Design of Wireless Sensor Network based Fuzzy Logic Controller for a Cold Storage System

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Abstract - **In spite of India holding the second position in production of fruits and vegetables in the world, about one third of these are wasted in post-harvest. Major chunk of post-harvest losses are attributed to lack of proper cold storage and cold chain facilities. The quality and life of the commodities are determined by their storage conditions. Hence, designing an intelligent cold storage system turns out to be very much essential in order to mitigate the post-harvest wastage of the perishable commodities. This enables remunerative prices to the cultivators in addition to making the commodities available at competitive and affordable prices to the consumers. Based on the technical standards for control atmosphere cold stores temperature, humidity, CO_2 level and light intensity level are the essential parameters to be monitored and controlled for maintaining their quality and life. However, currently available cold storage systems in India do not consider controlling of all these essential parameters. With an intention to address this, a wireless sensor network based fuzzy logic controller for monitoring and controlling these essential parameters is proposed here.**

Keywords - cold storage system; wireless sensor network; fuzzy logic controller; temperature; relative humidity; matlab.

I. INTRODUCTION

The diverse agro-climatic conditions of India ensures large producibility of variety of fruits and vegetables. As per the statistical data provided by National Horticulture Board (NHB), during 2014-15 our country has produced 86.602 million metric tons of fruits and 169.478 million metric tons of vegetables. The vast production base in India creates tremendous export opportunities. During 2015-16 India exported fruits and vegetables of worth Rs.8391.41 crores out of which the contributions of fruits and vegetables were Rs.3524.5 crores and Rs.4866.91 crores respectively. Despite being the second largest producer in the world after China, per-capita availability of fruits and vegetables in India is rather less since 25-30% of the production gets deteriorated and lost in post-harvesting before reaching the hands of the consumers. Post-harvest losses result in high marketing costs, market gluts, price fluctuations and other similar problems. Deterioration of fruits and vegetables during storage depends largely on temperature.

Hence, to slow down the deterioration and to increase the storage time, the produce has to be stored at an appropriate level of low temperature, keeping in mind that if the temperature is too low the produce will be damaged and also the deterioration will be at faster rate once the produce leaves the cold storage system. Some moisture loss occurs during cold storage causing the dip in relative humidity of the cold storage system. But most produces require high relative humidity for longer storage time. Fruits and vegetables take in oxygen (O_2) and give out carbon dioxide (CO_2) during respiration. Lack of O_2 and build-up of CO_2 cause demise of produce when enclosed over long periods, thus necessitating the proper control of CO_2 level in a cold storage system. Also the concentration of CO_2 level along with light intensity is considered to affect the ripening process of fruits in turn affecting the longevity of storage time. Hence, controlling the essential parameters namely temperature, humidity, CO_2 level and light intensity becomes all the more important in increasing the storage time of produces inside the cold storage system [1-5].

Wireless Sensor Network (WSN) is a collection of autonomous sensor nodes deployed for real-time monitoring of different parameters in the human unattended environment. WSN consists of sensing unit, data acquisition unit, a micro-controller and Radio Frequency (RF) transceiver. The sensing unit consists of various sensing nodes which can be interconnected in different kinds of topology such as star, mesh or tree. These sensor nodes communicate to the cluster head which further communicates with the coordinator or the base station through RF transceiver. Each RF module is responsible for data transmission and reception of control signals to and from the coordinator. Application of WSN in agriculture, food supply chain management, smart home and health care are discussed [6-9].

Non-linear mapping of an input data set to a scalar output data is called as Fuzzy Logic System (FLS). Fuzzy Logic System consists of four main parts fuzzifier, rules, inference engine and defuzzifier. Fuzzy logic is a problem solving control system methodology used in numerous applications due to its inherent robustness, ability to mimic human control logic, use of imprecise language and ease of modification. Implementation of Fuzzy Based Predictive Cluster Head Selection Scheme for Wireless Sensor Networks are discussed [10-11]. Fire prediction system in cracker industry using fuzzy logic based wireless sensor network is discussed [12].

