Control-Theoretic Dynamic Thermal Management of Automotive Electronics Control Units

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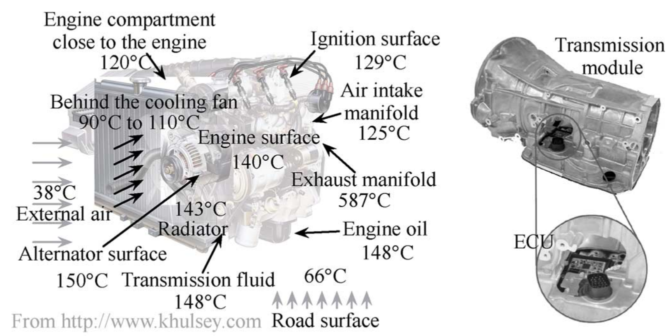
(Invited Paper)

***Abstract*—There has been a large body of research on dynamic thermal management (DTM) to manage the die temperature of integrated circuits against their high power density. Control-theoretic DTM is one of the most effective DTM schemes that guarantee stability criteria while meeting several performance requirements such as response time, steady-state error, overshoot, undershoot, phase margin, gain margin, and so forth. Conventional control-theoretic DTM schemes show reasonable stability and performance for general-purpose processors, but they may not fulfill those requirements for vehicle electronics control units (ECUs) primarily because the ambient temperature of an ECU is dependent on the associated unit temperature that often exceeds 100 °C. This results in a high steady-state die temperature and a very narrow temperature headroom. Furthermore, the unit temperature dynamically changes according to the driving condition that acts as a major disturbance to the DTM system. This paper introduces an advanced control-theretic DTM mechanism for high-performance vehicle ECUs. We model such ambient temperature variation as a disturbance, and adopt a disturbance predictor and compensator that effectively mitigates the effects of ambient temperature variations. We demonstrate that the proposed method is superior to the previous control-theoretic DTM in terms of RMS errors, peak temperature, and thermal violation.**

***Index Terms*—Ambient temperature variation, automotive electronic control units (ECUs), disturbance observer, dynamic thermal management (DTM), proportional-integral-derivative (PID) control.**

I. Introduction

THERE used to be very few electric components in a vintage car. However, after the first electronic fuel injection system has been introduced in late 1950s, the electronics control units (ECU) began to replace legacy mechanical controllers in automotive systems. These electronics subsystems include the powertrain, chassis, and body control. Most importantly, electronics components for automotive applications are operating in an extremely harsh environment, as shown in Fig. 1(a) [1], [2]. Due to additional heat dissipation from the exhaust manifold, the engine compartment temperature well exceeds 100 °C. The typical rating of electronics components for automotive applications is up to 120 °C ambient temperature and 140 °C junction temperature. The extreme ambient temperature makes it difficult to cool ECUs. Consequently, vehicle ECUs mandate a proper dynamic thermal management (DTM) to avoid thermal emergency in the near future.



(a) (b)

Fig. 1. Vehicle under-the-hood environment [1]. (a) Engine compartment temperature. (b) Transmission and transmission ECU.

There are two important observations on the vehicle under-the-hood environment for ECUs. First, each ECU is directly attached to the associated unit. Therefore, the mechanical module temperature directly impacts the ambient temperature of the associated ECU. Integration of the electrical and mechanical systems offers numerous advantages in automotive assembly, presetting, tuning and testing [1]. For example, integration of an ECU into the transmission reduces the wiring harness requirements at the automotive assembly level [see Fig. 1(b)]. As of today, previous centralized ECUs have been distributed to separate engine control modules (ECMs), transmission control modules (TCMs), and so forth, and directly attached to the associated parts such as engine, transmission, etc., respectively [2]. As the industry moves to more X-by-wire systems, the proximity of the mechanical module and associated electrical module will continue [1].

