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Design and development of a high precision thermocouple based smart industrial thermometer with on line linearisation and data logging feature

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ABSTRACT

Design and development of a high precision thermometer for industrial application is described in this paper. A class-1 grade K-type Thermocouple is considered for this purpose. The conditioned signal is linearised using a 9th order polynomial based on National Institute of Standards and Technology (NIST) data with the help of a 12-bit analog-to-digital converter and a 8-bit microcontroller. The cold junction compensation is achieved using a serial synchronous temperature to digital converter. The linearised data is transmitted for remote monitoring and logging via RS232C. The system is calibrated with 20 calibration point from 0 °C to 200 °C with a low cost calibration setup. The precision index of the system is also calculated.

1. Introduction

High precision thermometry is an essential component of any process control and lab applications. Variety of transducers are used for these purposes. Thermocouple (TC) is one of the highly reliable temperature sensors whose range of application is quite wide; from harsh industrial environment to cellular environment [1–4]. Other types like resistance temperature detector (RTD) require stable excitation source. Difficulties with TC in high precision applications are nonlinearity in response and its differential nature. Various ways are present to remove the nonlinearity like considering the response as piecewise linear, linearisation using electronic circuit, using look up table, use of artificial neural network etc. [3–10]. Size of the look up table increases with accuracy. Use of electronic circuit for linearisation may add temperature drift. It is difficult to implement ANN in lower end processor like 8051. Least square polynomial fitting method can be employed for linearisation. Here we have implemented this method. The linearisation is done in the system itself employing embedded processor. So though PC is used for data logging and monitoring, it can be used as a stand alone system with on line thermocouple linearisation. In smart sensor application the coefficients of the polynomial can be used in the data correction engine [11–13].

As the TC response is differential in nature so reference junction compensation must be done for getting absolute value. There are many ways to sense the reference junction like RTD, semiconductor junction diode etc. which require extra conditioning hardware [14,15]. By employing pre-calibrated temperature to digital converter we get rid of additional signal conditioning hardware which helps to reduce the effects due to Electromagnetic (EM) and Radio Frequency (RF) interferences.

Data acquisition systems are generally used for central monitoring. Temperature in the form of voltage or constant current loops is taken to these cards which are again affected by EM and RF interference in an industrial environment. This introduces high wiring cost also. To reduce it, the signal is processed locally with minimum length of sensor probes. The conditioning circuit is isolated from EMI and RFI by proper metallic shielding. The processed

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data i.e. the temperature corrected using polynomial and compensated by the TDC, in the digital form is sent to a central room for monitoring and storage using RS232.

The required firmware for embedded processor and software has been developed for performing the above tasks. The system is calibrated using a novel calibration setup.

2. Method of analysis

For the K-type TC the highest temperature extends up to 1372 °C. The maximum input for a common ADC with 12-bit resolution is 4095 mV. We have considered the range from 0 °C to 200 °C with a gain of the instrumentation amplifier set at 500 such that it lies within the range of the ADC. The TC used is of a class-I K-type, twin twist thermocouple (Make: Labfacility – CT-Z2-PFA-K-2) which has a temperature range of 0–220 °C.

The least square polynomial fitting algorithm is used to find the co-relation of temperature and amplified thermo-emf. For this the NIST data for K-type TC with a multiplying factor equal to the set gain of the instrumentation amplifier is considered [16]. There are systems which use the NIST coefficients for TC linearisation.

The value of the coefficients of the polynomial.

$Y = A + B1 * X + B2 * X{\wedge}2 + B3 * X{\wedge}3 + B4 * X{\wedge}4 + B5 * X{\wedge}5 + B6 * X{\wedge}6 + B7 * X{\wedge}7 + B8 * X{\wedge}8 + B9 * X{\wedge}9$; Y – temperature in °C and X – amplified thermoemf is shown in the Table 1 and the same for linear fit is shown in Table 2.

$$Y = a + bX$$

The temperature is recalculated from the polynomial as well as using the linear fit. The variation of error with actual temperature is observed (Fig. 1) using the polynomial fitting. It is found that maximum error in ninth order polynomial regression is ±0.02 °C, but in linear regression it is found to be +0.83 °C to −0.5 °C (Fig. 2).

