The development of PID temperature controllers based on FEM thermal analysis

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Abstract. Nowadays, most of the electronic components that are deployed in industrial devices represent active heat sources that demand adequate cooling solutions to ensure their safe and reliable operation. Thermal design and the development of temperature controllers represent the two essential branches of the cooling system development process. Both workflows can be tackled with the support of Computer Aided Engineering software. In this regard, the parametric study of coolers based on Finite Element Method thermal analysis is widely discussed throughout the literature. Even so, the use of such simulation tools for further developing temperature controllers is only addressed from theoretical point of views. The present paper represents an approach for implementing PID controllers that are applicable to industrial electronic devices. Tuning of the gains is completed by using the Ziegler-Nichols heuristic method. The proposed approach replaces the physical system with simplified thermal modelling. The given concepts are verified by means of a simple experimental setup.

1 Introduction

Industrial electronics and the proliferation of Embedded Systems play an essential role in the wide scale adoption of real-time manufacturing environments [1]. To fulfil the networking and computational demands of the forthcoming industrial revolution, the developers of computer control units rely extensively on complex electronic circuits (i.e. solutions based on Multi-Processor System on Chip) [2]. The synergy between hardware and software in the emerging industrial ecosystems brings into discussion arising thermal issues, such as increased power densities or the coexistence of localized hot spots [3]. From this perspective, the safe and reliable operation of the entire shop floor device is in a close relationship with the adequate thermal management of its active electronic components [4]. In this regard, the cooling system development process is employed in new or retrofitted computer control units in the early product life cycle stages [5]. The process comprises two engineering branches: thermal design and the development of temperature controllers [6, 7]. Both workflows demand extended knowledge in heat transfer and control engineering, being tackled with the support of diverging software and tools. A wide body of literature has been published in the past decades to address the underlying disciplines of cooling

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systems. From this point of view, simulations based on the Finite Element Method (FEM) are the most popular choice for evaluating thermal and fluid domains [8, 9]. Thus, the optimal heat sink configuration can be decided by means of parametric studies. On the other hand, the design and tuning of closed-loop feedback controllers is carried out most of the times by using numeric computing environments [10, 11]. In this way, the relationship of the cooling system output to its input heat is derived under the form of transfer functions, allowing a wide variety of control strategies to be evaluated prior to the physical implementation of the final solution. The first step in the formalization of the cooling system development process consists of lowering the software and engineering knowledge requirements. From this perspective, the present paper proposes a simplified approach for developing PID temperature controllers by re-using existing FEM thermal analysis models. In the first stage, the dimensionality of the problem is reduced to lower the computational costs of the transient thermal analysis. Unidirectional elements are deployed to replicate the behaviour of the proportional, integral and derivative terms based on user defined expressions. To facilitate parametric studies, the range of results is limited only to the output of the controller. Tuning of the gains is accomplished by using the Ziegler-Nichols heuristic procedure. This objective can be completed by bringing the system to neutral stability, considering the flexibility of users to adjust the process parameters without damaging the physical hardware. Altogether, the given concepts minimize the knowledge requirements for developing temperature controllers while maximizing the efficiency of the simulation procedures. The reminder of the work is organized as follows: section 1 described the theoretical considerations of the FEM PID controller development process with emphasize on the computational demands of the simulation models. The second section details the constitutive steps of the proposed approach. The third section of the work proves the given concepts by means of a simple experimental setup comprising a resistor – heat sink model. Finally, the conclusions are included in section four.

2 FEM PID temperature controllers

PID temperature controllers represent closed-loop feedback systems that operate alongside active cooling components (i.e. fans or blowers) for maintaining the thermal behaviour of the heat sources (i.e. transistors or CPUs) close to a set point value. This is achieved by continuously calculating the difference between the desired temperature and the actual one. The resulting signal is fed to the PID controller. From here, the derivative and the integral terms of the error are calculated with respect to time. An actuating signal is generated for dynamically adjusting the parameters of the cooling system (Figure 1).

