Wireless Temperature Sensor Using Bluetooth

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***Abstract*- Convenient and reliable temperature monitoring systems are increasingly demanded in vehicle refrigerators. However, difficulties exist in wiring between temperature recorders and sensors in vehicles such as trailer-tractor. To solve this problem, this paper provides a novel solution: wireless temperature sensors using Bluetooth. A prototype of the wireless temperature sensors has been developed. The technologies and mathematical models used are presented in this paper.**

KEYWORDS: Bluetooth, refrigerated vehicle, Stein-Hart Equation, wireless temperature sensor, Thermistor.

I. INTRODUCTION

In Europe, it is a mandatory requirement to keep records of the air temperature in vehicles used in the primary distribution of quick-frozen foodstuffs. Automatic air temperature monitoring equipment should be fitted to all refrigerated delivery vehicles [1]. Convenient and reliable temperature monitoring systems are increasingly demanded for vehicle refrigerators. However, difficulties exist in wiring between temperature recorders and sensors in the vehicle, for example in the case of trailer-tractor. To solve these problems, it is necessary to investigate the potential and possible technologies and strategies. A strategy using wireless sensor networks has been investigated by Shan *et. al.*[4]; likewise, technologies using thermistor and Bluetooth have also been investigated by Shan *et. al.* [4]. This paper gives particular emphasis to application of the mathematical model and the technology for wireless temperature sensors (WTS) to vehicle refrigerator.

II. MODELS AND TECHNOLOGIES

A. Stein-Hart Equation

Although there are many choices for temperature sensors, the thermistor is the best candidate for temperature measurements in refrigerated vehicle as it is cost effective and technology appropriate [4]. A thermistor is a type of electronic component whose principle characteristic is that its electrical resistance changes in response to the changes in temperature. The relationship between the resistance and temperature is non-linear. Although there are mathematical models available for establishing the non-linear relationship, for example the Exponential Model and Stein-Hart Equation, the mathematic approximation with the Stein-Hart Equation achieves greater accuracy in a large temperature range [12].

The Stein-Hart thermistor equation is derived from mathematical curve-fitting techniques and examination of the Resistance versus Temperature characteristic of thermistor devices. In particular, using the plot of the natural log of resistance value, ln(R) versus (1/T) for a thermistor component to consider (1/T) to be a polynomial in ln(R), an equation of the following form is developed:

$$\frac{1}{T} = A_0 + A_1(\ln(R)) + ... + A_N(\ln(R))^M \qquad (1)$$

Where T is the temperature in Kelvin, and $A_0, A_1 ... A_N$ are polynomial coefficients that are mathematical constants.

The order of the polynomial to be used to model the relationship between R and T depends on the accuracy of the model that is required and on the non-linearity of the relationship for a particular thermistor. It is generally accepted that use of a third order polynomial gives a very good correlation with measured data, and that the "squared" term is not significant. The equation then is reduced to a simpler form, and it is generally written as:

$$\frac{1}{T} = A + B(\ln(R)) + C(\ln(R))^3 \qquad (2)$$

Equation 2 where: A, B, and C are constant factors for the thermistor that is being modelled. This is the Steinhart-Hart equation, with Temperature as the main variable. The equation is presented explicitly in resistance. Some general points of relevance in understanding the practical issues associated with it are discussed. The equation is relevant for the complete, useful temperature range of a thermistor. The coefficients A, B, and C are constants for the individual thermistors. Unlike Alpha and Beta, they should not be regarded as material constants. The equation is considered for three temperature points in the range – usually at the low end, the middle and the high end. This ensures the best fit along the full range. (The smaller the temperature range, the better the calculations will match the measured data.) The temperature values are usually taken to be 0°C, 25 °C and 70 °C, therefore these values are used to illustrate the principle. It should be noted that the Stein-Hart equation produces a good approximation of the relationship between T and R for the complete range of a thermistor, based on data from just three calibration points.

B. Bluetooth

Wireless technology for WTS is proposed for low cost, low power, small size and communication over short distances in a refrigerated vehicle. ISM band communication technologies, such as infrared, Zigbee and Bluetooth, are of particular interest in these features. The conclusions from the investigation by Shan *et. al.*[4] were:

The drawback of infrared technology is the requirement of a line of sight between sender and receiver. This makes infrared a reluctant choice for the transmission medium in a sensor network scenario, particularly in refrigerated vehicles, because it is very easy for the transmission path to be blocked. Zigbee is an ideal technology for WTS, however, it is not yet available for real application, due to the relatively short time since the introduction of the Zigbee. Bluetooth has been used in a wide range and the technology is available in the market. These encourage us to introduce it to WTS for refrigerated vehicles.

