signal to the controller. This scheme allows network zones to be treated independently and simultaneously for uniform and precise control of ambient temperature over the network area. Preprogrammed in embedded software each node, samples temperature sensor, forms message packet containing digital information about temperature, zone ID and node ID with other header parameters and transmit the packets to the sink node server system [9]. The acquired message packets are deciphered and collaboratively preprocessed by the application program layer to indicate best zonal temperature value, best measured voltage value, voltage and temperature alarm functions as explained below.

For such a sampled WSN system, consider a network of area A units with n number of zones and m number of sensor nodes in each zone with the elements designated as:

Zone = Zi (i varies from 1 to n)

Sensor node in Zi = SNij (j varies from 1 to m).

where each sensor node SNij measures node voltage and environmental temperature.

The best sampled temperature value (SNijT)t at the instant of sampling time t, is the mean of the latest five samples of temperature collected and is given by equation 1.

$$(SN_{ijT})_t = \sum_{k=0}^{5} (SN_{ijT})_{t-k} \;/\; 5 \qquad (1)$$

and the best recorded value of zonal temperature (TZi)t at the instant of sampling time t, is the mean of the best sampled temperature values of the nodes in the zone and is given by equation (2).

$$(T_{Zi})_t = \sum_{j=1}^{m} (SN_{ijT})_t \;/\; m \qquad (2)$$

(TZi)t calculated for each zone based on double averaging technique, is the current value of zonal temperature and feedback signal to the controller to initiate controller action for that zone.

For temperature alarm annunciation, each best recorded value of zonal temperature (TZi)t is compared with low temperature (Tlow) and high temperature (Thigh) alarm values to activate low (ATlow)i or high (AThigh)i temperature alarms respectively using comparative logical statements given by equation (3) and (4).

$$\text{If } (T_{Zi})_t \leq T_{low} \Rightarrow (AT_{low})_{Zi} \uparrow \quad \text{else } (AT_{low})_{Zi} \qquad (3)$$

$$\text{If } (T_{Zi})_t \geq T_{high} \Rightarrow (AT_{high})_{Zi} \uparrow \quad \text{else } (AT_{high})_{Zi} \downarrow \qquad (4)$$

Similarly, battery voltage of each node is also measured to record the best sampled voltage value (SNijV)t at the instant of sampling time t, which is the mean of the latest five voltage samples collected given by (eq.5). To keep track of low battery condition of nodes, the current value of the voltage is compared with low battery voltage value to activate low battery alarm (ABlow)ij using comparative logical statements given by equation (6).

$$(SN_{ijV})_t = \sum_{k=0}^{5} (SN_{ijV})_{t-k} \;/\; 5 \qquad (5)$$

$$\text{If } (SN_{ijV})_t \leq B_{low} \Rightarrow (AB_{low})_{ij} \uparrow \quad \text{else } (AB_{low})_{ij} \downarrow \qquad (6)$$

In case of single zone\ area deployment, node based addressing scheme with double averaging measuring technique is used and each node is preprogrammed with node ID. This being the limiting case of above system mathematical description remains the same by just eliminating Zi and i .

(ii) Feedback controller: It is the core element that reflects the working performance of the system. As a support to meet expert linguistic description of temperature control strategy, used in many complex WSN application which are difficult to be modeled mathematically, a rule based fuzzy control model is used to design robust temperature controller10][11][12]. It is a dual I\P three term fuzzy controller. Each controller I\P variable, temperature error (TE= set point - current temperature and change in temperature error (CTE = (TE)t - (TE)t-1) in the range (-1,1), is fuzzified into seven linguistic terms: negative small (NS), negative medium (NM), negative large (NL), near zero (NZ), positive small (PS), positive medium (PM), positive large (PM) with triangular membership function and full term overlap and the controller O\P (FO) in the range (-1,1), is fuzzified into three linguistic terms: heater (H), OFF (OFF), cooler (C) with singleton membership functions. It has 49 control rules that capture the strategy for controlling temperature using heating and cooling system [8][13]. Depending upon the inputs, certain rules are fired and using Max – Min inference and Center of Maximum (CoM) defuzzification method most plausible crisp o\p is obtained.

