Design and Implementation of Fuzzy Temperature Control System for WSN Applications

Roop Pahuja, H.K. Verma, Moin Uddin

Abstract
With its low power embedded sensing\ actuation, computing, wireless RF communications and multihop mesh networking capabilities, Wireless Sensor Network (WSN) has emerged as one of the popular multidisciplinary technologies of the 21st century. Present day research trends focus on application specific deployment of network hardware with information processing, integrating it into commonly used development software and providing high level of abstraction to end user. Motivated by such challenges, this paper represents the design and implementation of rule based, simple, robust closed loop feedback temperature controller for plethora of WSN measurement and control applications in areas like environmental monitoring and control, control environment precision agriculture, building automation and process control. This dual input, three term controller translates the linguistic decision making for temperature control into rule based control strategy, ideal for complex systems which are difficult to be modeled mathematically. Based upon the real time temperature information from wireless nodes and user fed process information, the software controller is well designed and optimized to provide precise temperature control with offset of ±1% within wide temperature range of -10 to 70°C and time lag of 10s. The modified controller O\P drives the heating and cooling system with low duty cycle thus saving power and increasing the life time of devices. Looking into the practical aspects of deploying the network and actuation systems, this general purpose controller offers high compatibility with WSN using established wired or new generation wireless actuation systems. This paper also discusses the implementation of versatile software with effective GUI that not only integrates the controller with sensor network and control hardware from different vendors for real time PC based temperature monitoring and control but also executes salient features of network, battery and alarm status monitoring, data logging , historical trends viewing and plotting\ testing controller characteristics. Results obtained with the experimental field set up for ambient room temperature control are also discussed.

Index Terms
Fuzzy temperature control, Software tool, Wireless sensor network.

I. INRODUCTION

WSN consists of spatially distributed embedded devices, called sensor nodes, which form multi-hop mesh network, to cooperately measure the phenomenon of interest within the application domain and communicate it to a sink node server

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Roop Pahuja is with Department of Instrumentation and Control Engineering, Dr. Bhimarao Ambedkar National Institute of Technology, Jalandhar, Punjab (phone;09988651877, email: pahujar@nitj.ac.in)
H.K. Verma is with Department of Electrical Ensgineering, Indian Institute of Technology Roorkee, Roorkee, Uttrakhand (hkvfee@gmail.com)
Moin Uddin is with Dr. Bhimarao Ambedkar National Institute of Technology, Jalandhar, Punjab (moinuddin@nitj.ac.in).

system that is interfaced to backend communication wired\ wireless system for end user access [1]. 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 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, and 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 precision agriculture [6], 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 closed loop feedback robust fuzzy temperature control system (hardware and software elements) for such applications. Results as obtained on

GUI, displaying real time monitoring and control of ambient room temperature are also discussed.

For network deployment and automation, different control strategies such as wired\ wireless, distributed\ centralized, single\ multi zone are used in today's WSN application scenarios. Concept of 'Zone' here is introduced to refer to an entity that represents certain area within application domain of the network that is sensed by wireless sensor nodes and control by actuation system. Culminating the idea, broadly categories WSN as MWSAN (mixed wireless sensor and actuator network) deploying wireless sensor nodes and wired actuation systems and WSAN (wireless sensor and actuator network) deploying purely wireless sensors and actuators with single zone centralized or multi zone distributed controlling capabilities. MWSANs are generally used in deterministic, small to medium network applications where it is possible to physically create the zone\s and deploy network. It uses zone-node based addressing scheme without location awareness for data communication and established PC based wired analog\ digital, complex high performance conventional\ AI control logic techniques, compatible with different actuators and FCEs (final control elements). WSANs are well suited for non - deterministic set ups with adhoc placement of SN\s and AN\s where zones are dynamically created. It uses location based addressing scheme for data communication and simple ON\OFF or digital control logic techniques for actuating FCEs. Many deterministic setups with simple digital control also deploy WSANs.

Fig 1 shows the schematics of general WSN based closed loop feedback control system using different control strategies [8] [9]. Based on this concept, the following sections of the paper discusses the design of fuzzy temperature controller and its integration with WSN and control systems to suit wide range of temperature monitoring and control applications, implementation of controller software with salient features, real time deployment of wireless sensor network and wired control system for room temperature monitoring and control with test results.