Another important observation is that each unit temperature varies according to the driving condition, as shown in Fig. 2. For example, the transmission temperature rapidly changes by

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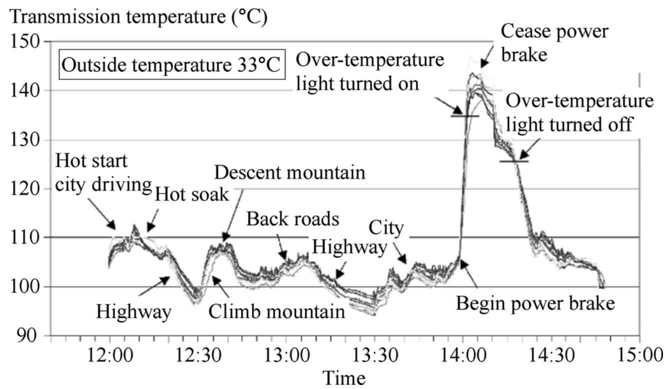

Fig. 2. Measured transmission temperatures during normal and excessive driving conditions (DaimlerChrysler) [1].

the driving condition with the variation of 45 °C. Thus, previous DTMs that regard the ambient temperature as a fixed value should assume the maximum ambient temperature to avoid thermal emergency at all times. To cope with this limitation, advanced cooling mechanisms have been proposed to mitigate the variable and extreme ambient temperature of ECUs[3], [4]. Such an effort helps reduce the temperature of ECUs at the expense of cost, but cannot tackle the root cause. One recent work dealt with dynamic thermal management of vehicle ECUs under variable ambient temperature by the use of computation migration [5].

Adopting control-theory for DTM is a complex procedure which involves stability analysis, fine-tuning of controller parameters to balance the various requirements, and moreover, real-world issues such as discretization and quantization error, and considerations for disturbance to the system. Unfortunately, previous control-theoretic DTM works often neglected such issues, might not suffice when it comes to automotive ECUs, and requires compensation scheme to guarantee reliable control of the die temperature.

We formulate the thermal model of an ECU in such a way that the ambient temperature is a variable voltage source rather than a circuit ground. Some previous works consider the effect of the ambient temperature. However, those works treat the ambient temperature as a static value, while our model incorporates dynamic variation of the ambient temperature. We utilize the fluid temperature information of hot units to estimate the future ambient temperature of ECUs. Most vehicles have temperature sensors to measure the fluid temperature such as transmission fluid. The fluid temperature change will be propagated though the unit housing (e.g., transmission housing), which has a large thermal capacitance. Therefore, after a time delay, the fluid temperature changes the ECU housing temperature (i.e., ECU ambient temperature). Based on the measured fluid temperature, the future ambient temperature estimation is accurate enough [5].

In this paper, we propose a different approach from [5] which exploits DVFS and computation migration among networked ECUs to deal with variable ambient temperature. We adopt a control-theoretic proportional-integral-derivative (PID) controller and propose a compensating scheme to deal with variable ambient temperature for a single ECU. We provide complete coverage in designing a control-theoretic DTM loop, and propose an architecture which comprises of a disturbance predictor and a compensator. Most importantly, we model the automotive ECU DTM as a feedback control system which is constantly influenced by external disturbance which is in our case, ambient temperature variation. We reinforce the conventional control-theoretic DTM schemes to better respond to variations in the ambient temperature by the use of a disturbance predictor and compensator.

II. Related Work

Recently, numerous DTM techniques have been proposed to avoid thermal emergency. One of the most common techniques discussed for DTM is dynamic voltage and frequency scaling (DVFS). Thermal characterization of Intel Pentium M system by real-machine measurement has shown that DVFS is well capable of controlling the processor temperature [6]. Architectural-level techniques focus on thermal control such as I-cache toggling, speculation control by limiting the number of unresolved branches, and decode bandwidth throttling [7].

Most DTM methods are reactive, which trigger thermal control actions after temperature reaches an emergent threshold. On the other hand, proactive DTM methods are proposed to predict future temperature and respond to thermal emergencies before they occur, and thus to minimize the adverse effects at lower performance cost. Application specific thermal behavior of a processor core helps predict the future temperature in [8]. Autoregressive moving average (ARMA) models are widely used to estimate autocorrelated time series data and also applied to future temperature prediction [9]. Linear approximation is useful to reduce the complexity of temperature prediction [10].

Feedback control is generally robust and provides a faster response time in comparison with open-loop controls. A PID controller throttles instruction fetch, reduces dynamic power consumption and thus heat dissipation of a processor [11]. There is a similar PID controller approach but using DVFS as the control knob [12]. This type of DTM assumes batch workload and tracks the desired die temperature. Tracking a certain die temperature is no longer valid if the workload is fixed, such as periodic workload. Thus, the control objective is to limit the maximum temperature rather than to track a target temperature even though a PID controller is used [13], [14].