For use in real time situation with wireless sensor and actuator network, FC I\Ps are derived from process information. For the given high (TRhigh) and low (TRlow) temperature range, temperature set point\ desired value

(TSP) and current value of zonal temperature (TZi)t as measured by WSN, the controller normalized I\P variables temperature error (TEZi)t and change in temperature error (CTEZi)t, for each zone Zi at that instant of time t are calculated using equations (7) and (8) receptively.

$$(TE_{Zi})_t = T_{SP} - (T_{Zi})_t / T_{Rhigh} - T_{Rlow} \quad (7)$$

$$(CTE_{Zi})_t = T_{SP} - (T_{Zi})_t / 2(T_{Rhigh} - T_{Rlow}) \quad (8)$$

Based on these real time I\Ps, FC produces O\P control signal (FOZi)t for Zi at that instant of time to drive actuation system. This being the common design element is time shared between temperature inputs from different zones to sequential drive actuator nodes of zones. The controller design is optimized to suit wide temperature range (-10°C to 80°C) and provide high accuracy performance with error of ±1% FSR.

An interactive program as shown in fig.2 is developed and used to test and plot simulated multiple o\p-i\p characteristics of the controller as a basis to study\ modify controller design and is also made a part of the main program for online access to the facility [13].

(iii) Actuation mechanism: The O\P of FC is an analog value in the range (-1,1), that is mapped to three terms (positive, negative and near zero) to drive the heating or cooling actuating nodes. Simple ON\OFF control logic [8] based on equation. 9 produces digital o\p control signals for cooler (CZi)t and heater (HZi)t of zone Zi at the instant of time t in response to (FOZi)t .

If $(FO_{Zi})_t < -0.003 \Rightarrow (C_{Zi})_t \uparrow$ otherwise $(C_{Zi})_t \downarrow$

If $(FO_{Zi}) > 0.004 \Rightarrow (H_{Zi})_t \uparrow$ otherwise $(H_{Zi})_t \downarrow$

If $-0.003 < (FO_{Zi})_t < 0.004 \Rightarrow (C_{Zi})_t$ and $(H_{Zi})_t \downarrow$

The fuzzified digital control o\p signals in real sense are coupled to digital output or relay ports of wired or wireless actuator network nodes of different zones to switch ON\OFF power supply to heating and cooling elements for temperature control. This fuzzy ON\OFF controller not only provides the simple expert model of control actions but also reduces offset and provide better control performance as compared to ON\OFF controller.

3. System Architecture

Temperature Control System for WSN is Virtual Instrumentation system that uses general purpose computing platform (PC), WSN data acquisition and actuator network hardware, graphical programming language and driver software [10][14] to develop software controlled PC based data acquisition and control network system where software (based upon design techniques) integrates all the hardware components and defines its functionality and features. The section below explains the hardware requirements and software development for system integration.

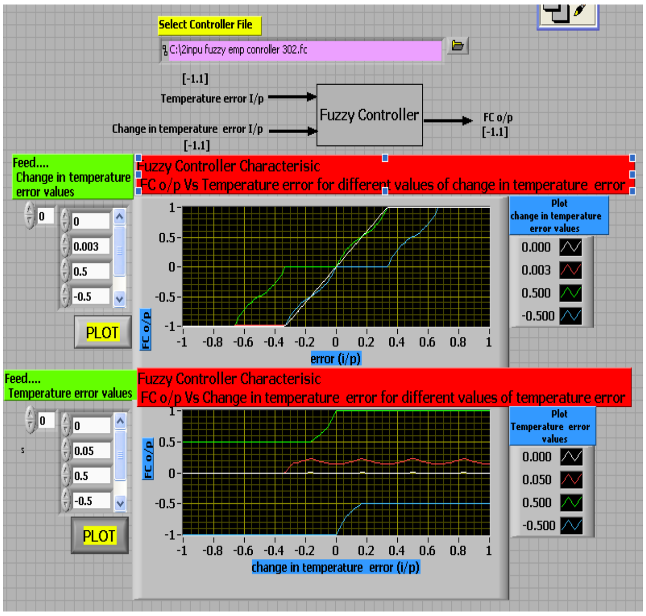

Fig 2. Fuzzy controller multiple I\O characteristics.

3.1 Hardware.

Fig.3 shows the general schematics of the hardware layout of the system. A host PC (Pentium III or higher, Win XP\ 2007 \Vista) is interfaced to distributed data acquisition wireless sensor network and wired\ wireless control system, with each application zone having a few wireless nodes and an actuator node for heating and cooling system. The section below explains in brief the main components of the system:

(i) WSN: It is the main data acquisition and collection network. Standard WSN is based on one of the recent wireless communication and networking technologies popularly known as ZigBee that caters to its unique needs in terms of limited battery, low memory, simple computation, low bandwidth and many a times unattended deployment [1]. Build on top of IEEE 802.15.4, which defines the physical and MAC protocol layers and ZigBee Alliance specifying network, security and application software layers, ZigBee has emerged as an open standard that enables low power, low cost, low data rate, low latency, reliable, fault tolerant and easily scalable short-range wireless protocol for embedded electronic devices especially sensors and control networks. ZigBee complements established WPAN and WLAN technologies ie Bluetooth and Wi-Fi , intend to be simpler and cheaper and well suited for WSN applications[15] [16] [17].

