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Sugeno Inference System for Estimating Non-linear Characteristics in Smart Sensor Applications

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Abstract: This work exploits Sugeno inference system in estimating the non-linear characteristics values closer to the physical quantities sensors measure. In general, the non-linearity of the sensor is modelled by fixing the input of the sensor to the membership function of the inference system and output response of the sensor to output constant of the inference system. In addition, the input membership function of the inference system is organized in a way that the middle arm of the first membership is vertically aligned to the left arm of the second membership and so for all of the membership functions. While the relationship of the input and output of the inference system thus the sensor is governed by the if-then-rules. The root-mean-square error of the overall developed system is relatively too small to be ignored in sensitive applications, signifying the closer fit to the actual physical quantity data. The minimal multiplication and addition to compute n number of membership functions is found to be n and 2×n respectively. The promising results offer the method to be applied in programmable smart sensor applications.

Keywords: curve-fitting, smart sensor, Sugeno Inference System

1. INTRODUCTION

In general, by nature's depending on the principle of operating almost all of sensors produce non-linear outputs. For instance, sensor which is depending on light will suffer from a degradation of intensity by square of the distance. In other words, the intensity is inversely proportional to the square of the distance from the source and in physics, this is stated as inverse-square law. Fig. 1 shows the response of an analogue voltage output and distance for sensor type GP2D120. It stays almost linear in short distance section, highly non-linear in middle distance section-both with high sensitivity. However, it becomes linear in long distance section with poor sensitivity.

In practical applications, due to the non-linearity characteristic of sensor, engineers have used number of hardware and software techniques to estimate the non-linearity of the sensor (Carstens, 1993). These techniques could in analogue form, in software or using ADC taking into account the nonlinearity. All are used for a direct and accurate measure of the physical quantities. Besides having the advantages, the additional hardware increases the overall system size while additional software increases memory and processing time of the system. For that reason, in some applications the non-linearity may not an issue, such as in water tap flow control, it does not need the installation of the hardware or software for non-linear estimating(Johnson, 1999).However, in some applications, the non-linearity issues will be of a great concern, for example, an error of even 1ºC in a boiler temperature could be detrimental. It is stated that, due to in ability on dealing of non-linearity of the sensor, in many applications, the capability of the analogue output sensor for example the GP2D120 is not fully exploited.(Khan *et. al*l, 2007).

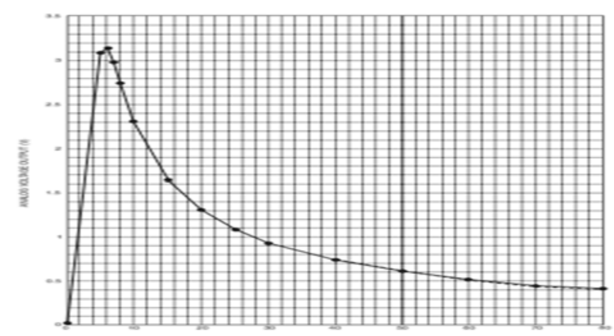

Fig 1: The output response of GP2D120

Fig-2 shows the block diagram of the smart sensor. A smart sensor-based system is able to sense and convert the physical or chemical quantity into the proportional measurable quantity. Pre-processes and temporarily stores the data; and relays the data whenever requested by end terminal (user).A piecewise segmentation technique is adapted, and an input circuit decides the response segment for trying to emulate very closely the nonlinear behaviour (Khan, *et al*., 2011) at the expense of circuit complexity. Resolution, sensitivity, accuracy and speed make the deciding parameters for specific application.