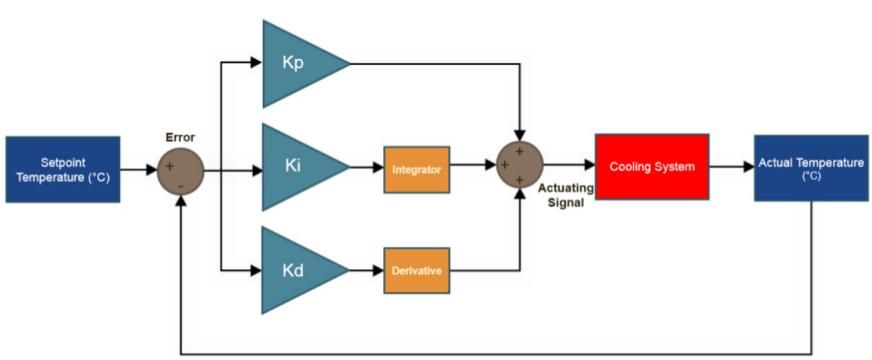


Fig. 1. The general structure of a PID temperature controller.

The first stage of the FEM PID controller implementation process consists of developing a lumped-parameter description of the actual system in conjunction with the first order system equations that govern FEM thermal analysis [12]:

$$[C]\{\dot{T}\}+[K]\{T\}=\{Q^a\} \tag{1}$$

Where: C represents the specific heat matrix, K the conductivity matrix, T the vector of nodal temperatures and Q^a the applied heat flow vector. The procedure for solving equation 1 is the generalized trapezoidal rule:

$$\{T_{n+1}\}=\{T_n\}+(1-\theta)\Delta t\{\dot{T}_n\}+\theta\Delta t\{\dot{T}_{n+1}\} \tag{2}$$

Where: θ represents a transient integration parameter, Δt = tn+1-tn, T_n the nodal temperature at a given time step. Because most transient thermal simulations are non-linear, the Newton-Raphson procedure is deployed for solving the resulting equations:

$$[K_i^T]\{\Delta T_i\}=\{Q^a\}-\{Q_i^{nr}\} \tag{3}$$

The output of a PID temperature controller is calculated in the time domain from the error term as [13]:

$$u(t)=K_p e(t)+K_i\int e(t)dt+K_d\frac{de}{dt} \tag{4}$$

Equation 4 represents the overall control function, where K_p, K_i and K_d resemble the proportional, integral and derivative gains. An analogy can be made between the physical parameters of a PID controller and their lumped-parameter equivalent based on the equations depicted above (table 1).

Table 1. Analogy between physical and lumped-parameter control variables.

Parameter Name	**Physical Controller**	**Unit of measurement**	**Lumped-Parameter Equivalent**	**Unit of measurement**
Set Point	Reference Voltage	mV	Reference Temperature	°C
Process Variable	Voltage Drop	mV	Nodal Temperature	°C
Control Variable	PWM Signal	-	Heat Removal / Generation	W

Table 1 depicts the controller parameters for a simple case thermal design solution comprising an active electronic component and a cooling fan. In this case, the error term is calculated based on the difference between the reference voltage (mV) and the voltage drop that occurs across a thermistor. This resistor is attached to the heat source, being used to measure its temperature during the operation of the device. Based on the PID gains, a Pulse Width Modulation (PWM) signal dynamically adjusts the speed of the cooling fan. The same system approximated by means of Lumped-Parameter modelling makes use of the nodal temperatures (°C) calculated by the FEM solver as process variable. The value is compared with a reference one. Positive term heat generation (W) takes place as control signal to replicate the behaviour of the forced convection cooling system.

Having the analogy between the physical and the lumped-parameter variables defined, the FEM PID controller can be implemented with the support of solvers subroutines that adjust the state of the transient analysis at each substep based on the output heat of the controller.

The advantage of FEM PID controllers is emphasized by the replacement of the physical hardware with a lumped-parameter simulation environment. From this perspective, a high level of formalization is achieved. Even so, the major drawback of such controllers is the iterative solving process involved in equation 3, the computational demands of transient thermal simulations being proportional to the size of the model and the applied time step. The coexistence of solver subroutines will further increase this complexity considering the extra equilibrium iterations required. From this perspective, additional simplification strategies are required to make the use of such controllers effective in practice.

3 The proposed methodology

The proposed methodology consists of 5 stages that aim developing a formalized simulation environment for prototyping, testing and implementing PID temperature controllers. A schematic representation of the proposed approach is depicted in Figure 2, followed by a detailed description of its constitutive blocks.

