Thermostatic control of MEMS IMU using a Peltier Plate

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Abstract

In recent years, the micro-electro-mechanical-system(MEMS) IMUs (Inertial Measurement Units) have been widely used in UAVs(Unmanned Aerial Vehicles), UGVs(Unmanned Ground Vehicles) and Robotics due to their small size, light weight, low power consumption and low cost.

MEMS IMU contains 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, thermometer, etc. in a single microchip, but MEMS gyroscope's accuracy tends to be low, especially by temperature influence, and they generally require error compensation in practical applications.

Especially, the zero-bias is greatly changed by temperature variations.

Considering the simplification and real-time requirement, we present the hardware and software design methods for thermostatic control of MEMS IMU using a peltier plate.

Then the Neural Adaptive PID (Proportion Integration Differentiation) controller is used to stabilize the inner temperature of MEMS IMU enclosure by controlling the amount of heating and cooling of a peltier plate.

As shown in the experiment, the transient time is less than 3 min , the rising time is less than 5s/°C and the falling time is less than 10 s/°C so the property of the dynamic response in the thermostatic control system is improved much better than in other methods.

The overall cost is lower than 100$ and it is easy to implement hardware and software.

Thus this can be widely used in UAVs, UGVs and Robotics.

Keywords: thermostatic control, peltier plate, neural adaptive PID controller, MEMS IMU

1. Introduction

In recent years, MEMS IMU has been used as a kind of inertial device for measuring the acceleration and angular velocity for the motion of object.

As we know, MEMS IMU contains 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, thermometer, etc. in a single microchip. Thus it has the advantages of small size, light weight, low power consumption and low cost, and it is easy for digitization and implementation of the light inertial navigation systems.

However, the precision and stability of micro-gyroscopes are prone to be affected by its structure of material, manufacturing technology and other factors such as the temperatures of the ambient environment, which could cause the serious drawbacks of low precision and even errors [1-3].

Especially, the micro-gyroscope temperature effect is an important factor which causes temperature drift.

It is very important to improve precision of navigation system by improving precision and stability of micro-gyroscope through the compensation and control to reduce the temperature effects.

It is very important to develop the inertial navigation systems using Low-Cost MEMS IMU in a GPS-denided environments.

In order to accomplish these purposes, many researchers have widely used the methods which compensate mathematically after expressing the micro-gyroscope drift character as the function of temperature [1-5].

Golrokh Araghi and René Jr Landry presented that traditional temperature compensation methods which rely on polynomial regression method fail to take into account the nonlinearities inherent in the sensor errors [4].

They proposed a new temperature compensation model for a full inertial measurement unit (IMU), based on a radial basis function neural network that compensates the significant deterministic errors of both accelerometer and gyroscope triads in a wide temperature range.

A high precision turn table and a thermal chamber are used for accuracy testing.

The effectiveness of the method is proved through various static and dynamics tests in the laboratory and a car, and results are compared with the traditional polynomial fitting method.

TU Haifeng and LIU Li established the 1st order polynomial model of temperature, then suggested the method to identify the model parameters in real time using a forgetting factor recursive least squares estimator adopted [3].

The temperature compensation models calculated by these methods cannot be reused to compensate the temperature drift of the MEMS gyroscope, because of the poor repeatability of the temperature drift with the low cost MEMS digital sensor.

The temperature compensation parameters need to be recalculated every time, before using this model.

Recently, peltier plate developed and has been used for the design of temperature control systems, especially, at thermostatic control system design.

Peltier effect is the phenomena to generate or absorb the heat when the current flows throughout the junctions between different kinds of metal [6-13].

Peltier plate is based on this principle of thermoelectric phenomena.

Hazli Rafis proposed a DC-DC boost converter that employs an integrated circuit MAX757 which is a CMOS step-up DC-DC switching regulators for small, low input voltage[8].

This circuit can provide the environment although input voltage goes down to 0.7V, and generate high output voltage in the range from 2.7V to 5.5V.

The disadvantage is that volume of designed DC-DC boost converter is larger.

Dunzhu Xia and so on proposed temperature compensation-control methods to reduce the temperature effects on the micro-gyroscope and built the temperature model of MEMS gyroscope using BP (Back Propagation) neural network and polynomial fitting.

They analyzed the effect of temperature for resonant frequency of silicon gyroscope and found that the optimal working temperature for the micro-gyroscope is about 55 °C and then proposed the methods of temperature control equipment construction and PID controller design and proved its effectiveness through the experiment but it has the disadvantage of insufficient analysis in respect of control engineering.