Most of all, all these works assume the ambient temperature is a fixed value for future temperature estimation. This is true for conventional computing environments, but not applicable to automotive ECUs. Recently, a DTM scheme specifically aimed at managing temperature of automotive ECUs has been proposed [5]. The work allows for variable ambient temperature and exploits computation migration for resolving the thermal problem.

III. Control-Theoretic DTM Under Automotive Computing Environment

A. Problem Statement

As we discussed in Section I, control-theoretic DTM guarantees stability and provides desired performance if the controller design obeys stability analysis, fine-tuning of controller parameters, consideration of discretization and quantization error, and considerations for disturbance to the system. Such controller

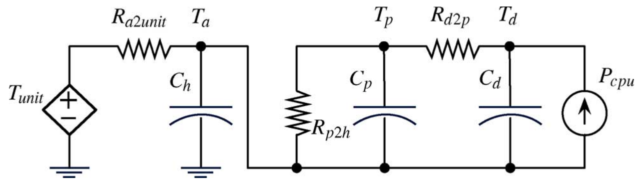

Fig. 3. RC-thermal circuit of an automotive ECU.

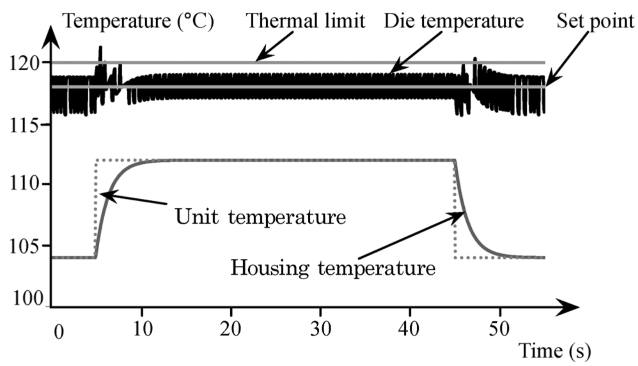

Fig. 4. PID control result under rapid ambient temperature change.

design generally assumes ideal operating condition of the controller in most control system design, but vehicle ECU design should also consider DTM of the controller processor.

The RC-thermal circuit in Fig. 3 implies that unit temperature change is propagated through the ECU housing and raises the die temperature directly by heat transfer, and by increased temperature dependent leakage current [5]. We demonstrate how the die temperature fluctuates with a conventional PID control DTM with a sudden ambient temperature in Fig. 4. Such an ambient temperature change often occurs whenever the driving condition changes. The control law of this experiment is DVFS of the ECU processor. The step input of the unit fluid temperature change incurs ECU ambient temperature rise after the thermal RC delay of the unit housing. The ambient temperature rise results in 4.81°C die temperature rise even with a PID controller.

As shown in Fig. 1, high unit temperature makes the temperature headroom of the ECU very narrow. Therefore, even a 4.81 °C die temperature overshoot might cause thermal limit violation. There is possibility of undershoots as well, which implies there might be unnecessary performance degradation since the ECU could run at a higher operating frequency.

In formal control-theory, a disturbance observer is often used to compensate the disturbance and maintain high quality of control [15]. In this paper, we model the variations in the ambient temperature as a disturbance to the system and use disturbance predictor and compensator to mitigate the effect. Fig. 4 shows that the unit fluid temperature propagates to the ECU housing after several seconds. Vehicles generally measure all the fluid temperatures, and the fluid temperature information can be used as an accurate ECU housing temperature predictor. We propose to use this information to compensate the disturbance and prevent potential thermal limit violation.

In this paper, we first address the problem of DTM in automotive computing environment and obtain a new thermal model to take ambient temperature variation into consideration. Second, we model the variations in the ambient temperature as a disturbance to a controlled system, and design a control-theoretic DTM framework.

B. Automotive ECU Thermal Model

We use a lumped RC-thermal circuit model [11] for temperature estimation, as shown in Fig. 3, without loss of generality. It reflects the ambient temperature, and the temperature of an ECU package and a die, altogether. We emphasize that the major difference between conventional thermal models and the proposed model is the voltage source. The voltage source represents change in the unit fluid temperature to which an ECU is attached.