II. PROPOSED SYSTEM

As detailed in previous section, cold storage system (CS) requires continuous monitoring and control of its essential

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parameters namely temperature, humidity, CO_2 level and light intensity. Plenty of WSN based cold storage systems are proposed. Remote temperature monitoring in a cold storage system is proposed [13]. Temperature control using fuzzy logic is discussed [14]. However, these proposal consider only the temperature. Temperature and humidity control using fuzzy logic is proposed in various applications such as room temperature & humidity control system, air conditioning system and poultry breeding yet not for CS [15-17]. Controlling the temperature, humidity and light in autonomous environmental control system and food storage depot using ZigBee mesh networking is discussed [18-19]. However, the CO_2 level is ignored. Monitoring of all the essential parameters; temperature, humidity, light intensity and CO_2 level is discussed [20]. However, control of these is not addressed. Hence, the design of WSN based Fuzzy Logic Controller (FLC) for controlling the essential parameters of a cold storage system is projected.

The proposed system consisting of two major parts namely (i) Wireless sensor network that monitors all the essential parameters of the cold storage system and (ii) Fuzzy Logic Controller to control these parameters is detailed below.

2A. Cold Storage Monitoring

The commodities of identical storage conditions are assumed to be stored in a chamber or chambers. Hence, the WSN for monitoring the cold storage system involves few sensor nodes that are placed at different locations in the chamber and a Cluster Head to which all the sensor nodes communicate. The Cluster Head collects the data received from the sensor nodes and aggregates based on the parameter. The aggregated data is communicated to the base station as shown in Fig.1 for store keeping and tracking. Such arrangement is replicated for monitoring all the essential parameters in each chamber. For commodities requiring different storage conditions, multiple chambers with unique environmental conditions are suggested.

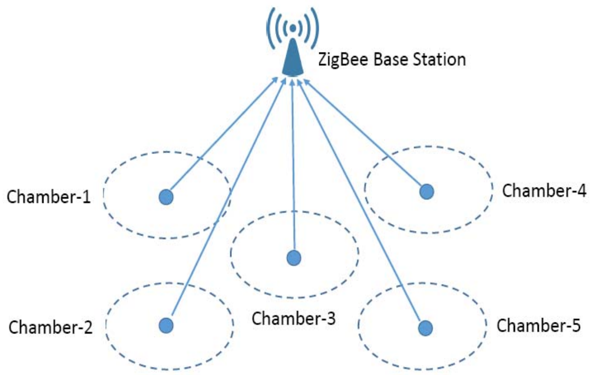

Fig.1 Network Topology

The block diagram of a typical sensor node shown in Fig.2 consists of a sensor and an RF module. The sensors placed at different locations inside the chamber monitor the respective parameters continuously and transmit the same to the cluster head through RF Module (ZigBee End Device) after conversion of analog signal to digital signal by Analog to Digital Converter (ADC).

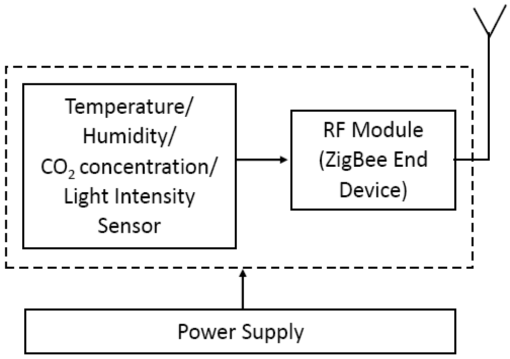

Fig.2 Block Diagram of a Typical Sensor Node

The block diagram of a cluster head shown in Fig.3 consists of an RF Module and a microcontroller.

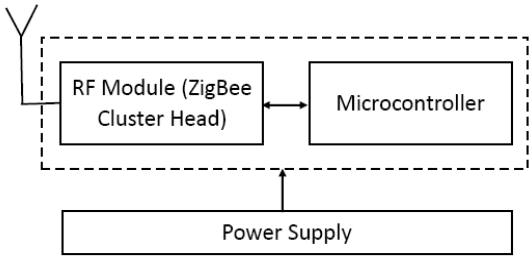

Fig.3 Block Diagram of a Cluster Head

The threshold limits for each parameter is pre-set in the microcontroller based on the storage conditions required for the commodity. The sensor values from different locations of the chamber are received by the RF module (ZigBee Cluster Head) and fed to the microcontroller for data aggregation. This aggregated data of the parameters is compared with their respective threshold limits in the microcontroller, which triggers data transmission from ZigBee Cluster Head to ZigBee Co-ordinator (connected to an FLC) for necessary control if the aggregated value is out of bounds of the threshold limits.

