A PID Controller Design for Dynamic Thermal Management Considering Performance of Mobile Processor

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Abstract: Recently, as mobile device processes heavy load program, operating frequency of mobile processor gets higher with more power consumption, which leads to high temperature problem. Therefore, a thermal management system became essential to guarantee reliable performance of system. In this paper, we propose a Dynamic Thermal Management (DTM) with PID controller. The advantage is that it can control temperature optimally based on thermal characteristic of chipset. Compared to conventional DTM, the performance has dropped for 0.5%, but core temperature and the number of data exceeding set point reduced for 1.11% and 26.06% for each. Therefore, DTM considering chipset thermal characteristic is necessary for suppressing high temperature.

Keywords—**High Thermal Problem, Dynamic Thermal Management, PID Controller**

1. Introduction

As high performance applications are being used in mobile devices, high CPU frequency is required to provide satisfactory performance to user. And to manipulate such high CPU operating frequency, high voltage should be provided to circuit. Because the chipset is composed of RC circuits, high voltage drives the chipset to high power consumption due to ohmic characteristic. Eventually, high power consumption leads to high temperature of the chipset [1]. Additionally, by adopting multi-core system, much more heat occurs than single-core system. Due to these phenomena, Dynamic Thermal Management (DTM) became essential in mobile devices to assure the system operating in reliable temperature range.

One easy method to manage temperature is Dynamic Power Management (DPM). This method manages power on/off of specific module. When the temperature of module exceeds threshold value, DPM turns off the power until the temperature goes down sufficiently [2]. This method may be effective to simple system which treats simple application and comprises of few hardware modules. But current mobile devices can't be managed with DPM method because of complexity.

DTM used in mobile devices usually controls temperature of the chipset. In controlling CPU temperature, DTM determines CPU maximum allowed operating frequency responding to core temperature. This method assures core temperature not to exceed specific target temperature which is called set point. Set point is the upper bound of chipset operating temperature range. And by limiting CPU temperature, the performance can be reliable. There are several methods to control core temperature by limiting maximum allowed frequency.

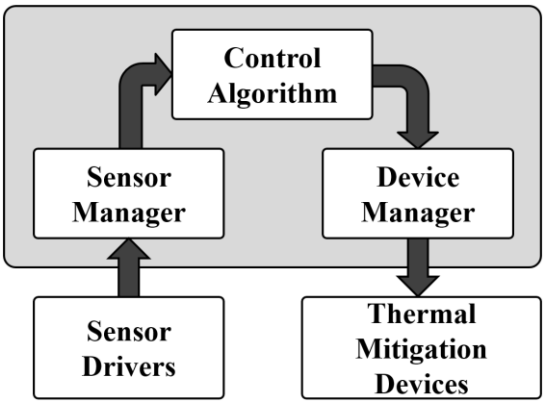

Figure 1. Dynamic Thermal Management System

One method is that DTM determines maximum allowed frequency by a given table. Maximum allowed frequency is matched with many levels of threshold core temperature. When core temperature exceeds specific temperature, it limits maximum allowed frequency paired to temperature written in table. However, this is static control method which doesn't consider performance of system. And it can't control sensitively to temperature in terms of quick and optimal response.

Another DTM method is a dynamic control which is responding to current core temperature every algorithm cycle. Figure 1 shows DTM with dynamic controller [3]. It calculates 'error'; difference between set point and current core temperature which is measured by sensors. By using an error as input of controller, DTM can aware whether core temperature is below or above set point. If core temperature exceeds set point in such moment, DTM lowers maximum allowed frequency by one level. And it keeps reducing level until core temperature becomes lower than set point. Otherwise, DTM keeps increasing the level to allow CPU to operate in high frequency which means high performance. Comparing to static method, dynamic control considers performance of system with sensitive control and limits core temperature at the same time.

However, it might have problem when core temperature soars steeply over the set point. In this case, one level control may not be able to reduce core temperature immediately below set point. And it can lead to successive high temperature problem. Considering that one level is not an enough control value, changing multiple steps (N-step) would be more effective in controlling temperature. Therefore, this paper proposes DTM with PID controller. This DTM determines optimal N-step change in maximum allowed frequency level based on thermal characteristic of target chipset. It is expected to control temperature faster than one level changing control method.