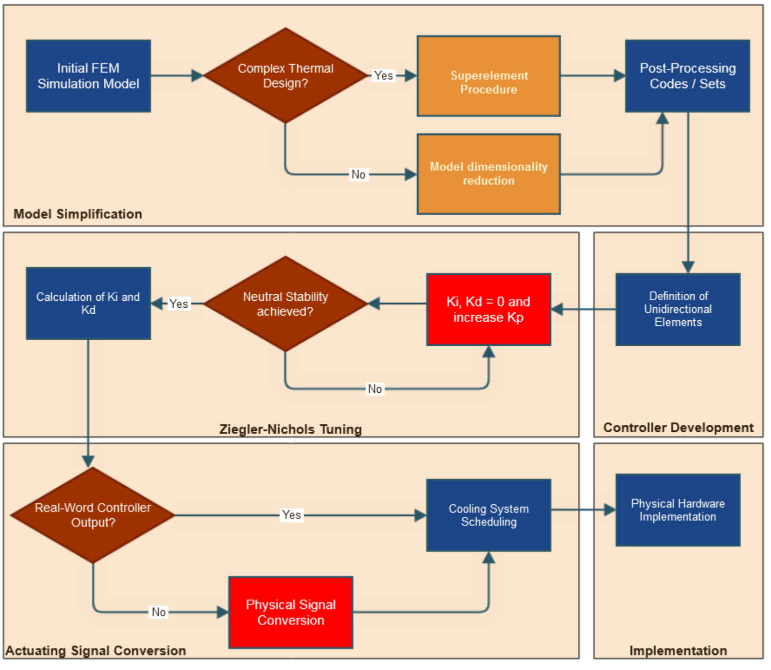


Fig. 2. A schematic representation of the proposed approach.

• **Model simplification:** The initial FEM simulation model that was previously completed in the thermal design stage is re-used. Two model simplification strategies can be deployed depending on the complexity of the cooling components. Simple solutions comprising extruded heat-sinks can easily be analysed with the support of the 2D plane stress heat transfer formulation. On the other hand, more complex coolers (i.e. die cast heat sinks) can be replaced by superelements using the retained degrees of freedom derived from the prior thermal analysis. Lower computational demands are also achieved by limiting the range of results that are written during the solving process. In this way, only the controller output and nodal temperatures occurring in the monitor and attachment nodes are considered.

• **Controller development:** this stage is characterized by the implementation of unidirectional or spring-damper-sliding elements. Such simulation procedures are included in most recent FEM solvers for replicating the behaviour of thermostats, relief valves or friction clutches. This is achieved by switching loads on and off during transient dynamics simulations in accordance with user-definable expressions. The typical structure of a unidirectional element deployed in a thermal system is depicted in Figure 3.

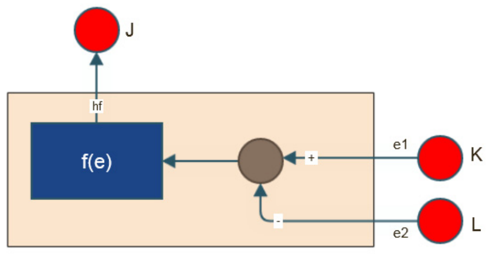


Fig.3. Typical structure of a unidirectional element deployed in thermal systems.

Nodes K and L represent the control nodes. The set point value is applied as a boundary condition (BC) at node K. Node L is attached to a specific location in the model that corresponds to the temperature sensor. The element internally subtracts the value of Node K (e1) from Node L (e2). Moreover, it allows a mathematical operation on this resulting error term (e). The output of f(e) represents a heat flow acting on node J (hf) that is proportional to (e).

$$h_f(t) = k_i \cdot |f(e)| \tag{5}$$

Three unidirectional elements are required for implementing a PID controller as part of a transient thermal analysis. Their equations are described below for proportional (7), integral (8) and derivative (9) terms:

$$h_f = e_1 - e_2 \tag{6}$$

$$h_f = \frac{d(e_1 - e_2)}{dt} \tag{7}$$

$$h_f = \int_0^t (e_1 - e_2) dt \tag{8}$$

• **Ziegler-Nichols tuning:** the main objective of the PID tuning is to adjust the response of the controller to set point changes and unmeasured disturbances such that variability of the error is minimized. The Ziegler-Nichols heuristic procedure is deployed to tackle the complexity of this stage. The process involves disabling the integral and derivative terms of the controller. In the next stage, the proportional gain is slowly increased until the system reaches neutral stability. Tables with constants are widespread for calculating the integral and derivative gains based on the achieved oscillation frequency [14].