Table 1
Value of the coefficients for 9th order polynomial fit for the range 0–200 °C.

Parameter	Value
A	0.00269
B1	0.05063
B2	−1.24656E−6
B3	−4.34493E−10
B4	9.39481E−13
B5	−6.8794E−16
B6	3.02726E−19
B7	−7.72974E−23
B8	1.04247E−26
B9	−5.76086E−31

Table 2
Value of the coefficients for linear fit for the range 0–200 °C.

Parameter	Value
a	0.27183
b	0.04887

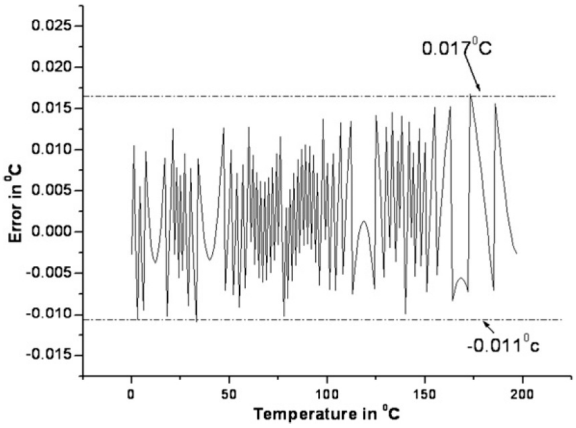


Fig. 1. Error curve for the range 0–200 °C with polynomial fitting.

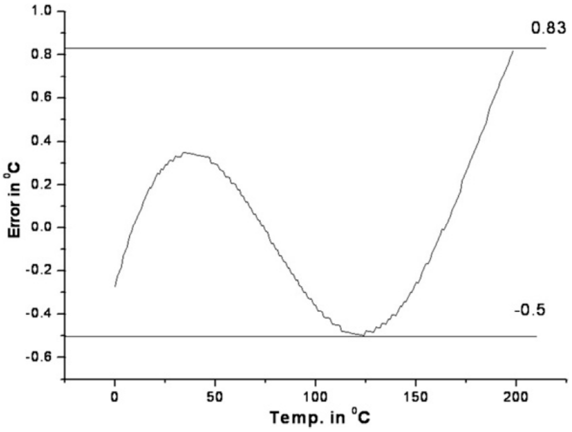


Fig. 2. Error curve for the range 0–200 °C with linear fitting.

3. System architecture

The basic block diagram of the system is shown in Fig. 3.

3.1. Analog part

The bath temperature is read by a K-type TC. The noises picked up by the TC are filtered with a low pass (10 Hz) filter. The circuit schematic is shown in Fig. 4. This signal is amplified with a gain of 500 by a variable gain instrumentation amplifier (U1) (INA110 from Texas Instruments) with high CMRR (106 dB). The gain of the instrumentation amplifier can be set at 10, 100, 200, and 500. This part is housed in a stainless steel box (size: length – 10 cm, breath – 6 cm, height – 3 cm, wall thickness – 0.08 cm) to shield the EMI and RF interferences at this high gain.

3.2. Reference junction compensation

For TC's reference junction temperature compensation different methods are used, viz, diode sensor [14], PT-100 [15] etc. In all these cases signal conditioning is necessary.

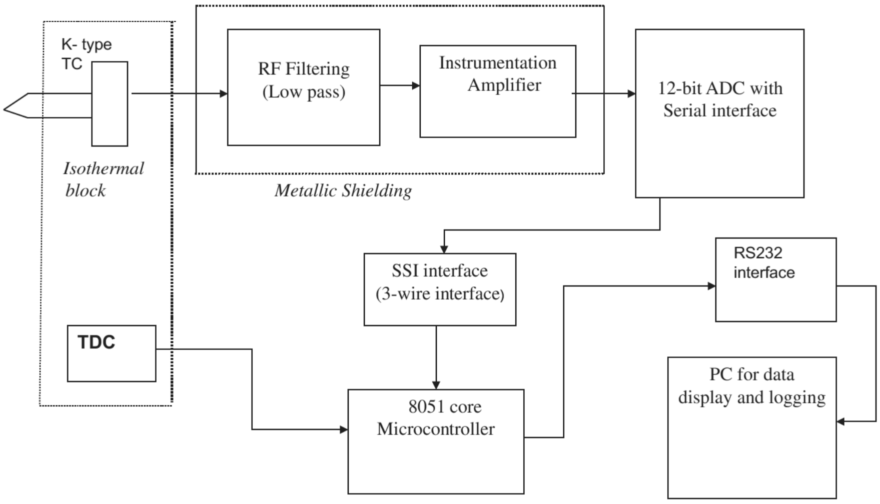


Fig. 3. Block diagram of the system.