A typical ZigBee WSN consists of sensor nodes (end devices) distributed in an adhoc manner within the application domain to form star, cluster tree or mesh network with multihopping and network coordinator (sink node\ gateway node) for connecting network to the external world through

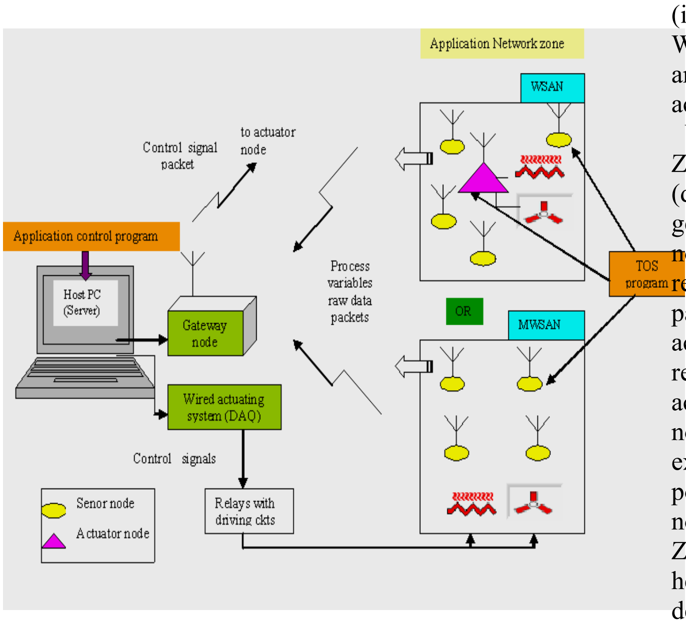

Fig.3 Hardware schematics of PC based WSN temperature control system

host PC or server system. Sensor node is a battery operated embedded device and has a microcontroller interfaced to IEEE 802.15.4 transceiver and sensor board with smart environmental temperature and other sensors. Preprogrammed in embedded WSN software (such as TinyOS, SOS, Mantis), each node is a FFD (full functional device) and has basis capability to sense, process and rout data packets to sink node using multi-hop mesh routing. It supports multiple traffic types including periodic data using beacon mode, intermittent data with beaconless mode, and repetitive low latency data with GTS to generate and transmit data packets in a MAC frame format using underlying CSMA-CA technique. Data packets as collected by the sink node are interfaced to PC control system using USB and Ethernet connectivity. A suitable high level application program running on PC collects, deciphers and processes the network data packets for information display and visualization on GUI [1] [19] [20].

Because of ZigBee (IEEE 802.15.4) standard there has been an ever-expanding market potential for short-range, low data rate wireless sensor network applications, according to ON World, and sheer volume of the low data rate wireless devices are predicted to be three times the size of Wi-Fi (802.11) in the next five years. With Crossbow Technology (now Mimsic) being pioneer to commercially manufacture WSN platforms and systems, designed by UC Berkeley in the research projects funded by DARPA, [1] the market is now flooded with sensor nodes from different vendors. Top on the list are: Mica2DoT, Micaz, Iris, Telos B, Wsapmote, Sensnode, T-mote sky, XYZ node, Neomote , Shimmer [21]

(ii) Control Systems: As discussed in section 1, in today's WSN application scenarios, two types of control strategies are deployed viz wireless actuating network and wired actuating network.

Wireless actuating network is a similar kind of standard ZigBee WSN where the nodes have actuating capabilities (digital or analog O\P) to drive FCEs [1].These nodes are generally static, small in number as compared to sensor nodes and form multihop network with other nodes. In response to the wirelessly transmitted control message packet as generated by network coordinator system, the actuator node drives the digital or analog output lines or relays terminals to control the operation of FCEs. However actuator nodes drain more power as compared to sensor node because of high duty cycle and moreover require external a.c or d.c power source to drive FCEs. Because of power constraint purely wireless solution for actuator nodes is still not realized practically. Recently launched ZigBee home automation systems and products for heterogeneous home area networks (HANs), control devices such as wireless ON\ OFF light switches and dimmers are available for such dedicated applications.[22]