Hanting Lu proposed temperature control method using peltier plate but has the disadvantage of limited usage due to double-power method [14].

Considering the simplicity and real-time requirement, in this paper, we present the hardware and software design methods for thermostatic control of MEMS IMU using one peltier plate.

The neural network PID controller is used for stabilizing the inner temperature of MEMS IMU enclosure by controlling a heating and cooling amount of a peltier plate.

The remainder of this paper is organized as follows: the overview of systems using a Peltier Plate and PID controller design is presented in Section 2. The design of software and hardware of thermostatic control system using a Peltier Plate is discussed in detail in Section 3. Experiment and results are provided in Section 4.

Finally, the conclusion are given in Section 5.

2. PID controller design

2.1. Overview of the Systems

Fig. 1 shows the overview of the control system.

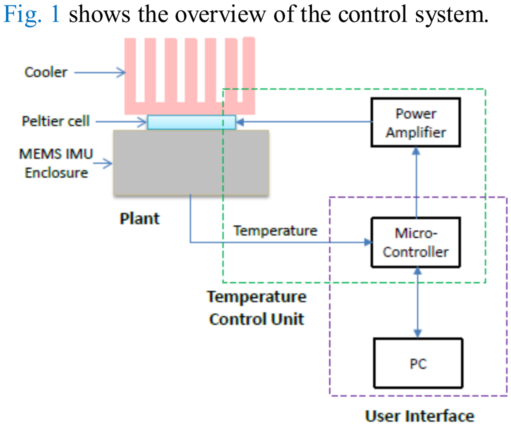

Fig. 1. Overview of the control systems

As the diagram shows, the device can be divided into three parts; temperature control unit, plant and user interface.

Here, the control plant represents the inner temperature of MEMS IMU enclosure made from aluminium.

We used MEMS IMU MPU9250 containing 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer and a thermometer, therefore it can measure the temperature itself.

This temperature measurement inputs to a microprocessor and compares with the required temperature value to attain the error value and then the control signal is generated to make error value zero.

Neural adaptive PID controller is chosen as a controller.

The control signal is inverted to PWM (Pulse-Width Modulation) and amplified for driving a peltier plate to heat and cool the MEMS IMU enclosure.

In cooling mode, cooler and fan are used to cool the heat generating from a peltier plate.

PC only displays the temperature control process and using MATLAB to analyze.

2.2. PID controller Design

2.2.1. Peltier plate

This section briefly introduces the principle of a typical modern peltier plate.

A peltier plate is based on the thermo-electric effect [14].

When a voltage is applied to it, it creates a temperature difference on each side of the device by Peltier effect and it corresponds to a voltage.

Heat is generated when an electric current flows from a cooler to a heater and absorbed in the reverse direction.

Fig. 2 shows the working principle of the peltier plate.

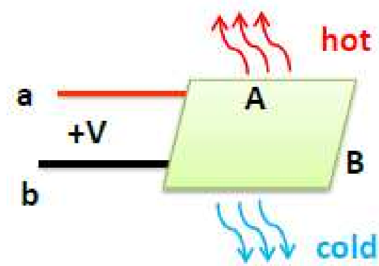

Fig. 2. Peltier plate working principle

When the voltage difference is positive between wire a and b, surface A will generate heat while surface B will absorb heat. However, when a negative voltage appears between wire a and b, and then the opposite effect occurs, therefore peltier plate serves as a good component for a thermostatic control system. One side is connected to a radiator and the other is connected to the object to control.

The heat absorbed on a cooling surface and generated on a heating side can be expressed as follows:

$$Q_c = \alpha T_c I_p - \frac{1}{2} R_p I_p^2 - K_p (T_h - T_c) \quad (1)$$

$$Q_h = \alpha T_h I_p + \frac{1}{2} R_p I_p^2 - K_p (T_h - T_c) \quad (2)$$

where I_p denotes the electric current. T_h and T_c denote the temperature of both sides, respectively.

α denotes the Seeback coefficient, R_p denotes the electrical resistance and K_p denotes the thermal conductivity.

In the next part, to achieve the thermostatic control using a peltier plate, we design a PID controller.

2.2.2. PID Controller

To make a correct mathematical model of the control plant, we suppose the following:

[Assumption] There is no heat loss into the ambient air.

First, the heat generating by the peltier plate is transferred on the top side of enclosure.