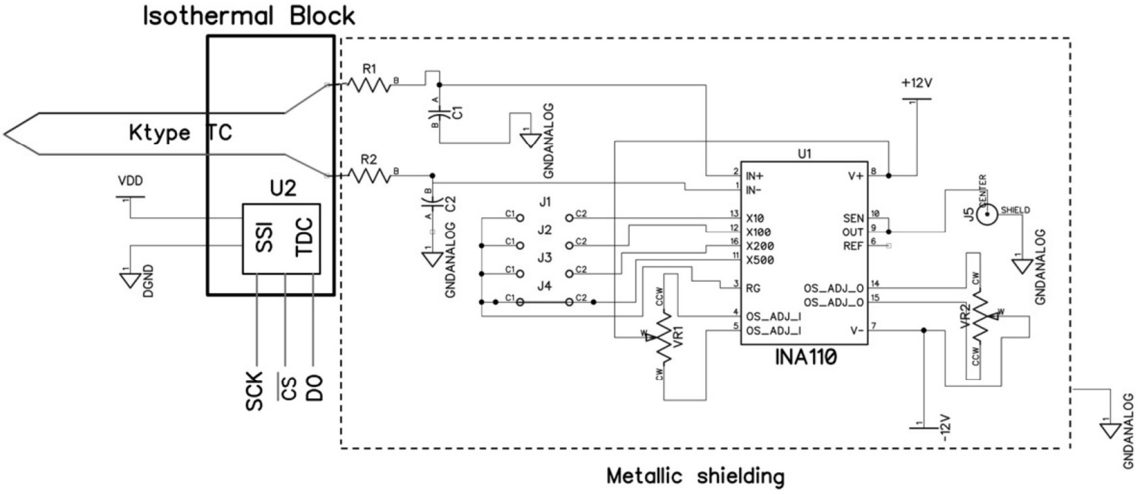


Fig. 4. Circuit schematic for analog part.

In the present case for reference junction temperature compensation a pre-calibrated temperature to digital converter is used which eliminates the necessity of taking into account the response of other detectors. The pre-calibrated temperature to digital converter (TDC) (U2) (TMP121, Texas Instruments, USA) which gives 14-bit resolution with the help of an internal sigma-delta ADC [16]. The communication with the microcontroller is achieved by its SSI interface.

3.3. Digital part

The schematic for the digital part is shown in Fig. 5. The amplified thermoemf is digitized by a serial interfaced 12-bit analog-to-digital converter (ADC) (U1) (ADS1286, Texas Instruments, USA). This is interfaced with an 8051 core microcontroller (AT89S52) (U2) with SSI interface. This serial ADC operates with no missing code, low power consumption (typically 250 μA) and occupies less board space (8 pin PDIP). The reference voltage of 4095 mV for the ADC is supplied from a floating gate reference device (U4) (X60003B, Intersil) [18]. Reading data and its processing is controlled by a firmware developed for this purpose. The firmware also sends the data serially to PC via RS232. MAX 232 (U3) is used for TTL to RS232 logic level translator.

The junction temperature is read from SSI interfaced temperature to digital converter. The temperature is given by T = (Temp. calculated from polynomial i.e. linearised temp.) + (Temp. of reference junction read from TMP121). Both parts are independently processed so this difference in temperature dependence will not cause any error.

Using the in built UART of the microcontroller the digital data is transmitted to the host PC via RS232.