Wired actuating network is a PC based network that uses one of the established industrial serial networking standard such as RS-485 to drive analog and digital output control modules. Easy to install, the network has simple point-to-point, multi-drop topology where all the field control modules are connected to the network communication module just over the differential twisted pair of data lines, thus minimizing noise interference and wiring cost [23]. Based upon master-slave, half duplex and command-response communication protocol, the field modules initiate the control action in response to the control command issued by PC to drive FCEs. DC and AC power lines running across the network supply power to actuator nodes and FCEs. Because of its high data transmission speeds (35 Mbits\s up to 10 m and 100 Kbits\s at 1200 m), relatively large distance span (up to 4000 feet or just over 1200 meters), easily scalable network from 32 to 255 nodes with repeaters, low installation cost, availability of multifunctional input\ output modules from different vendors, easily programmable command set, this network is recommended as an ideal solution for many applications such as building automation, environment control in closed chambers or agriculture greenhouses [24].

Rugged in construction, these nodes easily integrate FCEs that require external power to operate and form highly reliable functional actuator network, compatible to work with 2.4GHz wireless network without interference problems.

3.2 Software.

Software is the heart of the system that not only integrates the system components and control operations but define functionality and features using underlying techniques and methods. System software has two parts, one is Sensor node program and other is Controller Display program. Node program is Tiny Operative System (TOS) based application program, embedded in the nodes before deployment that define its functionality [19]. TOS Application component is developed by wiring together low level TOS driver components and other high level components through interfaces and implementing functionality using commands and event functions provided by interfaces in nesC programming language and TOS [25][26]. When the network is established and nodes are powered ON, TOS program in each node is executed to sample temperature and voltage A\D ports at the predefined rate, encapsulate raw sensor readings in the standard TOS message format with node and zone ID and transmit the packets to sink node using multihop mesh network protocol. Sink node preprogrammed with standard base program collects the network packets and interface them to host PC USB port

Controller Display program is high level application software running on host PC\ server (network coordinator, controller and display unit) based upon sampled point by point packet collection, analysis and control paradigm. It supports two operational modes to interface with single zone and multi-zone WSN, collects and deciphers sensor network packets information [26], does all data processing for temperature monitoring, calculates real time fuzzy controller inputs to drive predesigned fuzzy controller to obtain O\P, initiate digital controller to generate ON\ OFF control logic signals for FCEs, interface the control signals to RS485 actuating network or wirelessly transmit control packet to ZigBee actuator nodes to power ON\OFF heater and cooler for temperature control.

Fig.4 shows functional flowchart of the application software based on design techniques explained in section II and implemented using graphical system design Virtual Instrumentation programming platform, NI LabVIEW 8.5[9] [27][28]. It has a multi-panel, modular and hierarchical design with top VIs (virtual instrument) calling low level VIs (used as subVIs) with concurrency and synchronization among execution of various operations. Main front panel provides user options to select Crossbow WSN hardware and feed deployment information indicating number of zones (single zone\ multi-zone) and calls Temperature Control panel for single zone\ multi-zone to execute all functions and provide information. It has a well designed, interactive graphical front panel for user interaction (as shown in fig.6) linked to the block diagram program code, logically implemented with functional module subVIs. Depending on the user fed inputs from the front panel, program code is executed to display results on it. It supports multiple functionality of being a network temperature monitor, fuzzy controller, plotter, recorder and logger with many add-on features summarized below:

- Provides on line connectivity to Crossbow mixed node wireless network and Advantech RS-485 heating and cooling actuator network