When Q_p and T_p denote the quantity of heat generated by a peltier plate and temperature respectively,

Q_{conj} and Q_f denote the emanating and absorbing quantity of heat of the above respectively and its temperature is denoted T_f, the following heat equilibrium equation can be obtained:

$$Q_p = Q_{conj} + Q_f \tag{3}$$

$$Q_f = 2\delta F\rho(T_p - T_f) \tag{4}$$

where 2δ is the thickness of the top surface, F is the square of the top surface and ρ is the density of aluminium.

Fig. 3 shows the heating and cooling process of the infinite plane.

In Fig. 3, t_0 is initial temperature and t_f is target temperature of the infinite plane, respectively.

The regulating temperature, ϑ_0 is $\vartheta_0 = t_0 - t_f$ if the infinite plane is heated else $\vartheta_0 = t_f - t_0$.

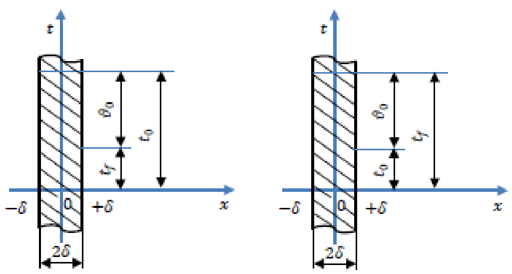

Fig. 3. Heating and cooling of the infinite plane

The purpose of our working is to stabilize the temperature of MEMS IMU by control the temperature of peltier plate, T_p, thus $\vartheta_0 = T_p$.

That is, T_p is controlling Quantity.

To simplify the consideration, we suppose $T_p = T_f$, that is, the quantity of heat is generated by the peltier plate, is the equal of the quantity of heat on the joint surface, thus the consideration of the heat balance equation can be divided into two parts as a thermal diffusion of the vertical section and the quantity of heat on the base side (MEMS installed side).

Therefore

$$Q_p = Q_{conj} = K_{al}(T_p - T_b) + K_{al}F\frac{\partial^2 T_p}{\partial x^2} \tag{5}$$

where Q_p is the quantity of heat generated by the peltier plate, Q_{conj} is the quantity of heat on the joint side of the peltier plate and its enclosure, K_{al} is the thermal capacity of the aluminium enclosure and F is the area of the enclosure bottom side

T_p and T_b denote the surface temperature of the peltier plate and the bottom of the enclosure, x is the distribution displacement of temperature according to the thickness of bottom surface.

We propose thermostatic control in this paper, namely, when an error occurs:

$$\frac{dT_p}{dt} = a\frac{\partial^2 T_p}{\partial x^2} \tag{6}$$

where a is the heat transfer coefficient.

Substituting Eq. (6) into Eq. (5), we can get the following result.

$$Q_p = K_{al}(T_p - T_b) + K_{al}\frac{F}{a}\frac{dT_p}{dt} \tag{7}$$

When the temperature of the MEMS installed side is measured, the following equation is obtained;

$$Q_p + K_{al}T_b = u = K_{al}\frac{F}{a}\frac{dT_p}{dt} + K_{al}T_p \tag{8}$$

Laplace's transformation for the Eq. (8) is:

$$U(s) = K_{al}(1 + \frac{F}{a}s)T_p(s)$$

$$\frac{T_p(s)}{U(s)} = \frac{1}{K_{al}(1 + \frac{F}{a}s)} \tag{9}$$

Eq. (9) can be transformed to the following equation:

$$W(s) = \frac{T_p(s)}{U(s)} = \frac{K}{Ts+1} \tag{10}$$

where T and K denote the time constant and transfer coefficient of the controlled object, it can be expressed as follows:

$$T = \frac{C_{al}}{K_{al}}, \quad K = \frac{1}{K_{al}}$$

As shown in the Eq. (10), the mathematical model of the control plant can be expressed as inertia element.

$$d_1 = 2\alpha$$

If we know the required transient time and overshoot in the system, we can obtain the poles.

$$t_s \approx \frac{3\sim 4}{\alpha}, \quad \sigma = e^{\frac{\alpha}{\beta}\pi} \times 100[\%]$$

As shown in above equation, t_s and σ denote required transient time and overshoot of the system, α and β are the real and imaginary parts of poles to obtain.