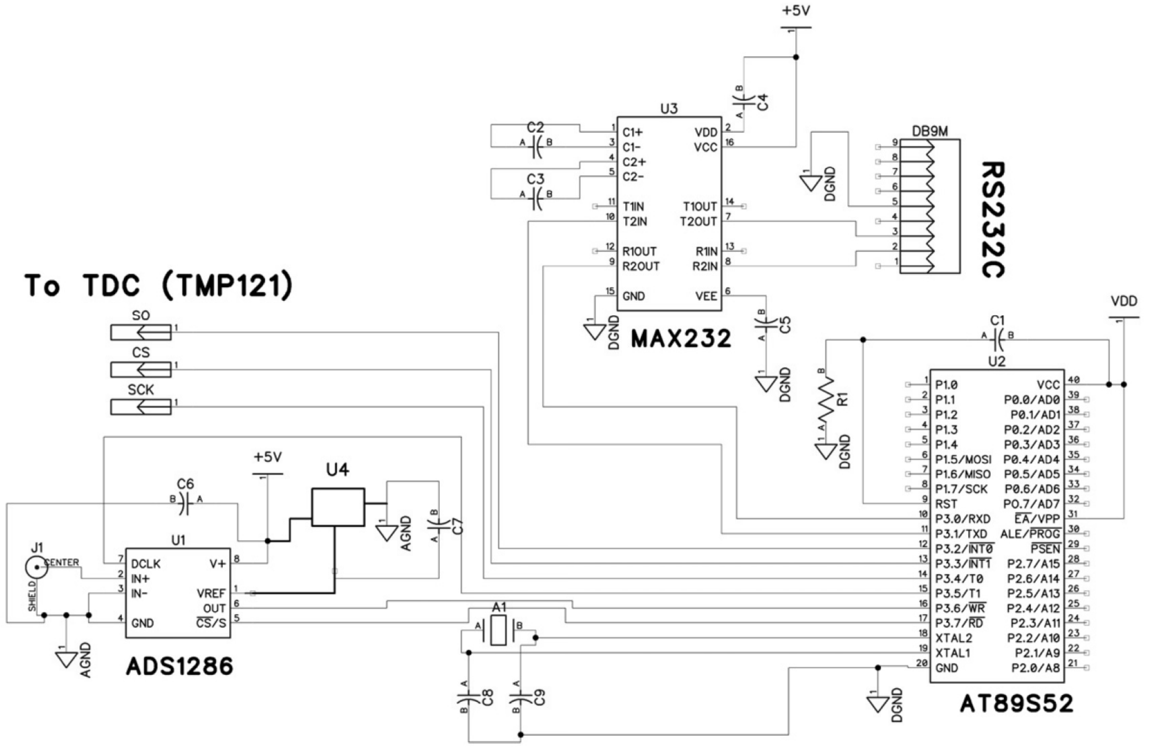


Fig. 5. Circuit schematic for digital part.

The function of the firmware developed for this purpose is described below:

i. initialize ADC,
ii. initialize built in UART of the microcontroller,
iii. read the ADC,
iv. convert it to corresponding temperature using the polynomial,
v. read the reference junction temperature,
vi. send the digital data corresponding to the corrected temperature by RS232.

3.4. Program for the host PC

The program in the host PC written in Visual Basic performs the following tasks:

i. Receive 4 bytes of digital data through COM port.
ii. Separates 2 bytes for junction temperature and 2 bytes for reference junction.
iii. The first two byte is converted to temperature with the help of the co-efficient of the required polynomial.
iv. Corrected temperature is calculated, displayed and stored onto the HDD.

4. Calibration

4.1. Method

The system is calibrated using a low cost setup as shown in Fig. 6. The variac is powered from stabilized AC outlet. To increase the stability of bath temperature thermal mass of the temperature bath is kept high. The thermoemf due to the temperature of the bath is measured simultaneously by a Digital Multimeter (DMM) and the system. Agilent U1252A in millivolt range is used to measure the thermoemf which gives a resolution of 1 μV for this range. The corresponding temperature from NIST data for K-type TC is taken. The reference junction temperature is measured with the help of the same TDC (TMP121, Texas Instruments). The error curve obtained from this calibration is shown Fig. 7. This is basically the calibration of the signal conditioning and digital part of the system. It can also be achieved by a stable microvolt source instead of the TC. But here TC is considered to see the effect of the noises picked up by the TC.