We assume that the temperature within an ECU is homogeneous and can be represented with a single scalar value. We denote the temperatures of the die, package, housing of the ECU, and the unit to which an ECU is attached with T_d, T_p, T_a, and T_{unit}, respectively. The symbols of C_d, C_p, and C_h represent thermal capacitances of the die, package, and housing, respectively. Lastly, the symbols of R_{d2p}, R_{p2a} and R_{a2unit} denote thermal resistances of die to package and package to housing and housing to the unit to which an ECU is attached, respectively.

The value of thermal resistances and capacitances are imported from the values in [16] and [17]. The thermal RC constants of a processor die, a package, and a housing differs greatly. The thermal time constants of the ECU die and package used in our work are in the order of tens of milliseconds, while the one for ECU housing is in the order of seconds.

We assume a futuristic ECU model which will likely be used in the next few years. Mechanical controllers are being replaced by electrical controllers such as electromechanical brakes (EMB), electromechanical steering (EMS), electronic traction control (ETC), etc. In addition, more auto- or semi-auto- pilots such as electric stability program (ESP), adaptive cruise control (ACC), active body control (ABC), etc., are involved. Ranging from a peripheral body and an instrument cluster to a state-of-the-art collision avoidance and an X-by-wire controller, their ECUs soon will be equipped with a high-performance 32-bit deep-pipelined RISC processors fabricated with a deep sub-micron technology processors running well over several hundred megahertz (MHz). This trend is being accelerated to accommodate heavy computation workload of Intelligent Vehicle Systems (IVS). Embedded processor Benchmark Consortium (EEMBC) has recently forecasted that the trend is likely to continue [18]. Thus, we scale the operating frequency and the power consumption of a currently used automotive ECU [19].

The dynamic and static power consumption of the ECU are modeled by the following widely used equations:

$$P_{\text{dyn}} = C_{\text{eff}} V_{\text{dd}}^2 f \tag{1a}$$
$$P_{\text{leak}} = \mathcal{A} T^2 e^{(\alpha V_{\text{dd}} + \beta)/T} + \mathcal{B} e^{\gamma V_{\text{dd}} + \delta} \tag{1b}$$

where C_{eff}, V_{dd}, f, and T are the effective capacitance, supply voltage, operating frequency, die temperture of the ECU, respectively. The symbols of $\mathcal{A}$, α, β, γ, and δ are parameters related to process technology, gate count, etc. Both Fig. 3 and (1) imply that there is a circular dependency between ECU power consumption and the die temperature. This circular dependency makes it hard to accurately predict the die temperature and derive a transfer function of the system.

C. Automotive Computing Tasks and Control Quality

There are a number of ways to enhance the control quality of an automotive tasks. First, we can increase the execution rate of a control algorithm. For example, a collision avoidance algorithm using dedicated short-range communication (DSRC) requires higher broadcasting frequency when vehicles run at a higher speed [20]. One might also increase the rate of an ABS system controller to accommodate higher vehicle speed.

Imprecise computation is often used for real-time tasks to provide acceptable control quality under hard real-time constraints. For example, imprecise computation is used for vehicle collision avoidance in Intelligent Transportation System (ITS) [21]. In such a case, it is important to maximize the performance of an ECU to achieve high-quality control. Therefore, a proper dynamic thermal management scheme that maximizes the performance of an ECU while meeting the thermal constraint is critical for modern automotive applications.

D. PID Control Using DVFS

PID controls have been widely used to obtain improvement in steady-state error and transient response of industrial systems such as motors, petroleum refinery, manufacturing machines, and so on. Specifically, P controls adjust outputs in proportion to the size of the error. I-controls reduce the steady state error by accumulating the past error and the future trend is anticipated via the D-controls in proportion to the derivative error. The overall performance can be improved by combining these controls. As common combinations, PI controls and PD controls can improve steady-state error and transient response, respectively. These useful functions are sufficiently transparent for a large number of process applications, which leads to wide acceptance in the field and hence brings out a lot of algorithms for automatic PID coefficients tuning.