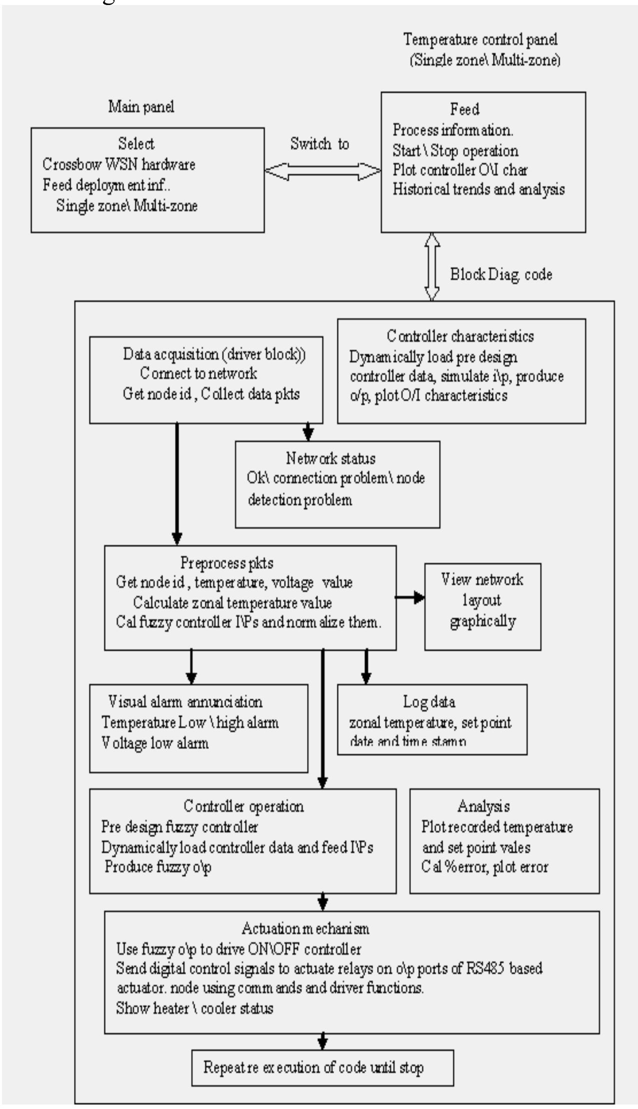

Fig.4 Functional flowchart of the Controller Display VI program

- Shows graphically the zonal view of the network with each node indicating best sampled temperature and voltage value.
- In response to real time zonal temperature values, calculates and normalizes the fuzzy controller input and provide controller o\p to actuate heating and cooling system on RS-485actuator network.

- Represents zonal temperature values and continuously plots its variation with time along with set point thus indicative of controller performance.
- Provides alarm annunciation visually to indicate high\ low temperature alarm condition and low voltage alarm condition by changing node color.
- Indicates heater and cooler ON\OFF status of each zone visually.
- Simultaneously log zonal temperature and set point values wih time and date stamp
- Provides options to view historical trends of data for off line statistical analysis.
- Indicates network status to warn user of network connection \ node detection problem.
- Allows user to feed and dynamically change temperature range, alarm values and set point in accordance with real process information. Provide options for individual set point for all zones.
- Allows access to Test panel to study and plot fuzzy controller characteristics.

4. Experimental Work

4.1 Field Layout

With an aim to demonstrate, the working performance of the designed fuzzy temperature control system for WSN applications, a novel ZigBee-RS 485 HWSAN is deployed for ambient temperature control of single zone prototype Greenhouse (GH) chamber. Greenhouse is one of the CAE (Controlled Environmental Agriculture) techniques that caters to the growth of plants\ fruits \vegetables\ flowers in a closed structure with the control of multiple interactive soil and ambient parameters that affect the plant growing process. The aim is not only to improve the plant quality and yield for better returns but to facilitate off-season vegetation, vegetations in harsh climatic conditions with conservation of energy\ water resources. In the on-going process to successfully automate production systems for optimal growth of plant species in different greenhouse structures, various engineering techniques and methods have been used and systems developed, from time to time, latest being WSN.

Reasons to use proposed ZigBee-RS485 HWSAN for temperature control in a complex GH and related applications are many folds. WSN provides a unique and easy method to facilitate distributive, multi-point temperature sensing with better spatial and temporal resolution, eliminating wiring cost and installation hassles. Over the past few years, it has been considered as a unique and acceptable data acquisition tool for collecting and accessing multivariables in GH environment that would also, in future facilitate remote control and management of GH\s.[29][30]. Use of node based (single zone)\ zone-node based (multi-zone) addressing with double averaging is ideal to accurately and co-operately report the best measured zonal temperature for instant distributive control action to cover up spatial and temporal temperature variations in GH network area. Actuator nodes being small in number, fixed in location and suitable to drive a.c\ d.c power controlled FCEs, reliable wired RS-485 actuator network is used that is easily scalable, simple to install, multi-drop network and uses programmable command-response based communication. Moreover use of fuzzy controller, captures expert linguistic description of temperature control rules, devise for complex GH applications, to intelligently control ON\OFF operation of heater and cooler to obtain high performance controller response with low offset .