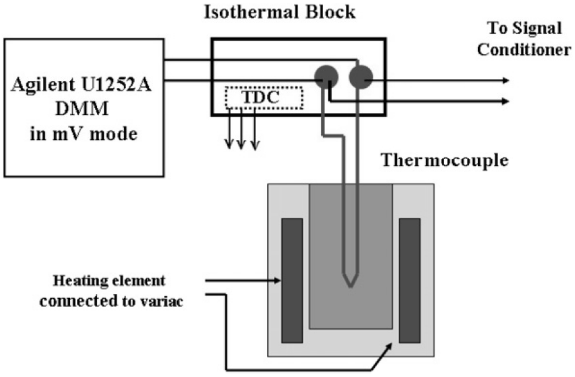


Fig. 6. Calibration setup.

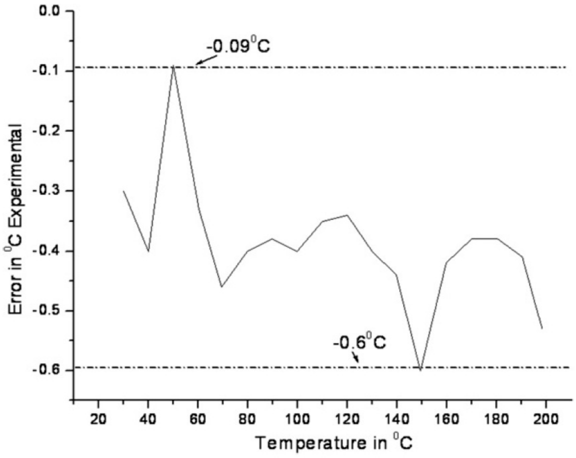


Fig. 7. Error curve (experimental).

The error is larger than the theoretical prediction. The sources of errors are mentioned below:

i. calibration error,
ii. accuracy limit of TDC (used for reference junction temperature measurement) which have maximum accuracy of 1.5 °C in this case.