Therefore, the polynomial equation is represented as follows:

$$d(s) = s^2 + d_1 s + d_0$$

where d_0 and d_1 can be expressed as follows:

$$d_0 = \alpha^2 + \beta^2, \quad d_1 = 2\alpha$$

According to the pole placement approach, the coefficients of the PID controller can be obtained as follows:

$$K_P = \frac{Td_1 - 1}{K}, \quad K_I = \frac{Td_0}{K}$$

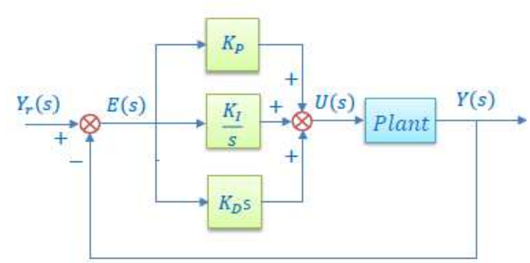

Fig. 4. The block diagram of the PID control system

But in complex control progress and time variant system, we can't regulate linearly the coefficients of this controller, therefore it affects the qualitative characteristic of the system in practical application. Moreover, the mathematical model of the temperature control plant mentioned in this paper, is represented as complex nonlinear model.

To overcome the following drawback, we suggest the software and hardware design method using the adaptation PID control method employing a neuron.

3. Design of software and hardeare

3.1. Design of software

Fig. 5 shows the configuration of adaptive PID control system using a neuron.

In that figure, an input of converter reflects both control process and control setting state.

Suppose $y_r(k)$ is set value and $y(k)$ is output value, after the transformation, input value of the neuron x_1, x_2, x_3 and etc are individually as follows:

$$x_1(t) = e(t)$$
$$x_2(t) = \int e(t)dt$$
$$x_3(k) = \frac{de(t)}{dt}$$
$$e(t) = y_r(t) - y(t)$$

Suppose $w_i(k)$ $(i = 1,\ 2,\ 3)$ is weight coefficient corresponding to input $x_i(k)$ and $K > 0$ is factor of proportionality of the neuron, nervous adaptive PID control algorithm is as follows:

$$u(t) = \sum_{i=1}^{3} w_i(t) x_i(t) \tag{11}$$

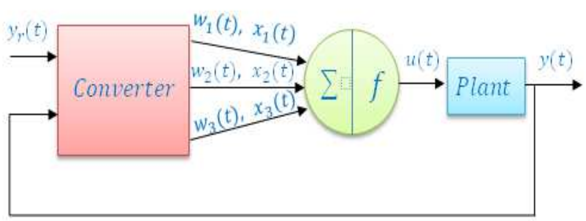

Fig. 5. Neuron Adaptive PID control system

Linear function is used as the activation function.

Generally, the weight updating of neural network is performed using the method adding the previous weight with present weight increment size.

The present weight increment size is determined by the product of learning step, learning signal and input signal.

Using this principle, weight coefficient is updated as follows:

$$\begin{aligned} \frac{dw_1(t)}{dt} &= w_1(t) + \eta_P e(t) x_1(t) \\ \frac{dw_2(t)}{dt} &= w_2(t) + \eta_I e(t) x_2(t) \\ \frac{dw_3(t)}{dt} &= w_3(t) + \eta_D e(t) x_3(t) \end{aligned} \tag{12}$$

In Eq. (12), η_I , η_P and η_D are integral, proportional and differential learning coefficient, respectively.

For high speed of convergence of learning, in Eq. (12) initial value of connection weight- w_1 , w_2 , w_3 are obtained by using the PID controller coefficient value designed for the model of linear control plant, Eq. (10).

Thus $w_1 = K_p$, $w_2 = K_I$ and $w_3 = K_D$.

This algorithm is performed using one-chip micro-processor(STM32F407V8).

Here, sampling period is 1s.

3.2. Design of hardware

TEC modules have the characteristic that operates in temperature range of -40℃ and +100℃ and they are sealed up with silicon to prevent the moisture.

In order to implement the thermostat of inertial measuring instrument, we put the sensor in the small box made from aluminium and hollow out some grooves from the surface of the box and then set the Peltier Cell(See Fig. 6).

We use MCPE1-03108NC-S as Peltier cooling cell and characteristic values of this cell are shown in detail in Table 1.

From Table 1, we know that Peltier Cell-MCPE1-03108NC-S has power source consumption of 32.3 W .Therefore current of 8.5 A is flown under 3.8 V of drive voltage.