Fig. 5 shows the block diagram schematics of PC based ZigBee-RS485 HWSAN to monitor and control ambient temperature of small Greenhouse chamber. Host PC is interfaced to Crossbow Zigbee WSN gateway node (USB gateway board with Iris mote preprogrammed with TOS Base application) and Advantech RS-485 network controller, to form a wireless and wired link to wireless sensor nodes and actuator node respectively, housed in a small greenhouse chamber (15 ft x 15 ft). 5 number of Crossbow wireless sensor nodes (battery operated Iris motes with MDA300 sensor board with on - board temperature sensor) are installed at the height of 2 ft in zigzag manner to cover the greenhouse area. Before deployment each node preprogrammed with TOS application program and node id (for area deployment), senses battery voltage and temperature periodically at the preset sampling time of 2s, encapsulate their digital equivalent values in data payload fields with node ID and other header information to form message packet and transmit each packet using multi-hop mesh networking to the gateway node. Packets thus transmitted by nodes are collected by gateway node and interfaced to USB port of PC for application layer to collect and process. Sensor nodes with gateway node thus form Zigbee multi-hop mesh network for periodic data traffic where each node is a FF ZigBee device with sensing and routing capabilities.[19][32]

For control purposes GH also has 1 no. of RS 485 network based Adventech 4000 series digital output module as an actuator node that is fixed at an appropriate place. Port 0 and 1 of the actuator node are connected to relay operated heater and cooling fan to control ON\OFF operation in response to fuzzy temperature based digital control signals issued by PC. [31]

Application program with GUI (described in section III), running on host PC integrates and controls the operation of multi-platform hardware components for automatic temperature acquisition, analysis and control with execution of intelligent features.

4.1 Results

When the hardware system as shown in fig.5 is deployed and power ON, Main panel of application program is configured to select WSN hardware (Iris motes and MDA300 senor boards) and feed deployment information specifying number of zones. Upon execution it opens Temperature Control panel for single zone (as shown in fig.6), that is configured with node deployment and temperature information related to set point, range and alarm settings and 'START' button is clicked to establish network connectivity and display results on GUI as indicated in fig 6. In continuous running mode, network packets are sampled and collected periodically with time interval of 2s signifying reported time instant, to update and refresh information on panel. As shown on GUI, at the current reported time network view indicator is graphically showing network area (single zone) with five number of detected sensor nodes, each operating within normal temperature range and battery voltage (Green color), and indicating node id and best sampled value of local environmental temperature. Temperature graph depicts variation in zonal temperature over time to track set point of 30°C. With present zonal temperature of 29.8°C and set point of 30°C fuzzy ON\OFF controller drives heater ON and cooler OFF, with status as indicated. Network current status as shown is OK, all the nodes deployed are detected with no network connectivity or node detection problem. Simultaneously each value of zonal temperature and set point with date and time stamp are logged in spreadsheet data files. Fig.7 plots the historical trends of 8 hours recorded data showing how temperature tracks the changes in the set point thus providing precise control of temperature with offset of ±1% FSR

Evaluating the working of the system for obtaining desirable control action and validating the accuracy of temperature measurement by comparing the results against standard software, [33] it is assured that the system has high measurement and control performance. It also provides satisfactory network performance with desire level of security. Based on standard ZigBee wireless protocol with true multi-hop mesh networking capabilities, sensor nodes provide reliable and timely data delivery on self healing, self configuring fault tolerant network. RS - 485 wired actuation network offers rugged and reliable control system, with minimum wiring installation cost compatible to work in close proximity with WSN without signal interference problems. Moreover, system software allows the user to continuously monitor battery and network status and take corrective measures in case of alarm situations thus enhancing physical security level of WSN.

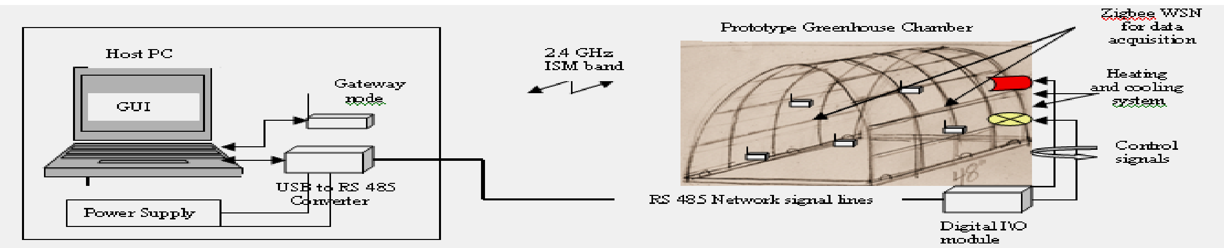

Fig 5 Schematic of Zigbee - RS485 MWSAN for temperate control of prototype greenhouse chamber