2B. Fuzzy Logic Controller

The block diagram of a ZigBee Co-ordinator connected to an FLC shown in Fig.4 consists of a RF module, FLC and Driver circuits for controlling the speeds of heat fan, cool fan, humidifier, dehumidifier, exhaust fan and the voltage of the luminance controller.

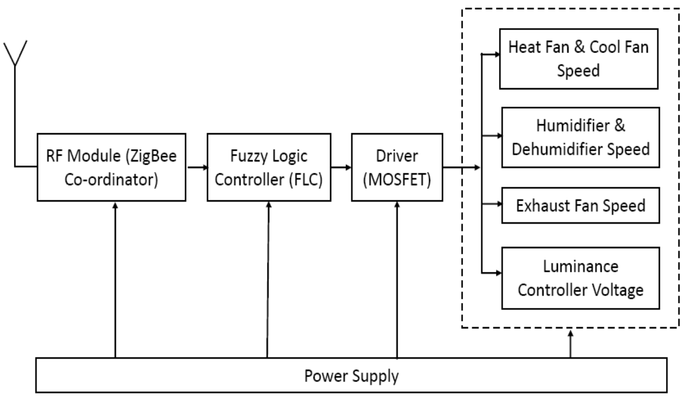

Fig.4 Block Diagram of the Co-ordinator with the FLC

The aggregated sensor value and error value received by the ZigBee co-ordinator from the ZigBee Cluster Head are fed as crisp inputs into the FLC. Based on the crisp inputs and Fuzzy Rule Base, through the process of fuzzification, inference engine and defuzzification, FLC provides a crisp output which controls the essential parameters by varying the duty cycle of the supply voltage applied to the control elements using MOSFET in Pulse Width Modulation (PWM) technique.

III. FUZZY LOGIC CONTROLLER DESIGN

NHB provides guidelines regarding the essential parameters of the cold storage system [1]. The Technical Standards Number NHB-CS-Type 02-2010 published by NHB, classifies fruits and vegetables into 7 distinct groups based on their storage condition compatibility as shown in Table I, which is used as a basis for designing the FLC for controlling the essential parameters of the cold storage system.

TABLE I. COMPATIBILITY GROUPS FOR STORAGE OF FRUITS AND VEGETABLES

Compatibility Group	Temperature	Relative Humidity
Group-I	0°C -2°C	90%-95%
Group-II	0°C -2°C	95%-100%
Group-III	0°C -2°C	65%-75%
Group-IV	4.5°C	90%-95%
Group-V	10°C	85%-90%
Group-VI	13°C -15°C	85%-90%
Group-VII	18°C -21°C	85%-90%

It can be derived from the above table that the suggested storage temperature of fruits and vegetables varies between 0°C and 21°C and the relative humidity varies between 65% and 100%.

The standard also suggests the maintenance of temperature range within ±1°C from the recommended storage temperature of the commodity being stored for increasing storage life. To achieve this, the threshold limits of temperature stored in cluster head are set as recommended temperature ±1°C. The FLC has been designed to operate between 0°C and 50°C.

For most of the groups in Table I, the difference between the recommended Relative Humidity (RH) ranges is 5%. Hence, the mean value can be taken as recommended %RH and the threshold limits of relative humidity can be set as recommended %RH ±2.5% in cluster head. The FLC has been designed to operate between 0%RH and 100%RH.

The maximum CO_2 level permissible in cold storage system as per the standard is 4000ppm and 2000ppm while loading and storage respectively. The CO_2 level present in atmospheric air is 400ppm which will increase further due to exhaled CO_2 from respiration of stored produce. Considering this, FLC is designed to operate between 400ppm and 4000ppm.

The lighting condition prescribed by the standard for cold storage system during storage is dark. On the other hand light is required during loading and unloading of the commodity. Also it is alleged that light treatment decrease the respiration rate of the fruit due to the utilization of CO_2 evolved from respiration by the green fruit in photosynthesis, thus controlling of light intensity in a cold storage chamber finds its significance. The possible extreme light intensity levels are mapped to a scale of 0% to 100% corresponding to extreme darkness and maximum possible brightness. The desirable light intensity level range is stored in cluster head as the threshold limit. Accordingly the MF ranges of FLC are defined to trigger the required control to maintain the desired light intensity levels.