II DESIGN BACKGROUND

The overall system design concentrates in developing a PC based sampled, point by point temperature data acquisition, analysis and actuating system in which a control loop iterates at each sample of temperature information from WSN to generate an optimal control signal for temperature control within error band of ±1% [10]. The important design components are discussed below:

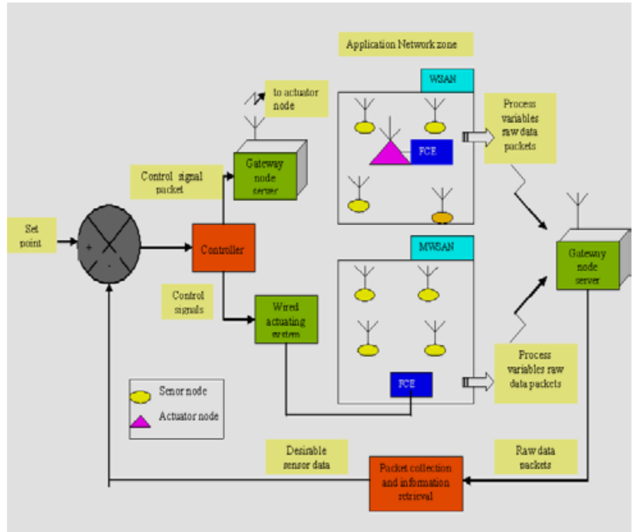

Fig1. Schematics of general WSN based closed loop feedback control system

(i) Data acquisition and analysis: Wireless sensor nodes distributed within the application area senses environmental temperature locally. Each sampled temperature value with zone id and node id encapsulated within the message packet is transmitted to the sink node server system [9] .The acquired message packets are deciphered and collaboratively preprocessed to indicate best temperature value.

In the case of deterministic WSN with zone node based addressing scheme, **Double Averaging** method to minimize error in sensing, is proposed to obtain the best reported zonal temperature as a feedback signal to the controller. 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 $= Z_i$ (i varies from 0 to n)

Sensor node in $Z_i = SN_{ij}$ (j varies from 0 to m).

where each SN_{ij} measures node voltage and environmental temperature.

The best sampled temperature value $(SN_{ijT})_t$ at the instant of sampling time t, is the mean of the latest five samples of temperature collected and is given by equation 1.

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

and the best recorded value of zonal temperature $(T_{Zi})_t$ 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).

m

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

$(T_{Zi})_t$ calculated for each zone, 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 $(T_{Zi})_t$ is compared with low temperature (T_{low}) and high temperature (T_{high}) alarm values to activate low $(AT_{low})_i$ or high $(AT_{high})_i$ respectively using comparative logic statements given in equation (3) and (4).

If $(T_{Zi})_t \leq T_{low}$ => $(AT_{low})_{Zi}$ ↑
else $(AT_{low})_{Zi}$ ↓ …………………………(3)

If $(T_{Zi})_t \geq T_{high}$ => $(AT_{high})_{Zi}$ ↑
else $(AT_{high})_{Zi}$ ↓…………………………...(4)

Similarly, battery voltage of each node is also measured to record best sampled voltage value $(SN_{ijV})_t$ (eq.5) and to indicate low battery condition (eq.6)

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

If $(SN_{ijV})_t \leq B_{low}$ => $(AB_{low})_{ij}$ ↑
else $(AB_{low})_{ij}$ ↓ …………………………(6)

(ii) *Feedback controller* : It is the core design element that reflects the working performance of the system. As a support to meet expert linguistic description of control strategy, used in many complex WSN application, a rule based robust temperature controller has been designed [11] [12] [13]. 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]. LabVIEW based program with GUI as shown in fig. 2 depicts multiple O\P – I\P characteristics of the controller. Pre designed controller data file is loaded and fuzzy controller O\P based on Max – Min inference and Center of Maximum (CoM) defuzzificaion method is obtained for different simulated values of the I\Ps using controller functions [14]..