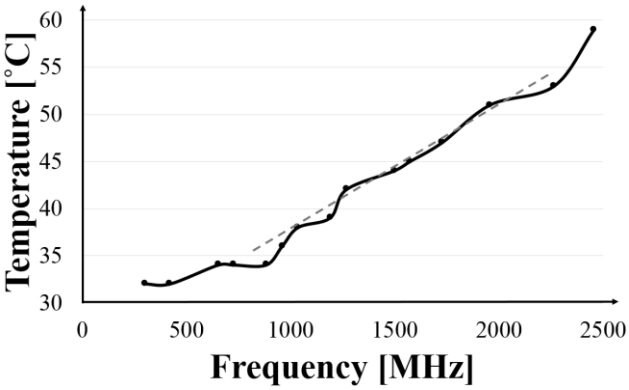

Figure 2. Linear Model of Chipset Thermal Characteristic

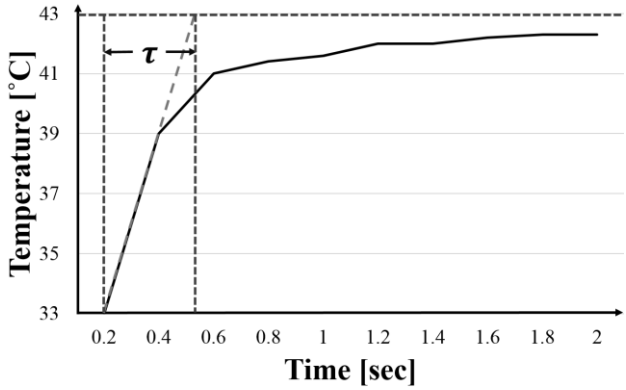

Figure 3. First-order Model Applied to Target Chipset

2. Methodology

2. 1 Thermal Model of Chipset

Thermal model of chipset should be defined in mathematical form, because PID controller parameters can be calculated by chipset system parameters. So experiments were conducted to figure out thermal model of target chipset. MSM8974 which is made by Qualcomm is used as target chipset, and the platform of the system is smartphone LG G3.

Thermal model of the system can be defined by system parameters. These parameters can be obtained by giving specific input to system and monitoring output response. The one method is that giving 'step input' to the system. In MSM8974 case, maximum allowed frequency can be determined as step input. And the output response should be core temperature. By monitoring core temperature while tests conducted, system parameters – time constant, steady-state gain – could be obtained. Therefore, the model of system can be defined as step response. Also system performance indicator – response time, overshoot – was able to be defined by experiments. System performance shows how much the system responses to input. So, these are going to be used when designing controller.

'Dhrystone' benchmark test was used to define the relation between frequency and temperature. It sets one maximum allowed frequency and gives 100% load to CPU, so it is suitable to step input test [4]. Tests were executed for 15 operating frequencies for sufficient time to measure the steady-state temperature. As the result of tests, Figure 2 shows the linearity in five frequencies between 1.2GHz and 1.9GHz. This linear system with five frequencies is used to define thermal model of the chipset because PID controller is defined to operate in LTI system.

As the result of Dhrystone tests for linear range, the temperature curve was shown and this curve was used to analyze system parameters. To approximate chipset thermal system, first-order model was adopted based on temperature curve which is shown at Figure 3. There are system parameters of first-order system; time constant and steady-state gain. First-order system can be shown mathematically as formation (1).

$$G(s) = \frac{g}{\tau s + 1} \qquad (1)$$

Time constant (τ) counts time from beginning point of the test to steady-state value of the system output. It shows how fast the system can reach to set point. And steady-state gain (g) is the ratio between input and output. It shows how much the system can reach to set point. In Dhrystone test, unit of input and output is different; input is maximum allowed frequency and output is core temperature. So it can't be calculated with different unit. Therefore, steady-state gain should be calculated in ratio as formation (2).

$$g = \frac{\frac{t - t_{MIN}}{t_{MAX} - t_{MIN}}}{\frac{f - f_{MIN}}{f_{MAX} - f_{MIN}}} \qquad (2)$$

After several tests, average system parameter values in linear range of thermal system were defined. Steady-state gain was 0.84, and time constant was 0.52 seconds. According to test results, this thermal system isn't able to reach to set point, which means that controller should complement input value to thermal system to reach exact set point.