PID controls are designed according to the requirements described with rising time, overshoot, steady-state error, and so on. The overshoot would be an important factor in automotive ECU DTM not to violate the maximum allowable temperature. Steady-state error is also highly related to the performance. If the die temperature is far below a set point value, this is an evidence that we operate the processor with an unnecessarily low performance. A high steady-state die temperature is of course dangerous.

The designer should be extremely careful in determining the sampling rate. The major effect of sampling is a time delay of about half a sampling period. A long sampling time has a destabilizing effect on the system, which implies extreme difficulty in controlling the system. If the sampling time is too low, the disturbance in ambient temperature will have significant impact on the die temperature control quality. The sampling rate should be carefully chosen in consideration of rising time, overshoot, and steady-state error.

Practical DVFS has discrete levels of voltages and frequencies. Such discrete voltages and frequencies incurs a mapping issue between continuous variables and discrete DVFS levels.

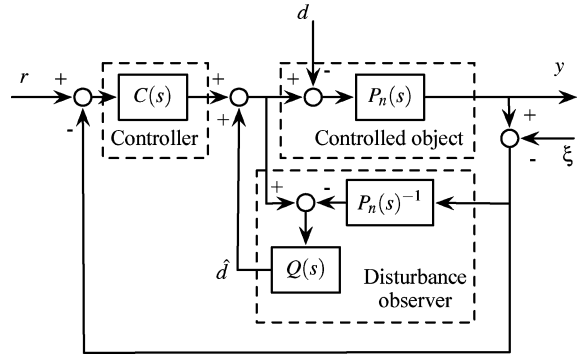

Fig. 5. General disturbance observer architecture [15].

The mapping strategies have an effect on the rising time and steady-state error. Besides, the system may exhibit a limit cycle with the high frequency due to discrete modes of an input [22]. Since this limit cycle implies the performance overhead for changing operating modes of a CPU, we should avoid too frequent voltage and frequency transition by employing a proper hysterisis.

IV. Proposed DTM Architecture Using Ambient Temperature Compensator

A. Prediction of Ambient Temperature Variation

Generally, disturbance to a controlled system is unpredictable and makes quality control hard to achieve. Thus, many systems adopt disturbance observer to predict the disturbance and mitigate its adverse effects. Fig. 5 shows the general architecture of a disturbance observer [15]. However, we do not directly apply the disturbance observer in Fig. 5 for many reasons. First, we can easily estimate the disturbance by measuring the unit temperature. The complex disturbance observer design involving inverse transfer function, and so on, is an overkill in our case. Second, there is a time delay for the controller output to take effect on the output. Temperature rises after the thermal RC time delay while ambient temperature prediction is based on current observation. Without noticing the delay information architecture in Fig. 5, it might result in instability. These issues forbids us from using disturbance observer to predict the ambient temperature.

Once again, we can easily predict the change in the ambient temperature by measuring the unit fluid temperature. The temperature of the ECU housing is largely dominated by the unit housing temperature. For example, the fluid temperature of the Chrysler transmission module increases as the vehicle climbs a mountain, as shown in Fig. 2. The increase in unit fluid temperature is propagated through the ECU housing which acts as an thermal RC filter shown in Fig. 3. The ambient temperature of the ECU increases after the thermal constant delay we discussed in Section III-B. We can use the following equation to estimate the ambient temperature:

$$\begin{aligned} T_a(t) =& T_a(t_0)\cdot \exp\left(-\frac{1}{C_h Ra2\text{unit}}(t-t_0)\right) \\ &+ \int_{t_0}^{t} \frac{1}{C_h R_{a2\text{unit}}}\cdot \exp\left(-\frac{1}{C_h R_{a2\text{unit}}}(t-\tau)\right) \\ &\cdot T_{\text{unit}}(\tau)d\tau \end{aligned} \quad (2)$$

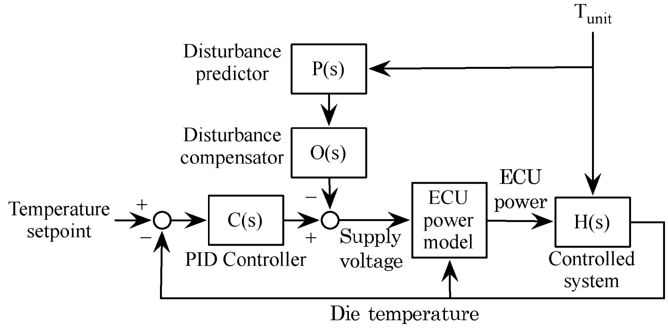

Fig. 6. PID control with proposed disturbance observer.

where C is a constant number obtained from initial conditions. This compact prediction method relieves us from implementing a complex disturbance observer but provides accurate estimation of the disturbance in ambient temperature.