In real time situation, FC I\Ps are mapped with the process information to produce most plausible crisp O\P to drive actuation system. For the given temperature high range (T_{Rhigh}) , low range (T_{Rlow}), desired value (T_{SP}) and current value of zonal temperature $(T_{Zi})_t$, as measured by WSN, the normalized controller I\P variables temperature error $(TE_{Zi})_t$ and change in temperature error $(CTE_{Zi})_t$, for each zone Z_i at that instant of time t, are given by equations (7) and (8) receptively.

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

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

Based on these real time I\Ps, FC produces O\P control signal (FO_{Zi})$_t$ for Z_i at that instant of time to drive actuation system.

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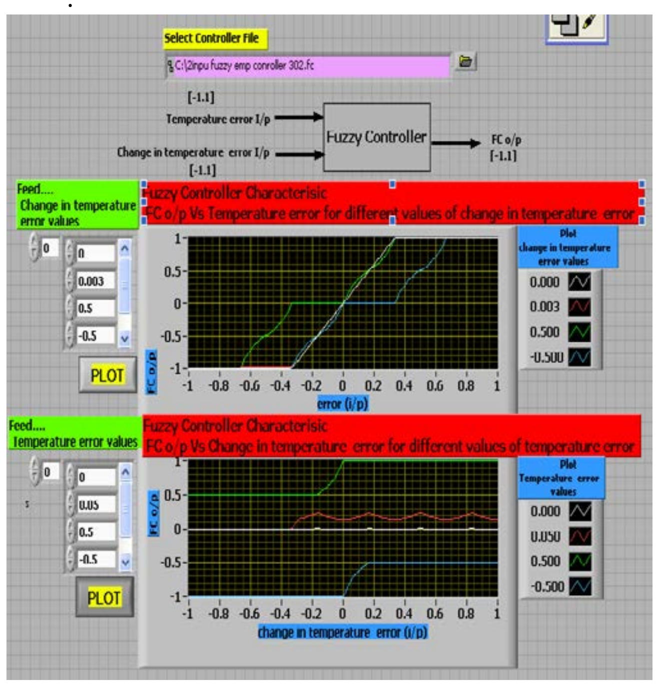

Fig 2. Fuzzy Controller multiple O\I characteristics .

The design of the controller is optimized to suit wide temperature range (-10°C to 80°C) and provide high accuracy performance with error of ±1% FSR

(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 actuating system for heating or cooling temperature. Simple ON\OFF control logic based on equation. 9 is employed to issue o\p control signals for cooler $(C_{Zi})_t$ and heater $(H_{Zi})_t$ of zone Z_i at the instant of time t in response to $(FO_{Zi})_t$.

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 $(H_{Zi})_t \downarrow$

The fuzzified digital o\p control signals are compatible with both MSAN using PC based wired data actuation systems or WSAN using wireless relay actuation on sensor nodes to power ON\OFF heating and cooling element .

III SYSTEM DEVELOMENT

Temperature control system for WSN is a graphically designed, software controlled PC based data acquisition and control system. The software integrates all the hardware components and defines its functionality and features [10]. The section below summaries the hardware requirements and software implementation to facilitate system integration.

A. HARDWARE

Fig.3 shows the general schematics of the hardware layout of the system. A host PC (Pentium III or higher, Win XP) is interfaced to distributed data acquisition wireless sensor network and established wired or new generation wireless control system, with each application zone having wireless nodes and heating and cooling system.

WSN is a typical Crossbow network consisting of number of nodes distributed in the area where temperature is to be controlled and a gateway node connected to host PC. Each node is a battery operated device with a mote (radio and processor board , IRIS\ MICAz\ MICA2) and sensor board (MDA300\ MTS 420\ MTS 400\ MTS320) embedded with a smart or thermistor based temperature sensor. Variation in temperature changes the ADC count that is encapsulated in the TOS message for transmission [15]. Nodes forming multihop mesh network, communicate their data packets to the gateway node PC [11] for further processing and information display by the application software.