2. 2 PID Controller

Basically, controller makes system stay near a set point value using several methods. First, to design controller, expecting system performance should be determined. It can be designed based on system performance. After designing controller, controlled closed loop can be made. Usually input value of the controller is error, and it calculates control value as output according to control algorithm. By controller, the system finally can reach to set point with expected system performance.

PID controller which is used in proposed DTM is one of frequently used controllers that changes system performance by tuning controller parameters P,I and D. P is proportional factor of error (difference of set point and input data) which speeds up system response. In most system, time constant can be reduced by this parameter. I is integral factor of error which reduces steady-state error – difference between input and steady-state output data – of the system. D reduces overshoot of the system, and makes system more stable [5]. PID Controller transfer function can be shown as formation (4).

$$G_C(s) = K_P + K_I \frac{1}{s} + K_D \qquad (4)$$

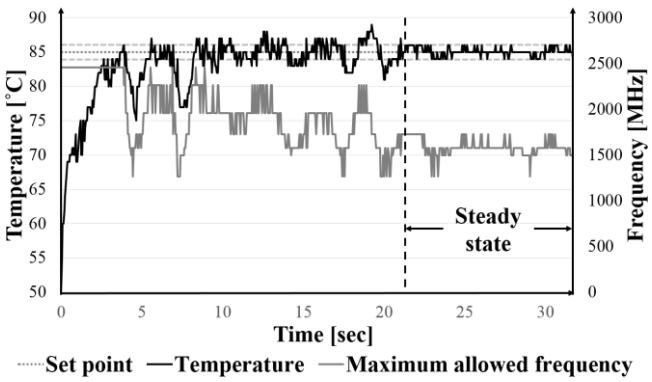

Figure 4. Steady-state Temperature Controlled by DTM

To change the original system performance to expecting system performance by controller, closed loop transfer function should be analyzed shown as formation (5).

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G(s)}{1 + G_C(s)G(s)} = \frac{g(K_P s + K_I)}{\tau s^2 + (1 + gK_P)s + gK_I} \quad (5)$$

In this formation, a characteristic equation can be defined by putting zero to the denominator of a transfer function. Characteristic equation is used to analyze the system performance. A basic form of characteristic equation can be shown as formation (6).

$$s^2 + 2\omega_n\zeta + \omega_n^2 = 0 \quad (6)$$

In case of second order equation, overshoot and rise time can be calculated as formation (7), (8).

$$\mathrm{OS}(\%) = e^{-\left(\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)} \times 100 \quad (7)$$

$$T_s \cong \frac{4}{\omega_n\zeta} \quad (8)$$

By formation from (5) to (8), system performance can be determined by controller parameters. That means, by using controller, original system performance can be changed as controller designer wanted.

Changed system performance by controller is called Closed Control Loop (CCL) system performance. The CCL system performance can be determined by considering original system performance. Because the existing system shows smaller gain than 1, slight overshoot can be allowed. So, 2% overshoot was set as CCL system performance. And at the same time, time constant needs to be smaller than original performance to manage core temperature faster. Considering that original system time constant was 0.524 second, CCL time constant can be set as 0.5 second. After setting the system performance, controller parameters can be calculated by analyzing characteristic equation.

As seen at formation (5), D parameter is not included for CCL system. In designing controller, D value was tuned by experimental results after calculating P,I parameters. for accuracy when controller is adapted to real mobile device system [6]. As the result of calculating P,I value in average, 2.85 and 10.77 were figured out for each parameters. These values are fixed value of controller whether D value changes for any reason or not.