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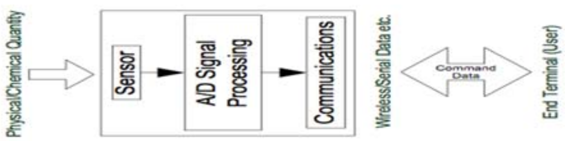

Fig. 2: The block diagram of smart sensor

The advancement in microelectronics has allowed the system to incorporate sensor, ADC, processing and communication units on-board a single chip (Pereira *et. al*., 2007). In this work, the communication unit is configured to work wirelessly using purposely developed serial technique called inter-integrated-chip (I^2C) standard. Consequently, the feature of smart sensor is thus implemented in none of the sub-blocks but its processing unit. The non-linearity issue is addressed in programming using the Sugeno Inference System (SIS).

2. THEORY AND BACKGROUND

2.1. Memory Mapped Technique

In general, memory mapped is the most popular technique in solving the non-linearity characteristic of sensor (Khan *et. al*l, 2007). In this technique the output of sensor, which is voltage of the GP2D12, for example, is used as a pointer to an array of data representing the distance. The corresponding data is arranged in the flash memory as shown in Fig. 3. In C programming the data can be defined and arranged as:

```
const data[n]={d0,d1,d2,d3……d(n-1)}
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For a byte of data and n-bit ADC, the number of memory spared for this technique is 2^n. Therefore, the technique requires $a x 2^n$to represent a, alphanumeric results for n-bit ADC.

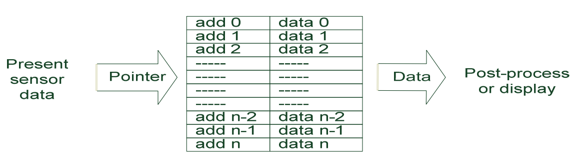

Fig.3: Arrangement of output data in the system

This technique though complex and error-prone, needs less processing time.

2.2 Piece-Wise Straight Line Technique

In a straight-line technique, the equation for each tangent line is derived. For example, the straight-line equation for segment shown in **(Fig-4)** can be written as:

$$d = \frac{v - c}{m} ==> v = md + c$$

Where

$$m = \frac{v_1 - v_2}{d_1 - d_2},$$

$$c = v_1 - m \times d_1$$

Fig. 4: Tangent line of two consecutive points on a response curve

Memory mapped technique is simpler and requires less memory. However, it requires n-1 expressions of given n-tangent data points to be implemented into program code.

2.2. Interpolation Technique

Similar to the straight line technique, in interpolation technique the equation for each tangent lines have to be deduced. By interpolation, the equation for tangent line in **(Fig-4)** can be written as:

$$d = d_0 + \frac{v - v_0}{v_1 - v_0} \times \left(d_1 - d_0\right)$$

As shown, less mathematic is required in interpolation technique thus it is expected to have less error compared to straight-line technique. (Khan *et. al*., 2007, Khan *et. al*. 2011).

2.3. Sugeno Inference System

The output expression of Sugeno Inference System (SIS) can be expressed:

$$y(t) = \frac{\sum_{i=1}^{n} k_i \times r_i}{\sum_{i=1}^{n} r_i} \rightarrow (i)$$

Where

***k_i* makes thei_{th}output constant**
***r* us rule i_{th}**
***n* is the number of membership-rules**

In the SIS, the output expression is the function of output constants divided by the sum of rules.If the SIS has 2 membership functions, m_1 and m_2, governing rules r_1 and r_2 respectively, equation (i) can be re-written as:

$$y(t) = \frac{k_1 \times r_1 + k_2 \times r_2}{r_1 + r_2} \rightarrow (ii)$$

By ensuring the membership functions are arranged in a way that the middle arm of m_1 is vertically aligned with left arm of m_2 and right arm of m_1 is vertically aligned with middle arm of m_2 as shown in **(Fig-5)**.

Fig-5 Input membership functions proposed

It is clear that at point of the membership function r_2 is equal to $1 - r_1$ or vice versa. Therefore, equation (ii), can be re-written and further reduced to:

$$y(t) = \frac{k_1 \times r_1 + k_2 \times (1 - r_1)}{r_1 + (1 - r_1)}$$

$$y(t) = k_2 + r_1 \times (k_1 - k_2) \rightarrow (iii)$$

Equation (iii) suggests that the output yields k_2 when r_1 is equal to 0 and yields to k_1 when r_1 is equal to 1. While at any other value of r_1, the output is expressed linearly by the equation (iii).It is observed that, provided the membership functions are arranged as in Fig. 5, the nonlinearity characteristic of the sensor can be estimated and mapped to its respective value in the table by using the Sugeno Inference System.

3. METHODOLOGY USED

In this section, the simulation of Sugeno Inference System in solving of the non-linearity of the sensor using Matlab® simulation package is discussed.

3.1. Setting of Input Membership Functions

The membership function of the SIS system is defined by using the output voltage of the sensor as given **(Table-1)**.

Table 1: GPD2D120 Distance and voltage relationship

Distance(cm)	Output (volt)
6.00	3.139
7.00	2.981
8.00	2.704
10.00	2.308
15.00	1.638
20.00	1.304
25.00	1.079
30.00	0.923
40.00	0.735
50.00	0.606
60.00	0.509
70.00	0.439
80.00	0.412

There are 13 membership functions formed by 2 trapezoid and 11 triangular membership functions. The membership functions are formed using **(Fig-6)**.

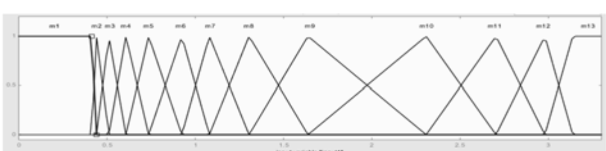

Fig-6 The input membership plots – Fuzzy Tools

Fig-7 shows eight membership functions. As shown the left, middle and right arms are set to 1.079, 1.304 and 1.838 respectively.

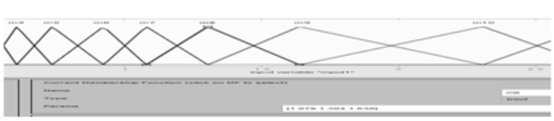

Fig-7 Example of setting the input membership function of m8

3.2. Setting of Output Constants

The membership function of output constant of the system is defined by using the measured distance of the sensor which data is in column 1 of **(Table-1)**. As shown in **(Fig-8)**, there are 13 membership functions of the output constant corresponding to total number of input membership functions.

Fig.8. Membership function plots of output constant– Fuzzy Tools

Fig-9 shows the fixing of the output membership functions mf1. The parameters are directly obtained from **(Table-1)**.

Fig-9 Example of setting the output membership function of mf1

3.3 Setting of Rules

As there are 13 input membership functions and output membership functions, the number of rules required for the system is also 13 as shown in **(Fig-10)**.