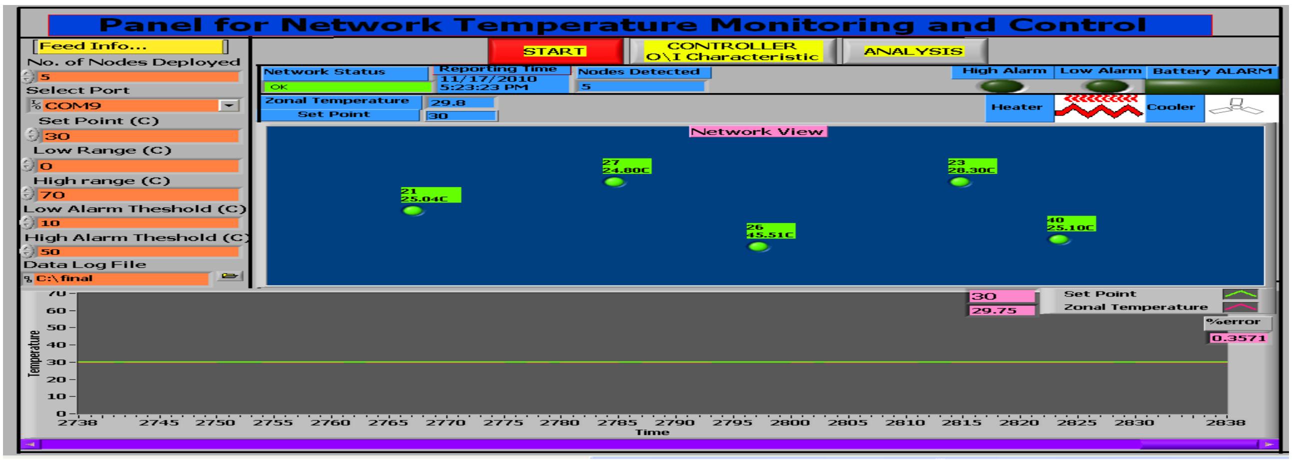

Fig 6. GUI showing results of real time network environmental temperature monitoring and control

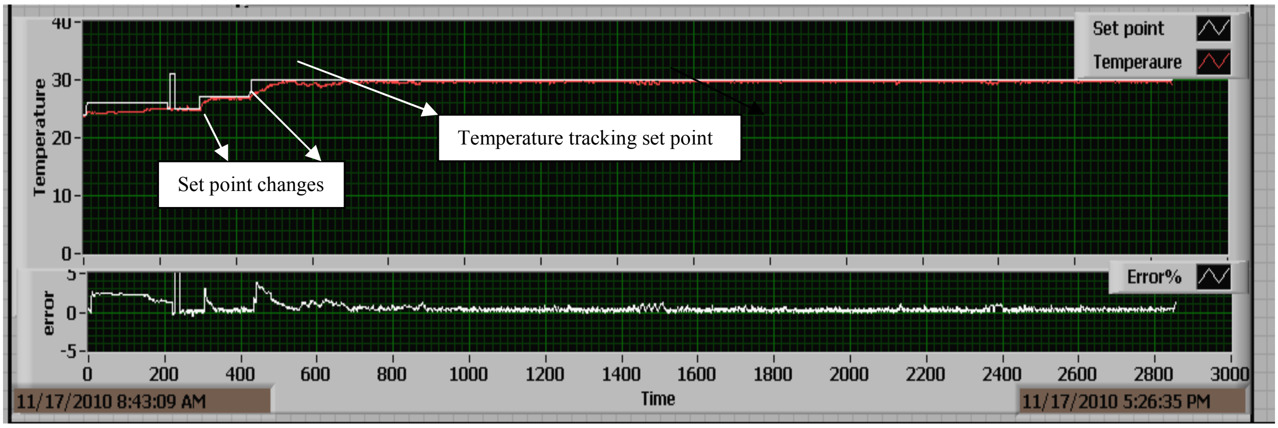

Fig.7 8 hrs of recorded data trends indicate precise temperature control with offset of ±1%FSR

5. Conclusion

ZigBee-RS485 MWSAN, based on node\ zone-node based addressing, double averaging and fuzzy temperature control techniques, is a well featured, high performance, versatile, programmable temperature monitoring and control system for WSN applications. In fact the proposed system is general purpose, simple, real time, practical solution for LR small to medium scale deterministic WSAN applications in the field of precision agriculture, control environment agriculture, building automation etc. that require temperature control over the network area or zones, where each zone is treated independently to meet same or different set point conditions

Implemented using Virtual Instrumentation technology, system software, integrates multi-platform data acquisition WSN and actuator network, control its operation and provide all functionality for temperature monitoring and control with execution of multiple intelligent features and display of network data and information on intuitive GUI. Tested under various conditions, it offers continuous temperature control with maximum offset of ±1% FSR in a wide temperature range of -10°C to 80°C at a fast rate. It has the capability to capture and display the network information with refresh rate as high as 2s and optimally drive the final control elements with low duty cycle. It not only provides reliable data transfer over self healing, multi-hop network but also offers scalable and flexible system configuration.