B. Proposed DTM Architecture Using Ambient Temperature Compensator

We propose a feedback control loop architecture, as shown in Fig. 6. The proposed architecture consists of a disturbance predictor, a disturbance compensator in addition to a normal PID control loop. The disturbance predictor computes the ambient temperature for the next PID control period. The disturbance observer compensates the disturbance in the ambient temperature with the computed prediction. This work shows that even a simple compensator which exploits the derivative of the ambient temperature change can dramatically reduce the peak temperature.

The transfer functions of each block in Fig. 6 are given as follows:

$$C(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s} \quad (3a)$$

$$H(s) = \frac{\left(\frac{\frac{R_{p2h}}{sC_p}}{\left(R_{p2h}+\frac{1}{sC_p}\right)} + R_{d2p}\right)\frac{1}{sC_d}}{\frac{\frac{R_{p2h}}{sC_p}}{\left(R_{p2h}+\frac{1}{sC_p}\right)} + R_{d2p} + \frac{1}{sC_d}} \quad (3b)$$

$$P(s) = \frac{\frac{1}{sC_h}}{R_{a2unit} + \frac{1}{sC_h}} \quad (3c)$$

$$O(s) = k_1 s + k_2. \quad (3d)$$

The equations are rather straightforward. Transfer function of the PID controller is described by (3a). We obtain (3b) by solving the RC-thermal circuit and hence obtaining a gain function with processor power consumption input and die temperature output. The solution of the thermal RC filter derives (3c). This equation is closely related to (2). The transfer function for the proposed compensator is given by (3d). There is also a nonlinear block ECU power model which we cannot describe in form of transfer function. The behavior of the block is described by (1).We use a linear equation of the derivative of the ambient temperature value.

We tune the PID controller parameters such as K_p, K_i, and K_d by the use of a PID tuner in MATLAB/Simulink. There

TABLE I
CONTROL QUALITY AND ECU PERFORMANCE OVERHEAD OF THE PID CONTROLLER ACCORDING TO PID CONTROL PERIOD, UNDER THE SYNTHETIC UNIT TEMPERATURE TRACE IN FIG. 4

PID control period (ms)	RMS error (°C)	Peak temperature (°C)	Response time (ms)	Performance overhead (%)
10	0.55	1.18	0.0617	2.79
50	1.40	2.18	0.482	0.62
100	1.54	2.36	0.567	0.39
500	2.33	4.67	2.52	0.1
1000	2.64	4.66	4.97	0.07

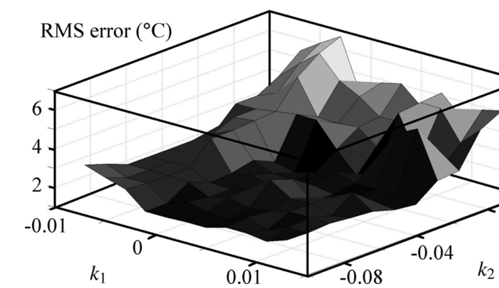

Fig. 7. Search result for compensator parameters k_1, k_2.

is a trade-off between the response time and the overshoot or the settling time. The response time should be short enough to follow the die temperature changes, but should not be too short to cause unwanted amount of overshoot that might lead to potential thermal limit violation or oscillation in the die temperature. The PID control period is also very important in control quality [23]. A shorter control period guarantees fine control of the die temperature but, at the same time, the computation and DVFS transition overhead could be significant. On the other hand, a longer control period may cause degradation in the response time. It turns out through experiment that longer PID control period implies a longer response time. Fortunately, a longer response time does not cause serious faults under normal ambient temperature situations. On the contrary, we emphasize that a longer response time may incur serious degradation of the die temperature control quality when there is non-negligible amount of ambient temperature changes which is typical in vehicle ECUs. We demonstrate impact of the PID control period in Table I.