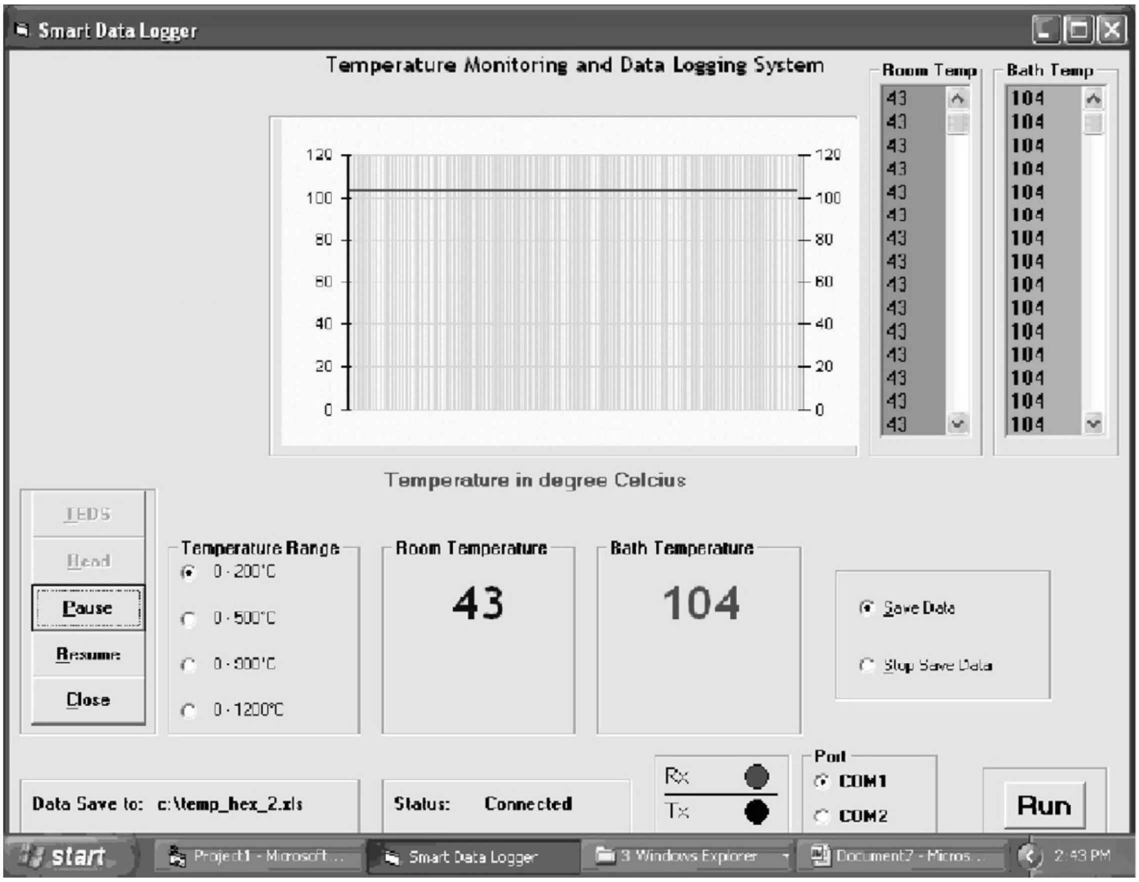
5. Precision of the system

The precision of the system is primarily determined by the precision of the instrumentation amplifier, the reference used for the A/D converter, and the junction temperature sensor. In this application the single chip instrumentation amplifier is made up of precision operational amplifier and LASER trimmed resistor [14]. The reference used for the A/D converter has long term stability with a factor 10 ppm/1000 h [18]. For measurement of the reference junction temperature, a temperature to digital converter is selected. This has an on chip diode temperature sensor interfaced with a delta-sigma A/D converter [17]. This is directly interfaced with the processor. It requires no external components for analog conditioning. The features of the components mentioned contribute to the precision of the system.

For measurement of precision index of the system, the bath temperature is kept at 100.2 °C [19]. A set of 20 readings are taken at constant bath temperature and unaltered ambient condition. The precision index is found to be ±0.08 °C at this temperature.

6. Field trial

The system has been installed for testing at Sonapur Tea Factory, Sonapur, Kamrup, Assam (India). The system is



Room Temp: 43 43 43 43 43 43 43 43 43 43 43 43 43 43 43

Bath Temp: 104 104 104 104 104 104 104 104 104 104 104 104 104 104 104

Temperature Range
● 0 - 200°C
○ 0 - 500°C
○ 0 - 900°C
○ 0 - 1200°C

Room Temperature: 43

Bath Temperature: 104

● Save Data
○ Stop Save Data

Data Save to: c:\temp_hex_2.xls

Status: Connected

Port
● COM1
○ COM2

Fig. 8. Screen shot of the GUI (time 30 min).

used to monitor continuously the inlet temperature of one dryer during its operation. The screenshot of the graphic user interface (GUI) for data logging and monitoring is shown in Fig. 8. Even under the industrial environment the performance of the system is found to be satisfactory.

The dryer is situated at a distance of 20 m from the control room. So RS232C communication works properly in this environment.

The horizontal axis represents the time. The bath temperature represents the dryer temperature. The room temperature is the surrounding temperature of the dryer. In the screenshot the room temperature is 43 °C and dryer temperature is 104 °C.

7. Conclusion

Co-efficients of the 9th order polynomial for amplified thermoemf with a gain 500 is calculated. From the error curves it is found that maximum error in ninth order polynomial regression is ±0.02 °C, but in linear regression it is found to be +0.83 °C to -0.5 °C . The method of polynomial fitting improves the accuracy of the system. Such a system has been successfully implemented in smart transducer interface module. This method can also be applied for other sensors with nonlinear characteristics.

Use of temperature to digital converter reduces errors arising out of difference of response between TC and reference junction compensation sensor. This also reduces the parts count like ADC, signal conditioning for reference junction compensation sensor and therefore reduces the cost. The accuracy of the TDC will limit the accuracy of the system.

The temperature correction using polynomial and the reference junction compensation is done online using the embedded firmware.

Taking 100.2 °C as true temperature, the precision index of the system is found to be ±0.08 °C.

The use of the serial ADC saves the power consumption. The system is operated successfully using RS232C communication.

The calibration setup discussed here is a simple one which can be easily assembled in a laboratory environment.

For reasonable code size the regression is restricted to 9th order. System may be made more precise using regression of higher order and high precision signal conditioner. For better accuracy a high accuracy TDC can be used.

The same method can be implemented for other range of temperature also.

As the system is a standalone one with serial communication interface, the system can be implemented for any kind of multidrop sensor network with slight modification on the firmware and serial interface hardware.

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