In response to the real time temperature information, software controller generates control signals that are interfaced to actuation system to affect the process . Wired actuation system consists of PC based NI or third party DAQ cards or modules with multifunctional digital O\P and driver circuits to actuate relays to ON\OFF heating and cooling systems. In case of wireless actuation system, special wireless actuator nodes, part of WSN, are deployed in each zone. Downstream message packet wirelessly transmitted by the host PC, actuate relays on

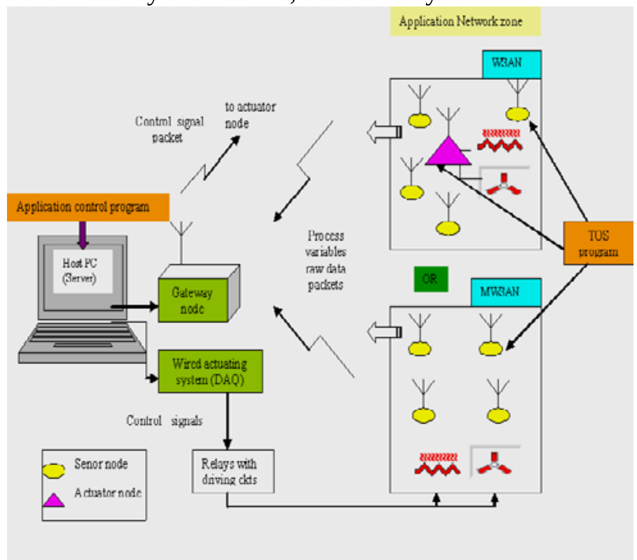

Fig.3 Hardware schematics of PC based WSN temperature control system

nodes to ON\OFF heating and cooling system connected to it.

B. SOFTWARE

Software has two parts, one is Node Program and other is Server Program. Node Program is Tiny Operative System (TOS) program, embedded in the nodes before deployment that define its functionality. 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 [9]. Application software running on host PC collects and deciphers packet information for analysis and display. Fig.4 shows the design functionality of the software that is programmed using graphical system design virtual instrumentation platform, provided by LabVIEW 8.5[17]. It has a multipanel, hierarchical design with the main front panel (GUI), 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 provides on line network connectivity to Crossbow mixed node wireless network and graphically shows the zonal view of the network with each node indicating best sampled temperature and voltage value. It represents zonal temperature and continuously plots its variation with time along with set point thus indicative of controller performance. It also provides alarm annunciation visually to indicate high temperature, low temperature and low voltage condition by changing node color and indicates heater and cooler ON\OFF status. It simultaneously log zonal

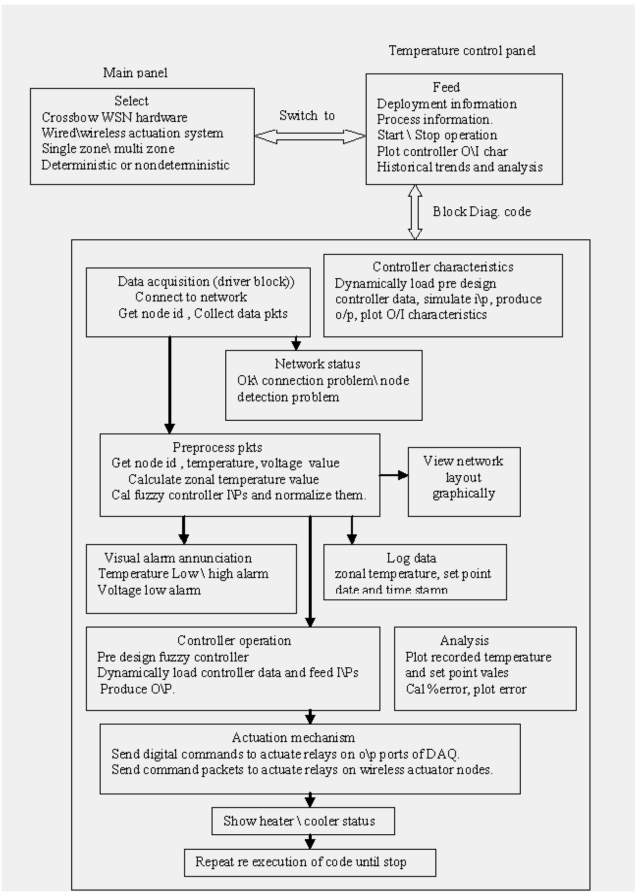

Fig.4 Flowchart of the application software indicating functional design.