Bluetooth is an open standard for short-range digital radio. It is designed to operate in the unlicensed ISM band. It has been developed to set-up 'Pico' networks. Bluetooth uses a master/slave-based MAC protocol and enables low power consumption and short-range wireless connection between various electronic devices. Bluetooth is intended to replace the cables connecting portable and/or fixed electronic devices. The technology also offers wireless access to LANs, PSTN, mobile phone networks and the Internet. Wireless Internet access using Bluetooth is becoming popular. Applications in accessing the Internet have been investigated in experiments by Kraemeer and Schwandeer [5] for indoor hot spots, and by Tan and Soh [6] for home control systems. A home automation system, using Bluetooth, has been experimentally built up with Sriskanthan *et al* [7]. Integration of Bluetooth and mobile products has been discussed in a study by Kirby [8]. It is already possible for Bluetooth to extend its application scope to 3G wireless communication systems. A strategic analysis of its role in the global 3G wireless communication era has been addressed in a study by Erasala and Yen [9]. The possibility of an industrial use for Bluetooth in data collection has been discussed in a study by Anderson [10]. Bluetooth using data transmission from inside vacuum chamber measurements [11] is an actual example of industrial usage.

III. PROTOTYPE

The prototype of WTS is designed for application to the area of refrigerated vehicles. WTS has functions of measurements of air temperatures of a vehicle refrigerator, A/D conversion, measurement calculations and wireless data transmission. The firmware and hardware for WTS have been developed in house. The following sections give details of WTS.

A. WTS hardware

WTS hardware consists of a microcontroller, Bluetooth module (BTM), thermistor and power supply, as shown in Fig.1. The thermistor measures air temperature in the vehicle's refrigerator. The microcontroller, with embedded software, does measurements and calculations. The microcontroller commands BTM activities, such as inquiry, connection and reset. The microcontroller manipulates the sensor data transmission to BTM. Then wireless data transmission is carried out by BTM.

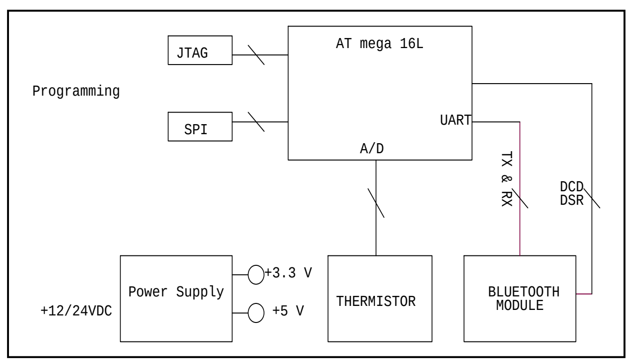

Fig. 1. Block diagram of WTS

B. Measurements

WTS circuit for measuring temperature is shown in Fig.2: RT: Thermistor, R: Standard resistor, Vref: Voltage reference. The WTS's accuracy depends on the accuracy of RT, R, Vref and Microcontroller ADC. Due to design parameters of Vref low enough and R big enough, the current *I* through thermistor is limited. Therefore, selfheating effects of thermistor are minimized so as not to significantly affect measurement accuracy.

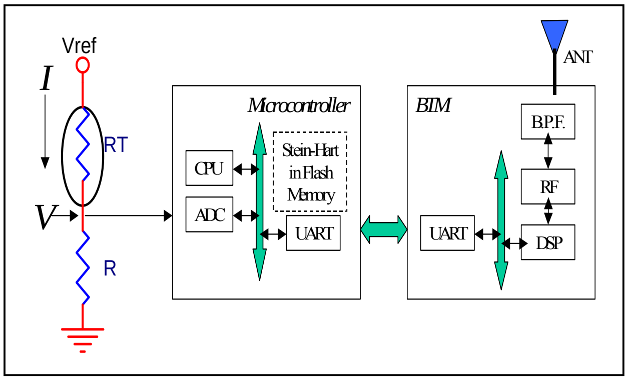

Fig. 2. Schematic diagram of WTS

The analogue voltage *V* on R is detected by the microcontroller. The microcontroller ADC converts the analogue datum to a digital one. The current *I* through RT is calculated by knowing the value of *V* and *R*. The resistance of RT is calculated by knowing Vref and *I*. The temperature is calculated by knowing RT resistance with the Stein-Hart equation. All calculations are implemented by software. The final calculated value, temperature, is sent to BTM through UART. Then the temperature datum is transmitted in RF through BTM.