We tune parameters k_1 and k_2 for the compensator manually under objective of minimizing the rms error in presence of rapid unit temperature change. The surface of peak temperature according to values k_1, k_2 is roughly convex so that the values can be easily found. The peak temperature according to k_1, k_2 is shown in Fig. 7. We have found by manual search that the values $k_1 = -0.012$ and $k_2 = 0.000$ produces the minimum rms error.

V. EXPERIMENT

This section evaluates the performance of the proposed PID control framework equipped with the disturbance predictor and compensator. We demonstrate superior performance in terms of the peak temperature, and rms error of the die temperature control. The baseline scheme is the same PID controller without the predictor and compensator in the loop. We consider an ECU mounted on a transmission, and thus ambient temperature of the

TABLE II
THERMAL PARAMETERS OF OUR ECU MODEL

Parameter	R_{d2p}	R_{p2a}	R_{a2unit}
Value (°C/W)	2	0.61	1.36
Parameter	C_d	C_p	C_a
Value (J/K)	11.25e-3	35e-3	10.53

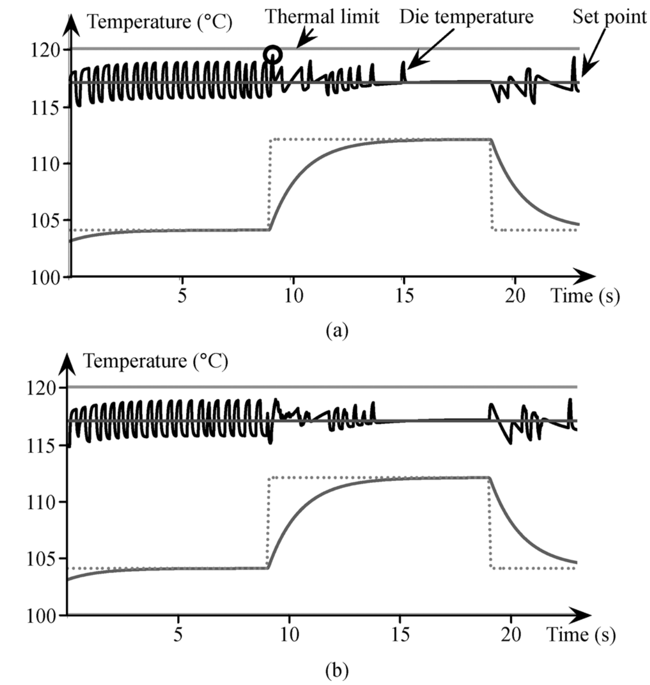

Fig. 8. Temperature profile of the baseline and proposed architecture (T_{unit} step input). (a) Baseline. (b) Proposed architecture.

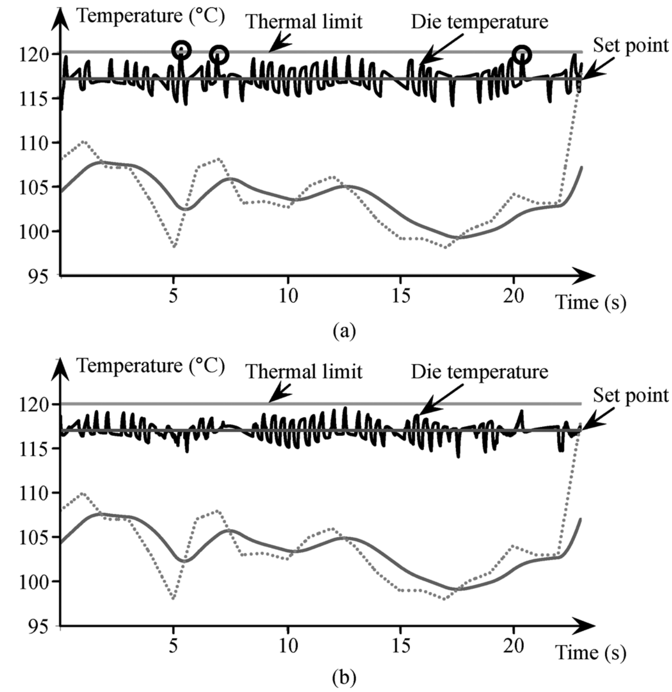

Fig. 9. Temperature profile of the baseline and proposed architecture (synthetic T_{unit} trace). (a) Baseline. (b) Proposed architecture.