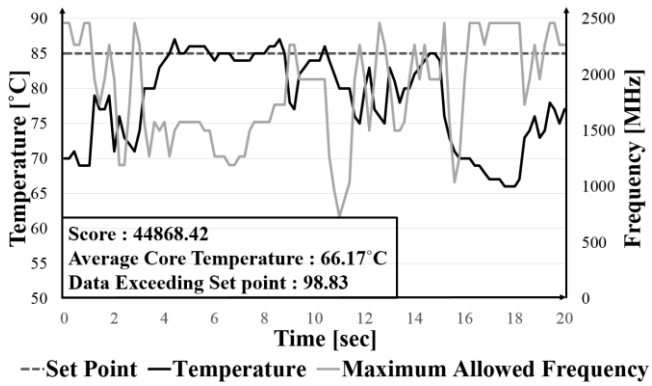

Figure 5. Example of AnTuTu Test Result Using Proposed DTM

For D value, several experiments were conducted. As explained before, as D value increases, controller suppresses overshoot and system becomes more stable. But, D value also makes system slow in responding to input, which lowers performance. Therefore, the goal of experiments was to choose lower bound value of D which make system stable. 'Fast Discharge Application' which utilizes CPU 100% was used for fine tuning of D value.

The necessary condition of stable system is that steady-state error – difference between steady-state value of system output and set point – becomes in the range of ±2% of steady-state value. During Fast Discharge Application tests, core temperature and maximum allowed frequency were monitored for every tests. Experiments were done by after changing D value and monitoring the output values. The initial value of D was 0.6 which is one of values of non-stable CLL system. After finding out that D value doesn't make system stable, 0.02 was added to D value. After repetitions, D value was tuned as 0.9, and the result of experiment is shown in Figure 4. Temperature goes into steady-state after several seconds. And the temperature was controlled rapidly by N-level changes of maximum allowed frequency. By fine tuning tests, controller parameters were determined for five cases of linear system models.

3. Experimental Results

DTMs with PID parameters were adapted to G3 smartphone. And several tests were conducted to evaluate performance of entire system. It shows how much the system performs well with temperature management policy. For the tests, 'AnTuTu' benchmark tests were executed. This benchmark includes several kinds of test programs which are able to evaluate smartphone performance including graphic test, memory test, CPU test, etc. And it calculates 'score' for every tests executed. At the end of the tests, AnTuTu shows total score which is a sum of each test program results. At the same time, core temperature data were gained as log data.

A goal of AnTuTu tests were to make a trade-off between performance and thermal characteristic of system which is managed by DTM. Consequently, the best DTM among five DTMs will be chosen by comparing results. An example graph of test is shown in Figure 5. It shows how the core temperature is controlled by DTM changing maximum allowed frequency.

Table 1. Comparison between Conventional DTM and Proposed DTM

	Conv. DTM[1]	Prop. DTM[2]	Difference (%)
# of Data Exceeding Set Point[3]	133.67	98.83	-26.06
Core Temperature (℃)	66.91	66.17	-1.11
Score	45093.89	44868.42	-0.5

AnTuTu tests were conducted consecutively for five times. Among five tests, just the third to fifth test results were analyzed to measure saturated value of results. And this whole five consecutive tests were done for ten times to get the average value of score, core temperature and the number of data exceeding set point. The number of data exceeding set point can tell that how fast DTM suppresses high temperature with control algorithm.

By comparing results for five DTMs, the best one satisfies optimal control ability and little performance reduction at the same time. The chosen DTM dropped average score from 45093.89 to 44868.42 which is just 0.5% of reduction. However, the number of data exceeding set point was hugely reduced from 133.67 to 98.83 which is 26.06% drop. Additionally, the average core temperature was reduced from 66.91℃ to 66.17℃, 1.11% reduction. Table 1 shows a comparison between conventional DTM and proposed DTM in score, core temperature and the number of data exceeding set point.

4. Conclusion

DTM becomes essential in mobile device system because of its thermal issues. It should be designed optimally to relieve high temperature problems. Additionally, performance degradation also must not happen. In this paper, the reduced number of data exceeding set point shows that proposed DTM controlled temperature more optimally than conventional DTM. It could reduce temperature below set point with optimal control. At the same time, it showed similar performance by giving high maximum allowing frequency to the core when the temperature was below set point. These were possible because PID controller adopted thermal characteristic of chipset and calculated optimal control value. Therefore, this paper showed better solution than conventional method in managing core temperature by optimizing DTM to the G3 chipset, MSM8974. For the further study, in addition to CPU temperature control, other on board devices – GPU, LCD display, etc – may have similar thermal problem. Especially, in case of GPU, usage of GPU is extremely increasing in mobile devices. So, controlling GPU temperature will be helpful to manage thermal problem.

[1] Conventional DTM
[2] Proposed DTM
[3] Number of data exceeding set point

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