Future scope involves implementation of intelligent multivariable control system for WSAN applications with integrated software having additional test facility to evaluate the field performance of the network.

References

[1] K. Sohraby, D.Minoli and T. Znati, Wireless Sensor Networks-Technology, Protocols and Applications, Wiley Interscience, 2007

[2] D.J.Cook and S.K.Das, Smart Environment: Technology, Protocols and Applications, John Wiley, 2004

[3] D. Culler, and H. Mulder, Smart Sensors to Networks the World , *Scientific American,* June 2004.

[4] O.Green, E.S. Nadimi, “Monitoring and modeling temperature variation inside silage stacks using novel wireless sensor networks.”, Computers and Electronics in Agriculture, pp. 149-157, 2009

[5] J. Burel, T. Brooke, and R. Beckwith, “Vineyard computing: Sensor networks in agricultural production”,IEEE Pervasive Computing, vol. 3. no.1, pp. 38. ,2004,

[6] G.Fang Li, S. T Liu, Li D. Chen, “Design on Environment Monitoring System for Greenhouse Based on Wireless Sensor Network” , Advance Materials Research, vols 108-111, pp 145-150, May 2010.

[7] A.N. Das, F L. Lewis, D. O. Popa, "Data-Logging and Supervisory Control in Wireless Sensor Networks,", Seventh ACIS International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing, pp.330-338, 2006.

[8] Surekha Bhanot, Process Control Principles and Applications , Oxford University Press 2008.

[9] S. Sumathi, P. Surekha, LabVIEW based Advanced Instrumentation Systems, Springer

[10] Yen John, R. Langari, Fuzzy Logic Intelligence, Control and Information, Pearson Education, India, 1998

[11] www.fuzzylogic.com/ch1.hm

[12] www.ausinlinks.com/Fuzzy/tuotrial.hml

[13] National Instruments Corporation, LabVIEW PID and Fizzy Logic toolkit User Manual, June 2009.

[14] National Instruments Corporation, Instrumentation NewsletterVolume 18, Number 1 First Quarter 2006.

[15] Bhavneet Sidhu, Hardeep Singh, and Amit Chhabra, “ Emerging Wireless Standards - WiFi, ZigBee and WiMAX”, *World Academy of Science, Engineering and Technology 25, 2007.*

[16] http://www.diffen.com/
[17] http://review.zdnet.com/4520-6033_16-4207317.html
[18] http://en.wikipedia.org/wiki/Bluetooth
[19] Crossbow Technology, MoteWorks Getting Started Guide", 2007
[20] Crossbow Technology, Xmesh User Manual", 2007
[21] http://en.wikipedia.org/wiki/Sensor_node.
[22] ZigBee Alliance, ZigBee Vision for the Home, November 2006.
[23] http://en.wikipedia.org/wiki/EIA-485
[24] http://www.bb-elec.com/tech_articles/rs485_basics.asp
[25] P.Levis., " TinyOS/nesC Programming reference manual.".
[26] Roop Pahuja, H.K Verma, Moin Uddin , "WSN application for power aware data acquisition and transmission", National conference on Computing, Communication and Control, October 2009.
[27] Roop Pahuja, H.K. Verma, Moin Uddin, " Design and Implementation of VI Tool for WSN Applications", World Congress on Engineering and Computer Science, Vol II , pp838-843, October 2010
[28] Gary W. Johnson, Richard Jennings, LabVIEW Graphical Programming, 4th edition, MGH
[29] Y W Zhu, X X Zhong and J F Shi, "The Design of Wireless Sensor Network System Based on ZigBee Technology for Greenhouse", Journal of Physics: Conference Series 48, pp1195–1199, 2006.
[30] Xinjian Xiang , Xiaoqing Guo, "ZigBee Wireless Sensor Network Nodes Deployment Strategy for Digital Data Acquisition",IFIP Advances in Information and Communication Technology, Vol 317, 109-11, 2010.
[31] http://www.advantech.com.tw/products/RS-485-I-O-Modules- ADAM-4000/sub_1-2MLKHT.aspx
[32] Crossbow Technology, "MTS\ MDA User Manual", 2007
[33] Crossbow Technology, "MoteVIEW Users Manual", 2007

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