• **Actuating signal conversion:** the simulation model output does not always match the physical hardware process variable. Therefore, it is imperative to convert the response of the controller in a meaningful signal. For example, the unidirectional elements heat flow can be interpreted as the reaction of a convection BC when power is removed from the system. On the other hand, the actuating signal can be converted into voltage drop across active electronic components in heat generation processes.

4 Case study

A simple experimental setup comprising a 27Ω ceramic resistor that is passively cooled by a thin sheet metal heat sink is developed to prove the given concepts. The aim of the controller is to maintain the temperature at the junction between the two components at 32°C by varying the power through the heat source. This is achieved with the support of an IRF1310N MOSFET that is controlled using an Arduino Uno development board through PWM digital output. An external power supply feeds 12V through the resistor circuit, causing a peak power dissipation of 10W. The temperature measurement procedure is conducted by using a LM35 temperature sensor that is attached to the analogue pin of an Arduino Mega compatible board. MATLAB software is deployed for reading the output of the sensor on a PC (Figure 4).

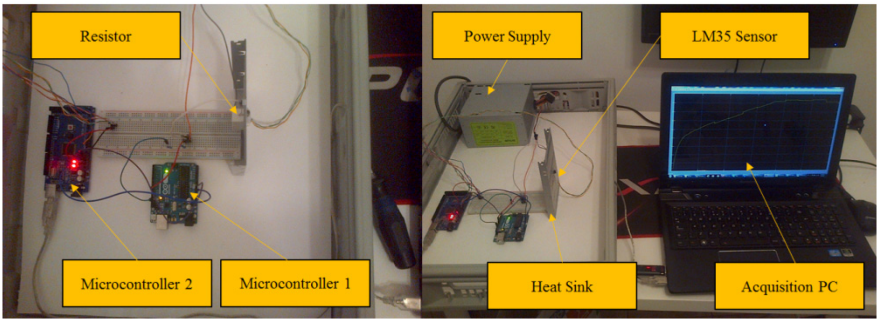


Fig. 4. Details regarding the experimental setup.

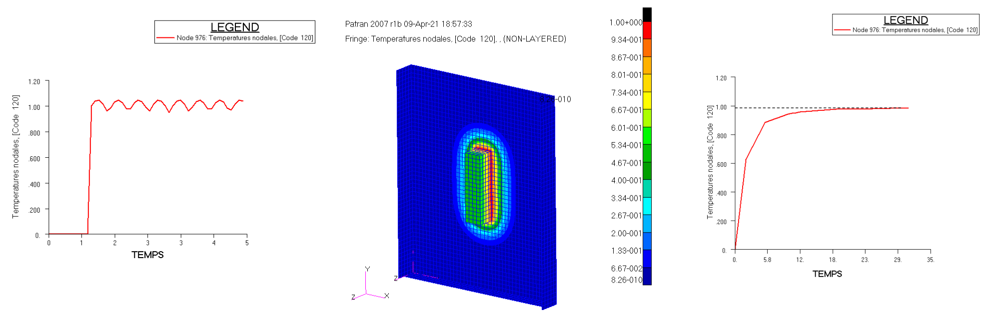
At first, MSC Patran pre/post-processing software for FEM analysis is employed to transpose the test bench system to a simplified simulation model. In this regard, 3D hexahedral elements are used for representing the resistor and 2D Shell elements for materializing the sheet metal body of the heat sink. The nodes found at the interaction area between the heat source and the cooler are merged, considering the existence of a thermal compound for facilitating conductivity. The material properties and BCs considered in the simulation are presented in Table 2.