The design of FLC schemes for the essential parameters of a cold storage system are elaborated below along with the MF ranges of input/output variables and Fuzzy Rule base (FRB).

3A. FLC Scheme for Temperature

Control scheme for the temperature of the cold storage system using fuzzy logic is shown in Fig.5. In this current temperature and deviation from set temperature are fed as crisp inputs to the FLC, which produces crisp outputs; heat fan speed and cool fan speed based on the FRB.

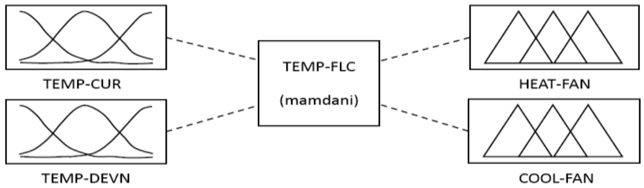

Fig.5 FLC scheme for Cold Storage Temperature

The MF ranges of input variables, output variables and sample FRB (due to space constraint) for temperature of the FLC shown in Table II, Table III and Table IV.

TABLE II. MF OF TEMPERATURE FLC INPUT VARIABLES

Input Variables	Term sets	MF Range
Current Temperature (°C)	COLD	[-8.5; 0; 8.5]
	COOL	[0; 8.5; 17]
	NORMAL	[8.5; 17; 25]
	WARM	[17; 25; 33]
	HOT	[25; 33; 41.5]
	VERY-HOT	[33; 41.5; 50]
	EXTRA-HOT	[41.5; 50; 58.5]
Deviation from Set Temperature (°C)	NE2	[-62.5; -50; -37.5]
	NE1	[-50; -37.5; -25]
	NL	[-37.5; -25; -12.5]
	NS	[-25; -12.5; 0]
	Z	[-12.5; 0; 10.5]
	PS	[0; 10.5; 21]
	PL	[10.5; 21; 31.5]

TABLE III. MF OF TEMPERATURE FLC OUTPUT VARIABLES

Output Variables	Term sets	MF Range
Heat Fan speed (%)	STOP	[-20; 0; 20]
	SLOW	[10; 50; 90]
	FAST	[70; 100; 130]
Cool Fan speed (%)	STOP	[-25; 0; 25]
	SLOW	[0; 25; 50]
	MEDIUM	[25; 50; 75]
	FAST	[50; 75; 100]
	VERY-FAST	[75; 100; 125]

TABLE IV. SAMPLE FRB FOR TEMPERATURE FLC (Total Rules: 33)

Current Temperature	Deviation from Set Temperature	Heat Fan Speed	Cool Fan Speed
COLD	NS	STOP	SLOW
COLD	Z	STOP	STOP
COLD	PS	SLOW	STOP
:	:	:	:
EXTR-HOT	NE1	STOP	FAST
EXTR-HOT	NL	STOP	MEDIUM
EXTR-HOT	NS	STOP	SLOW

3B. FLC Scheme for Relative Humidity

Control scheme for relative humidity using fuzzy logic is shown in Fig.6. In this current humidity and deviation from set humidity are fed as crisp inputs to the FLC, which produces crisp outputs humidifier speed and dehumidifier speed based on the FRB.

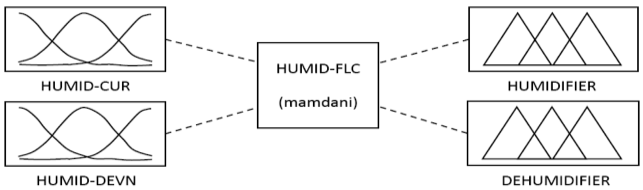

Fig.6 FLC scheme for Cold Storage Relative Humidity

The MF ranges of input variables, output variables and sample FRB (due to space constraint) for relative humidity of the FLC are shown in Table V, Table VI and Table VII.