TABLE III
PID CONTROL QUALITY AND ECU PERFORMANCE OVERHEAD ACCORDING TO PID CONTROL PERIOD (STEP INPUT)

PID control configuration	Peak temperature (°C)	RMS error (°C)	Performance overhead (%)
Baseline	119.4	0.83	0.32
Proposed	118.9	0.83	0.32

TABLE IV
PID CONTROL QUALITY AND ECU PERFORMANCE OVERHEAD ACCORDING TO PID CONTROL PERIOD (ACTUAL TEMPERATURE PROFILE FROM DAIMLERCHRYSLER TRANSMISSION)

PID control configuration	Peak temperature (°C)	RMS error (°C)	Performance overhead (%)
Baseline	119.5	1.87	0.37
Proposed	120.4	1.74	0.36

ECU is largely affected by the transmission fluid temperature change similar to the one in Fig. 2. We evaluate the framework under two unit temperature traces. One is step input of the unit temperature to better illustrate the performance metrics, and the other is random trace which exhibits more irregular behavior.

We build the simulation setup on MATLAB/Simulink environment with the aid of SimPowerSystems 5.2 library. The ECU power model is based on automotive applications processor SHARC ADSP-21375 from Analog Devices. The operating frequency and power consumption of the processor are scaled up to 800 MHz and 6 W as we discussed in Section III-B. The parameters for thermal model are calculated based on the values in [16] and [17]. The exact values are shown in Table II. We obtain the PID parameters using PID tuner provided in MATLAB/Simulink package. PID control period is set to 100 ms since it gives reasonable control quality while sacrificing little ECU performance as shown in Table I. We use compensator parameters $k_1 = -0.012$, $k_2 = 0$ obtained from exploration result in Fig. 7.

Figs. 8 and 9 show the effect of predictor and compensator under step input trace and random trace of unit temperature. In Fig. 8, it should be noted that just after 5 s, where step input to the unit temperature has occurred, the proposed mechanism reduces the peak temperature significantly, and thus leaving more thermal headroom for the ECU. Fig. 9 shows similar results. Without ambient prediction and compensation, the die temperature reaches the thermal limit several times. With the aid of compensation block, however, the peaks and thermal violations are safely removed. Tables III and IV show quantitative results. For the step input trace, peak temperature (circle on graph) is reduced by 0.5 °C. RMS error is almost the same because compensation is only effective when the ambient temperature is changing which is only a portion of total simulation time. The performance overhead does not differ much since the number of DVFS transitions are also almost the same. For the random input trace, peak temperature is reduced by 0.9 °C, and RMS error is improved by 7.0%. The reduction in peak temperature seems small, however, the peaks are successfully removed. The first peak caused by rapid change in ambient temperature is reduced by 3.8 °C.

VI. CONCLUSION

As modern vehicle ECUs are directly attached to the associated unit, the unit temperature directly affects to the ambient temperature of the vehicle ECUs. The vehicle ECUs then experience a very high steady-state die temperature leaving very small amount of temperature headroom. The unit temperature also significantly changes by the deriving condition which makes conventional DTMs, even control-theoretic DTMs, hard to meet the temperature constraints.

This paper is the first paper that introduces an advanced control-theoretic DTM for vehicle ECUs that: 1) models the unit temperature change as an ambient temperature disturbance; 2) reflects the disturbance modifying the RC thermal model with a voltage source; 3) combines a conventional PID DTM controller with a disturbance predictor and a disturbance compensator; and 4) predicts the future ambient temperature using the current unit temperature (e.g., transmission fluid) information. We also present a complete design procedure of the PID controller including PID parameter tuning, ambient temperature predictor and compensator design. We demonstrate superior performance of the proposed DTM in terms of peak temperature and rms error of the die temperature control. We achieve peak temperature reduction by up to 3.8 °C, and successfully remove all thermal violations.

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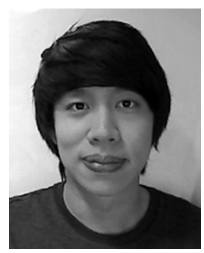

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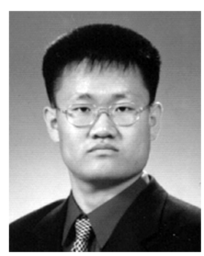

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