temperature and set point values and provide various options to view historical trends of data for off line statistical analysis. It has an important feature to indicate network status thus warning user of network connection \ node detection problem. It also provides options to select network hardware nodes platforms (Iris \ Micaz motes using MTS 420\ MDA300\ MTS320 sensor boards or combination of these), single zone and multi zonal deterministic or nondeterministic deployment , wired (NI 6015 or 6221 control card) or wireless (MDA300 actuator nodes) control systems to switch to the corresponding GUI for temperature monitoring and control. It allows the user to feed and dynamically change temperature set point, range high and low temperature alarm values for zones \ s.

IV FIELD SETUP

Fig.5 shows the physical setup of MWSAN for monitoring and control of room temperature. The experimental hardware consists of host PC, interfaced to Crossbow wireless sensor nodes (Iris motes with MDA300 board distributed in the room) and USB based wired data actuation system using NI 6015 multifunctional data acquisition card, transistor based relay driving circuit and room heater (1KW) and fan, power actuated through relay (6VDC, 48ohm, elecromechanical

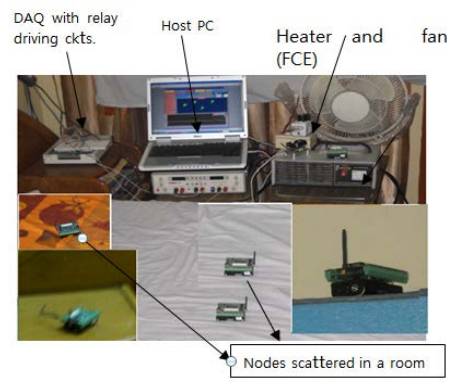

Fig 5 . Physical setup of MWSAN for room temperature control.

type). Software with GUI (described in section III), running on host PC controls the operation of the system for automatic temperature acquisition, analysis and control with execution of other intelligent features [9] [19].

A. RESULTS

When the hardware is powered ON and user feeds the related information on GUI (fig.6) and clicks the 'START' button, network connectivity is established and data packets collected by gateway node are interfaced to PC. The underlying application program displays the real time information. Network View shows zone with 5 nodes, each operating within normal temperature range and battery voltage (Green color), and indicating best sampled value of environmental local temperature. Temperature graph

depicts variation in zonal temperature to track set point (30°C). Presently temperature being less than the set point heater is ON, cooler is OFF and network status is OK with no packet drop out and connectivity problem. Simultaneously, zonal temperature, set point values are logged with date and time stamp for historical data viewing. In continuous running mode, information on the panel is updated at the sampling and transmitting rate of each node with the delay of 10s. 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.

V CONCLUSION

This general purpose fuzzy digital temperature control system is well suited for Crossbow mixed WSN real time applications deploying established wired or new generation wireless actuation system. Tested under various conditions, it is well designed, high performance system that offers temperature control with offset of ±1% FSR in a wide temperature range of 10C to 80°C and time lag of 10s. Moreover it drives the FCE with low duty cycle thus saving energy. Controller software with multiple, attractive features has well designed, easily operative GUI. It provides basic functionality of temperature monitoring and control with alarm annunciation, along with network status monitoring, low battery indication, options to select network hardware, deployment scopes and actuation system along with historical trend viewing and analysis. It also has a unique feature to plot controller characteristic, test and improve its performance for custom application.

Future scope involves, deployment of wireless actuation system for real time application, design and implementation of variable

power type fuzzy controller for wired actuation system as an alternative choice with an aim to save energy or designing a multi variable humidity based temperature fuzzy controller for further improvement in control behavior. Highly modular and flexible in design, controller performance can be enhanced easily to suit application needs