In the next stage, the SAMCEF Mecano Thermal solver is used for implementing the DIGI CBOX 1002 PID controller unidirectional element with upper and lower bounds [15]. In this case, the sensor is attached to Node 976 which materializes the location of the physical acquisition system. The actuator corresponds to the internal heat generation of the resistor. The saturation limits are specified between 0 and 1.31E+06 W/m^3 (or 0 and 10W package power dissipation). Heat is removed from the system assuming isothermal vertical plate natural convection. The methodology for deriving the film coefficients is based on Rayleigh and Nusselt numbers and is depicted in [16].

Table 2. FEM Simulation input data.

Part	Material Name	Thermal Conductivity (W/m°C)	Specific Heat (J/Kg°C)	Density (Kg/m^3)	Maximum Power Dissipation (W/m^3)	Natural Convection Heat Transfer (W/m^2°C)
Resistor	Aluminium Nitride	140	740	3360	1.31E+06	3.45
Heat Sink	A525 Galvanized Steel	52	469	7800	-	

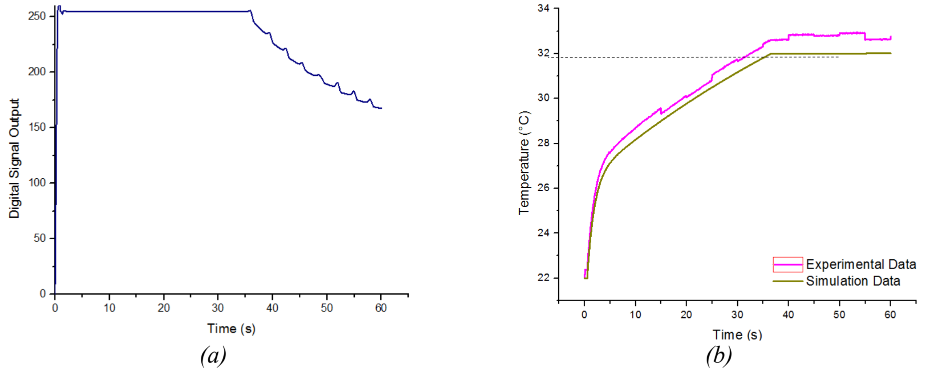
The tuning of the controller is completed by adjusting the initial temperature to 0°C. The set point value is defined as a step vector having both step time and final value set to 1. The gains of the integral and derivative terms are set to 0 and the proportional term is slowly increased. Neutral stability of the system is achieved at 0.00275 proportional gain (Figure 5 – a). The resulting PID gains are calculated as: Kp = 0.00165, Ki = Kd = 0.000826. The step response of the controller and temperature distribution of the studied assembly are depicted in Figure 5 – b and Figure 5 – c.



(a) (b) (c)

Fig. 5. FEM simulation results.

In the final verification stage, the model is evaluated on the physical system by scheduling the resistor to generate heat in accordance with the calculated process variable. This is achieved by replacing the analysis settings used in the previous stage with real ones. From this perspective, the ambient temperature measured during the test conditions is 22°C. The set point value is set to the initial objective of 32°C.



(a) *(b)*

Fig. 6. Shape of the digital signal output and the experimental vs. simulation temperature results.

The actuating signal of the simulated controller is converted into a digital one ranging from 0-255. The resulting voltage is further used to regulate the current through the gate of the MOSFET. Figures 6 – a represents the behaviour of the actuating signal while Figure 6 – b emphasizes the experimental vs. simulation temperatures.

The results indicate a maximum error of ε=4.55% between the experimental and simulation temperature curves. Even so, the slope of the two curves is comparable. Furthermore, the various sources of errors occurring due to the acquisition system also account for this divergence. In this regard, the approach proves an acceptable level of accuracy and can be considered suitable for developing FEM PID controllers with lower computational demands and a higher level of process formalization.

5 Conclusions

The present paper addresses the limiting aspects of the electronic components cooling with emphasize on the temperature controllers development process. Formalization of this workflow is achieved by re-using the simulation models that were previously completed in the thermal design stage. The issues related to computational costs of FEM PID controllers are tackled by reducing the dimensionality of the heat transfer problem. The tuning process is tackled by employing the Ziegler-Nichols heuristic approach. A simple experimental setup proves the given concepts with acceptable margins of errors when scheduling heat generating systems. The approach can be further used for developing more complex temperature controllers for the electronic units deployed in computer control units.

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