TABLE V. MF OF HUMIDITY FLC INPUT VARIABLES

Input Variables	Term sets	MF Range
Current Humidity (%RH)	VERY-DRY	[-16.5; 0; 16.5]
	DRY	[0; 16.5; 33]
	SLIGHT-DRY	[16.5; 33; 50]
	NORMAL	[33; 50; 67]
	SLIGHT-WET	[50; 67; 83.5]
	WET	[67; 83.5; 100]
	VERY WET	[83.5; 100; 116.5]
Deviation from Set Humidity (%RH)	NL	[-52.5; -35; -17.5]
	NS	[-35; -17.5; 0]
	Z	[-17.5; 0; 25]
	PS	[0; 25; 50]
	PL	[25; 50; 75]
	PE1	[50; 75; 100]
	PE2	[75; 100; 125]

TABLE VI. MF OF HUMIDITY FLC OUTPUT VARIABLES

Output Variables	Term sets	MF Range
Humidifier Speed (%)	STOP	[-25; 0; 25]
	SLOW	[0; 25; 50]
	MEDIUM	[25; 50; 75]
	FAST	[50; 75; 100]
	VERY-FAST	[75; 100; 125]
Dehumidifier Speed (%)	STOP	[-20; 0; 20]
	SLOW	[10; 50; 90]
	FAST	[70; 100; 130]

TABLE VII. SAMPLE FRB FOR HUMIDITY FLC (Total Rules: 32)

Current Humidity	Deviation from Set Humidity	Humidifier Speed	Dehumidifier Speed
VERY-DRY	PS	SLOW	STOP
VERY-DRY	PL	MEDIUM	STOP
VERY-DRY	PE1	FAST	STOP
:	:	:	:
VERY-WET	NS	STOP	SLOW
VERY-WET	Z	STOP	STOP
VERY-WET	PS	SLOW	STOP

3C. FLC Scheme for CO_2 Level

Control scheme for CO_2 level using fuzzy logic is shown in Fig.7. In this current CO_2 level and deviation from desired CO_2 level are fed as crisp inputs to the FLC, which produces crisp output exhaust fan speed based on the FRB.

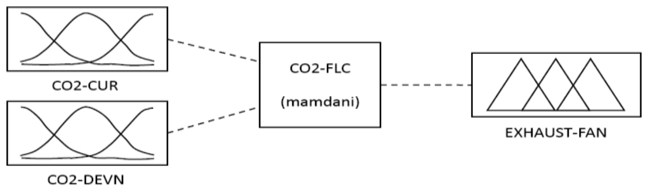

Fig.7 FLC scheme for Cold Storage CO_2 Level

The MF ranges of input variables, output variables and sample FRB (due to space constraint) for CO_2 level of the FLC are shown in Table VIII, Table IX and Table X.

TABLE VIII. MF OF CO_2 LEVEL FLC INPUT VARIABLES

Input Variables	Term sets	MF Range
Current CO_2 Level (ppm)	VERY-LOW	[-200; 400; 1000]
	LOW	[400; 1000; 1600]
	MID-LOW	[1000; 1600; 2200]
	MEDIUM	[1600; 2200; 2800]
	MID-HIGH	[2200; 2800; 3400]
	HIGH	[2800; 3400; 4000]
	VERY-HIGH	[3400; 4000; 4600]
Deviation from Desired CO_2 Level (ppm)	NE2	[-4500; -3600; -2700]
	NE1	[-3600; -2700; -1800]
	NL	[-2700; -1800; -900]
	NS	[-1800; -900; 0]
	Z	[-900; 0; 800]
	PS	[0; 800; 1600]
	PL	[800; 1600; 2400]

TABLE IX. MF OF CO_2 LEVEL FLC OUTPUT VARIABLE

Output Variables	Term sets	MF Range
Exhaust Fan Speed (%)	STOP	[-25; 0; 25]
	SLOW	[0; 25; 50]
	MEDIUM	[25; 50; 75]
	FAST	[50; 75; 100]
	VERY-FAST	[75; 100; 125]

TABLE X. SAMPLE FRB FOR CO_2 LEVEL FLC (Total rules: 33)

Current CO_2 Level	Deviation from Desired CO_2 Level	Exhaust Fan Speed
VERY-LOW	NS	SLOW
VERY-LOW	Z	STOP
VERY-LOW	PS	STOP
:	:	:
VERY-HIGH	NE1	FAST
VERY-HIGH	NL	MEDIUM
VERY-HIGH	NS	SLOW

3D. FLC Scheme for Light Intensity Level

Control scheme for light intensity level using fuzzy logic is shown in Fig.8. In this the current light intensity level and deviation from desired light intensity level are fed as crisp inputs to the FLC, which produces crisp output luminance controller voltage based on the FRB.