C. WTS Software

The software working procedures are:

```
BEGIN
    Initialise microcontroller
    DO FOREVER
        IF BTM is not OK THEN
            Reset BTM
        ENDIF
        IF BTM is OK THEN
            Open Bluetooth activity
            Enable BTM inquiry and paging
        ENDIF
        IF Inquired by master BTM THEN
            Send sensor ID to Master
        ENDIF
        IF Paged by master BTM THEN
            Connect with master BTM
            Read sensor data (Volts)
            Calculate resistance with the sensor data
            Calculate temperature with Stein-Hart equation
            Send temperature value to BTM
        ENDIF
        IF dropped connection by master BTM THEN
            Reset BTM
            Reset System
        ENDIF
    END
END
```

IV. RESULTS AND DISCUSSION

A. Accuracy

The prototype of WTS has been tested. The test was carried out in a temperature measurement range of –44.5 to 49.8 ^{0}C. This range covers the operation temperature range of vehicle refrigerators. The test results are shown in Fig. 3. The maximum measurement errors are -0.36^{0}C. The resolution is 0. 05^{0}C. The accuracy and resolution are better than the requirements of CLASS 1 in BS EN 12830 Standard: maximum permissible error ±0.5 ^{0}C and resolution $\leq$ 0.5 ^{0}C [14].

The traditional method of converting thermistor resistance to temperature in an embedded system is to map data by a look-up data table that is stored in the flash memory of a microcontroller. There are two drawbacks in the method. One is too much memory usage to a resource limited in embedded systems. Another is that resolution is limited in a range of 0.1 to 0.5 ^{0}C. Otherwise it will significantly increase usage of memory because of the size of a look-up data table will increase if resolution is increased.

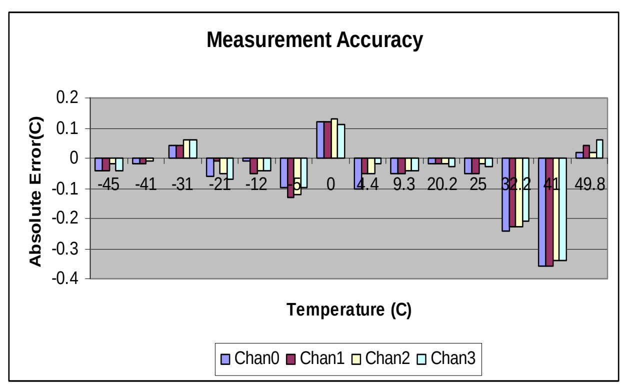

Fig.3. Temperature measurement accuracy with Stein-Hart Equation comparison to Exponential Model

The use of the Stain-Hart equation for conversion resistance to temperature has advantages; it does not need large extra memory space, does not limit the resolution of measurements (only limited by hardware) and gives good accuracy in a large range of temperatures.

The test of the prototype also proves that the wireless data transmission of WTS does not degrade temperature measurement accuracy.

B. Power consumption

The power consumption for a wireless temperature sensor is increased due to using BTM. The increased power consumptions are various, depending on BTM states. The power consumptions, along with BTM states, are shown in Table 1. The BTM works in slaver status. It is inquired and connected by Master BTM.

TABLE1
BTM Power Consumption

BTM Modes	Current (mA)	Description
No BT Activity	3.099	Require to open device for BT activity
Opened	3.114/17.948	Waiting for inquiry or connection
Inquired	65.128	Response to be inquired
Being Connected	32.905	During connection
Connected without DT/R	6.895	Connected without data transmission
Connected with DR	8.095--33.66	Receive data (9600Baud)
Connected with DT	8.65-24.65	Transmit data (9600Baud)

C. Range

The RF covering range of WTS is about 13 meters in radius within buildings (RF has to penetrate buildings). Within the range, BTM inquiry, connection and data transmission work properly. The cover range is ideal for refrigerated vehicles to have their own local wireless networks.

V CONCLUSION

The prototype of WTS developed in this study is feasible and accurate. The technology with Bluetooth and mathematical model with Stein-Hart Equation for WTS are appropriate. Although the power consumption increases for the temperature sensor by using Bluetooth, this increase is acceptable for a power source with vehicle battery.

There are four contributions in this work for monitoring temperatures of vehicle refrigerators; explorer in using Bluetooth, a novel prototype, improvement on accuracy and resolution of temperature measurements, reduction code size for an embedded system by using the Stein-Hart equation.

Future work is to further develop WTS in intelligences with self-calibration, self-validation and self-compensation.

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