Fig. 6. Setup diagram of peltier cell

Table 1. Characteristic value of MCPE1-03108NC-S

Parameter			Remark
Internal Resistance	0.35Ω ± 10%		At 25℃ Measuring with AC four terminal way
I_{max}	8.5 A		In ΔT_{max} I_{max}
V_{max}	3.8 V		In ΔT_{max} V_{max}
-	Th =27℃	Th =50℃	-
Q_{max}	27℃	50℃	In I_{max}, V_{max}, $\Delta T = 0$ Most cooling ability
ΔT_{max}	18.8 W	20.8 W	In I_{max}, V_{max}, $Q = 0$ W ΔT_{max}
Soldering melting point	235℃		Soldering melting point of thermoelectric module
P_{max}	1 Mpa		No breaking limit

Power amplifier is necessary to drive Peltier cell.

Internal resistance and V_{max} of selected Peltier cell is comparatively small but flowing current is high so we use MOS as output power drive cell.

And also we use drive cell-IR2110s to control the MOS.

Peltier cell requires the change of direction of voltage to absorb or release heat so we make control signal produce positive or negative signal.

In one-chip microprocessor, we calculate control algorithm based on difference between setting temperature and box's internal temperature with MEMS IMU inside.

And then through PWM1 port and PWM2 port, control signal with pulse width modulation flows out and thermostatic control by heating and cooling about TEC is implemented. The result is shown in Section 3, in detail.

Fig. 7 shows the designed output power drive circuit and Fig. 8 shows the total configuration of designed system.

4. Experiment and results

Let's determine the coefficient corresponding to Eq. (10).

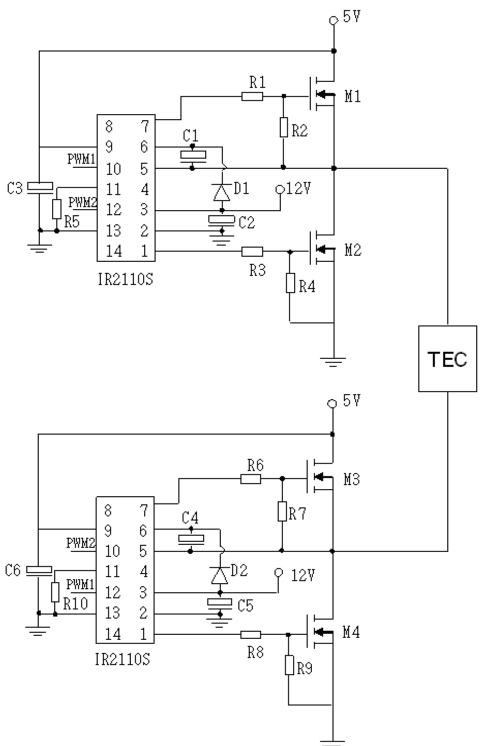

Fig. 7. Output power drive circuit

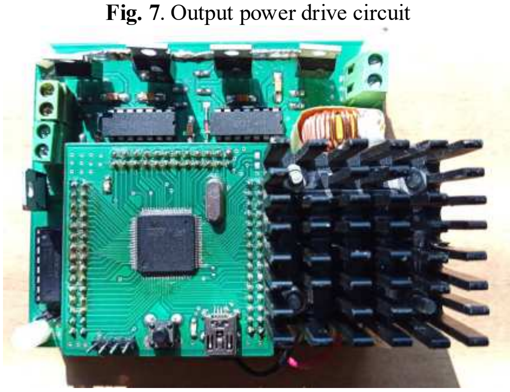

Fig. 8 .Thermostatic control unit of MEMS IMU

And then we calculate the thermal capacity of aluminium using the next equation.

$$K_{al} = m_{al} \cdot c_{al} = 0.025 \times 905 = 22.625\left[J/^{\circ}\mathrm{C}\right]$$

where, m_{al} is the mass of aluminium box and c_{al} is the specific heat of aluminium

$$m_{al} = 25[g] = 0.025[kg]$$

$$c_{al} = 905\left[\mathrm{J/Kg}\cdot^{\circ}\mathrm{C}\right]$$

We also calculate the diffusivity of heat of aluminium at 25°C based on data of Table 2.

$$a = \frac{\lambda}{c_p \rho} = \frac{237}{905 \cdot 2707} = 9.69 \cdot 10^{-5}\left[m^2/s\right]$$

Bottom plane is a square that length of one side is $3cm$ so its area is as follows:

$$F = 3cm \cdot 3cm = 9cm^2 = 9 \cdot 10^{-4} m^2$$

So the time constant and the transfer coefficient of the Plant (10) are as follows:

$$T = \frac{F}{a} = \frac{9 \cdot 10^{-4}}{9.69 \cdot 10^{-5}} \approx 9.3[1/s]$$

$$K = \frac{1}{K_{al}} = \frac{1}{22.675} = 0.044\left[^{\circ}C/J\right]$$

Table 2. Heat-physical characteristic of metallic material

Material Name	$\rho/$ $kg\cdot$ m^{-3}	$c_p/$ $J\cdot$ $kg^{-1}\cdot$ K^{-1}	$\lambda/W\cdot m^{-1}\cdot K^{-1}$ according to temperature			
			-100	0	25	100
Aluminium	2707	905	242	236	237	240