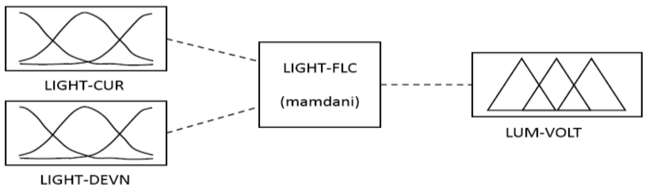

Fig.8 FLC scheme for Cold Storage Light Intensity Level

The MF ranges of input variables, output variables and sample FRB (due to space constraint) for light intensity level of the FLC are shown in Table XI, Table XII and Table XIII.

TABLE XI. MF OF LIGHT INTENSITY FLC INPUT VARIABLES

Input Variables	Term sets	MF Range
Current Light Intensity Level (%)	DARK	[-25; 0; 25]
	DIM	[0; 25; 50]
	MODERATE	[25; 50; 75]
	BRIGHT	[50; 75; 100]
	VERY-BRIGHT	[75; 100; 125]
Deviation from desired Light Intensity level (%)	NL	[-150; -100; -50]
	NS	[-100; -50; 0]
	Z	[-50; 0; 25]
	PS	[0; 25; 50]
	PL	[25; 50; 75]
	PE1	[50; 75; 100]
	PE2	[75; 100; 125]

TABLE XII. MF OF LIGHT INTENSITY FLC OUTPUT VARIABLE

Output Variable	Term sets	MF Range
Luminance Controller Voltage (%)	ZERO	[-25; 0; 25]
	VERY-LOW	[0; 25; 50]
	LOW	[25; 50; 75]
	MEDIUM	[50; 75; 100]
	HIGH	[75; 100; 125]

TABLE XIII. SAMPLE FRB FOR LIGHT INTENSITY FLC (Total rules: 27)

Current Light Intensity Level	Deviation from desired Light Intensity level	Luminance Controller Voltage
DARK	NS	ZERO
DARK	Z	ZERO
DARK	PS	VERY-LOW
:	:	:
VERY-BRIGHT	NS	ZERO
VERY-BRIGHT	Z	ZERO
VERY-BRIGHT	PS	VERY-LOW

IV. SIMULATION RESULTS

The FLC scheme is designed as per the design algorithms explained in previous section and simulated using MATLAB. The simulations were carried out for a particular commodity (Compatible Group-IV in Table I) with the following recommended value and current value(inside cold storage chamber) of essential parameters as shown in Table XIV.

TABLE XIV. RECOMMENDED AND CURRENT VALUES OF ESSENTIAL PARAMETERS FOR SIMULATION

Parameter	Recommended value	Current value
Temperature	4.5°C	40°C
Humidity	90-95%RH	40%RH
CO_2 Level	1400-1600ppm	4000ppm
Lighting condition	DARK(0-25%)	70%

The recommended values shown in Table XIV are stored as threshold limits in cluster head. When the aggregated sensor value of any parameter exceeds the recommended value, the corresponding FLC is triggered to provide the control signals required to maintain the recommended value. The simulation results of each FLC scheme for the conditions cited in Table XIV have been discussed further below.

4A. Cold Storage System Temperature FLC Scheme

Threshold limits for temperature are set as 3.5°C and 5.5°C in cluster head and the aggregate value of current temperature inside the cold storage system is 40°C. Hence the deviation is -35.5°C (4.5°C-40°C). With this current temperature and deviation as crisp inputs, FLC produces corresponding crisp outputs for heat fan speed and cool fan speed as 6.55% and 70% respectively as shown in Fig.9.