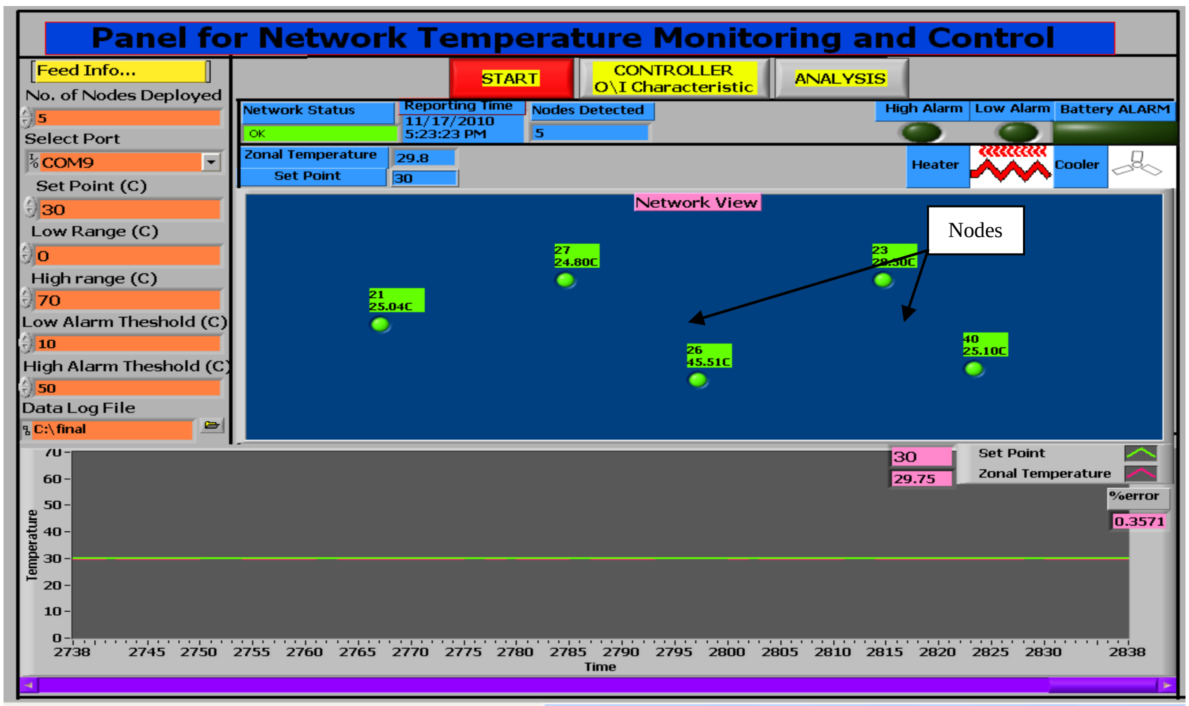

Fig 6. GUI showing results of real time network environmental temperature monitoring and control.

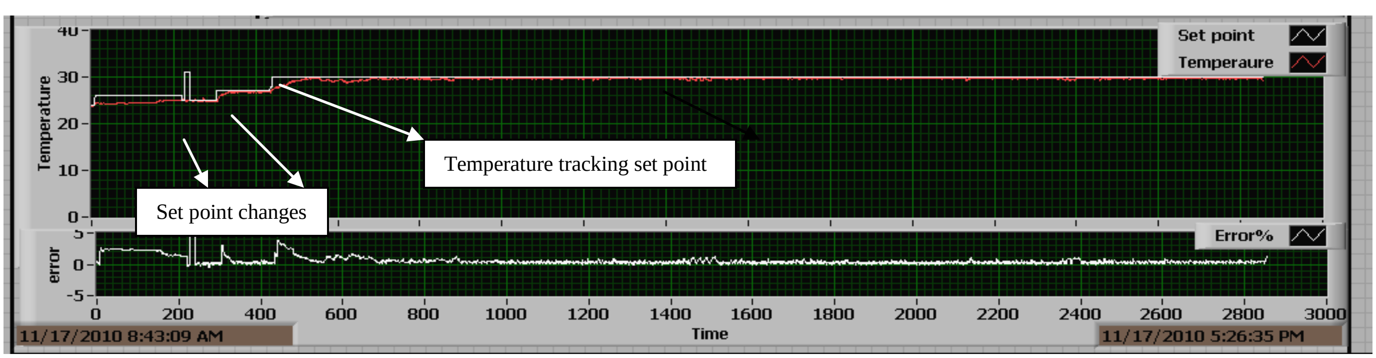

Fig.7 8 hrs of recorded data trends indicate precise temperature control with offset of ±1%FSR.

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