Finally, we can get the coefficient of PID regulator based on mathematical model of the plant and they are:

$$K_P = \frac{Td_1 - 1}{K}, K_I = \frac{Td_0}{K}$$

Design indexes are as follows:

Rise time: $5\,s/^{\circ}\mathrm{C}$

Fall time: $10\,s/^{\circ}\mathrm{C}$

MEMS IMU used in this experiment is MPU9250 IMU from Invensense Company-it has tri-axis accelerometer, tri-axis gyroscope and tri-axis magnetometer.

Through catalogue of the MPU9250 IMU, all the characteristics are determined under the condition of 25°C.

Thus, we determine the setting temperature as $y_r(k) = 25$ °C in the paper.

Fig. 9 shows the thermostatic control results.

In Fig. 9, the red line indicates the transient characteristic curve by neural adaptive PID control and the blue one indicates the transient characteristic curve with PI controller.

Through these figures, the designed thermostatic controller is satisfied with the requirement for system design.

5. Conclution

Using several Peltier plates, transient time can be reduced enough but it has some disadvantages in respect to power consumption, volume, cost and so on.

In the paper, we proposed the design method of thermostatic regulator for MEMS IMU using one Peltier plate.

We propose hardware design method to reduce temperature dependence deviation of MEMS IMU according to the temperature change and using the adaptive PID control with one neuron, we implemented the thermostatic controller.

Through the analysis experiment of temperature property in the static state, we proved the effectiveness of the proposed method.

PID controller using one neuron has high robustness due to the adaptive and learning ability against parameter and environment change for the plant.

In the paper, the transient time of the thermostatic control system is less than 3 minutes, and the overshoot is less than 5% so its dynamic response property is improved very much. Its cost is low, just 100$, and it is easy to implement hardware and software so it can be widely used for UAV, UGV, and robotics.

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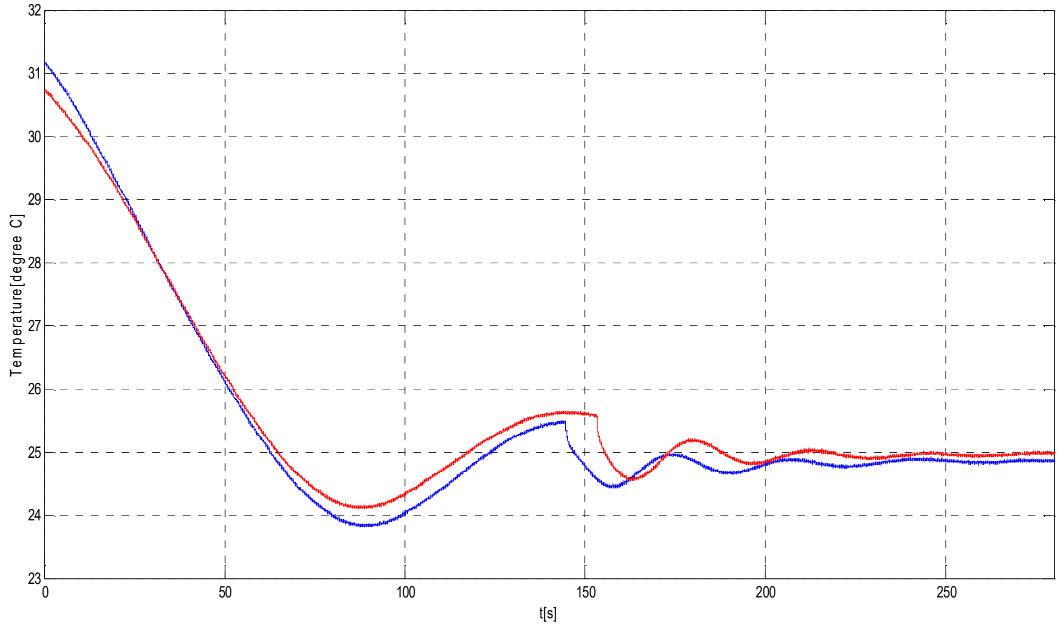

Fig. 9. Thermostatic control result of MEMS IMU