```
1. If (input1 is m1) then (output1 is mf1) (1)
2. If (input1 is m2) then (output1 is mf2) (1)
3. If (input1 is m3) then (output1 is mf3) (1)
4. If (input1 is m4) then (output1 is mf4) (1)
5. If (input1 is m5) then (output1 is mf5) (1)
6. If (input1 is m6) then (output1 is mf6) (1)
7. If (input1 is m7) then (output1 is mf7) (1)
8. If (input1 is m8) then (output1 is mf8) (1)
9. If (input1 is m9) then (output1 is mf9) (1)
10. If (input1 is m10) then (output1 is mf10) (1)
11. If (input1 is m11) then (output1 is mf11) (1)
12. If (input1 is m12) then (output1 is mf12) (1)
13. If (input1 is m13) then (output1 is mf13) (1)
```

Fig-8 The membership rules for the system – Fuzzy Tools

The system has 1 input variable and 1 output variable, thus for the linear fuzzy logic system the rule can be expressed as if input is x the output is y.

4. SIMULATION RESULTS

The simulation results of the system show that the SIS can be used to characterize the non-linearity of the sensor. From **(Fig-9)** it is proved that the system is able to evaluate the non-linearity characteristic of the sensor as the output of SIS lay on the middle of all real data.

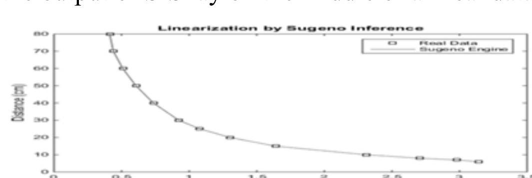

Fig-9 The plot of SIS output and real data.

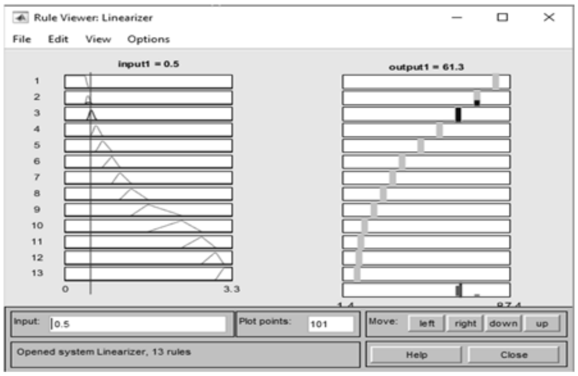

Fig-10 The distance versus voltage plots-Rule Viewer

By using the Rule Viewer, the system can be tested further. As is clear that by inputting 0.5 into the input drop box, the output is 61.3, which corresponds to the response of the sensor in **(Fig-11)**.

5. DISCUSSION

The Sugeno inference engine is used to estimate the non-linearity characteristic of the sensor, which shows a promising result. The simulation results show that by using the technique the non-linearity characteristic of the sensor can be estimated with an acceptable error. The sum-squared error given in **(Fig-11)** of the system is found to be 0.1940, which is similar to the sum-squared error of interpolation technique given in **(Fig- 12)**. Anyhow, the technique is much simpler to be implemented and modified. The technique requires only an array of data, which can be modified at a fly?

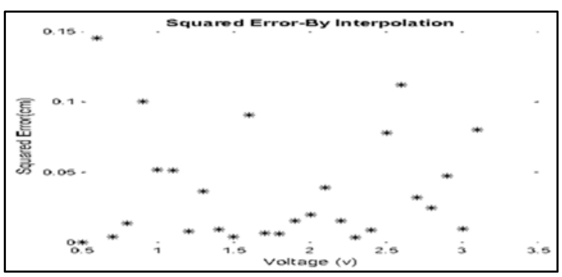

Fig-11 A sum-squared-error by Interpolation technique.

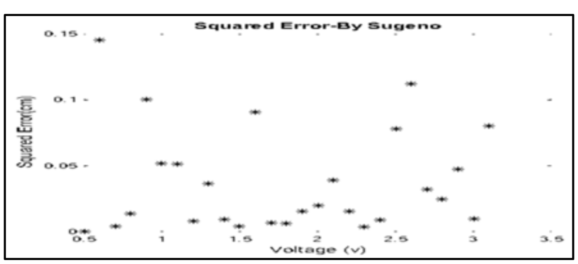

Fig-11 A sum-squared-error by SIS technique.

6. CONCLUSION

The non-linear characteristic of sensor is implemented in Sugeno inference system such it is read more accurately compared to other techniques. The non-linearity of the sensor is modelled by fixing the input of the sensor to the membership function of the inference system and output response of the sensor to output constant of the inference system. The input membership function of the inference system is organized in a way that the middle arm of the first membership is vertically aligned with the left arm of the second membership and so on for all of the membership functions. Surprisingly, the root-mean-square error of Sugeno, Straight line and Interpolation is relatively small to be 0.1940, too small to be ignored in some applications. This signifies how closer fit to data is obtained Anyhow, the straight line and interpolation techniques are prone to error, particularly rounding error. The minimal multiplication, addition to compute n number of membership functions is found to be n, and ***2xn***respectively. The simpler calculations lend the method to be used by a slower processor such as an 8-bit microcontroller..

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