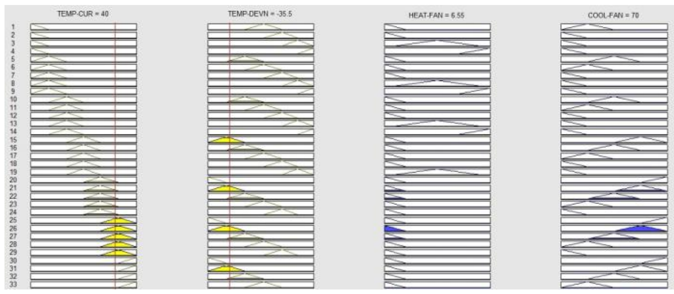

Fig.9 MATLAB rule viewer for simulation results of temperature FLC scheme

4B. Cold Storage System Humidity FLC Scheme

Threshold limits for relative humidity are set as 90%RH and 95%RH in cluster head and the aggregate value of current humidity inside the cold storage system is 40%RH. Hence the deviation is 52.5%RH(92.5%RH-40%RH). With this current humidity and deviation as crisp inputs, FLC produces corresponding crisp outputs for humidifier speed and dehumidifier speed as 53.9% and 7.2% respectively as shown in Fig.10.

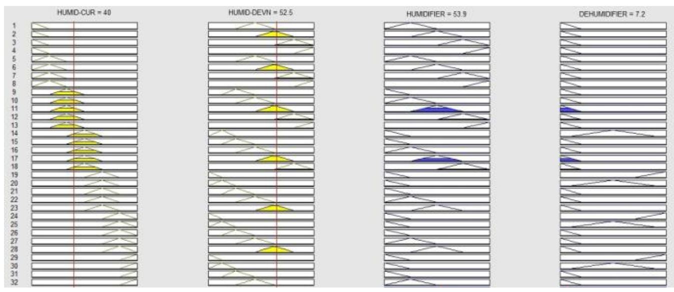

Fig.10 MATLAB rule viewer for simulation results of humidity FLC scheme

4C. Cold Storage System CO_2 Level FLC Scheme

Threshold limits for CO_2 level are set as 1400ppm and 1600ppm in cluster head and the aggregate value of current CO_2 level inside the cold storage system is 4000ppm. Hence the deviation is -2500ppm (1500ppm-4000ppm). With this current CO_2 level and deviation as crisp inputs, FLC produces the corresponding crisp output for exhaust fan speed as 68.4% as shown in Fig.11.

Fig.11 MATLAB rule viewer for simulation results of CO_2 level FLC scheme

4D. Cold Storage System Light Intensity Level FLC Scheme

Threshold limits for light intensity level are set as 0% and 25% in cluster head and the aggregate value of current light intensity level inside the cold storage system is 70%. Hence the deviation is -57.5%(12.5%-70%). With this current light intensity level and deviation as crisp inputs, FLC produces the corresponding crisp output for luminance controller voltage as 8.32% as shown in Fig.12.

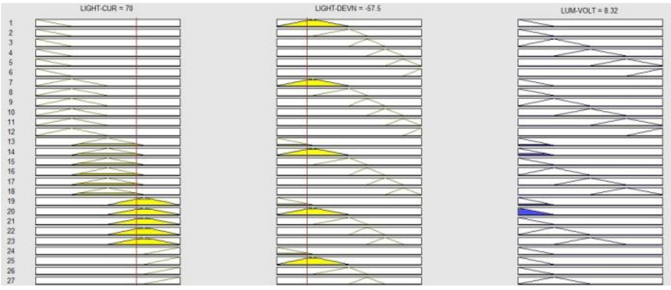

Fig.12 MATLAB rule viewer for simulation results of Light intensity level FLC scheme

V. CONCLUSION

Previous research works on cold storage system have focused on controlling only few of the essential parameters. Hence, an attempt has been made in this research work to design a WSN based FLC scheme for monitoring and controlling all the identified essential parameters of a cold storage system. The simulated results display the effectiveness of the fuzzy logic based controlling of cold storage system essential parameters. It controls the internal parameters of the cold storage chamber based on the recommended threshold values stored in the cluster head. This FLC has been designed to operate in wide range of temperature, humidity, CO_2 level and light intensity level thus making the cold storage chamber suitable for any compatible group of fruits and vegetables. As a further work, the proposed fuzzy logic controller can be realized in hardware. Also the proposed FLC scheme can be extended to monitor and control the essential parameters in multiple chambers of a cold storage system.

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