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Baseline Performance of Notebook Computer under Various Environmental and Usage Conditions for Prognostics

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***Abstract*—**A study was conducted to formally characterize notebook computer performance under various environmental and usage conditions. Software was developed to collect data from the operating system of the computer. An experiment was conducted to evaluate the performance parameters' variations, trends, and correlations, as well as the extreme value they can attain in various usage and environmental conditions. An automated software script was written to simulate user activity. The variability of each performance parameter was addressed by establishing the empirical relationship between performance parameters. These equations were presented as baseline estimates for performance parameters, which can be used to detect system deviations from normal operation and for prognostic assessment. The effect of environmental factors, including different power sources, ambient temperatures, humidity, and usage, on performance parameters of notebooks was studied.

***Keywords*—**Health monitoring, Electronic prognostics, Reliability, Usage monitoring, Notebook computer.

I. Introduction

PROGNOTICS involves assessment of a system's actual health condition, followed by modeling fault progression, predicting its performance, and determining remaining useful life. Results of diagnostic methods often provide the ground for prognostics. Diagnostic techniques for a system are based on observational data from that system and its operating environment, whereas prognostic techniques require historical performance data, system knowledge, a profile of future usage, and an understanding of the environment operating conditions.

Traditional reliability measures provide confidence that a product is going to serve its intended purpose for a certain period under specified operating limits [1]. However, they do not take into account the unforeseen changes in operating environment conditions or operating load [2]. The accuracy of any reliability prediction depends on the model defined for the system under specific environmental and usage conditions [1][3].

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Prognostics models consider the operating environmental and usage conditions in defining a prognostic distance for a product or system before it encounters a fault. This early warning may provide enough time for management to take necessary action before failure. Models assist in identifying fault progression, diagnosing faults, and predicting failures. The output of prognostic models help the system operating team to make intelligent, informed, and appropriate decisions about logistical actions based on available resources and operational demand [3] [4] [5].

For years, diagnostic and prognostic concepts and methods have been used for mechanical systems, but prognostic terminology is relatively new for electronic products and systems. For the latter, interest has been growing in predicting failures and providing warnings in advance of catastrophic, especially after the change in US DoD policy [6]. The policy mentions that the top design priorities for the development or acquisition of new weapons systems and end items are embedded diagnostics and prognostics, and equipment/system health management capability.

Electronic products can be monitored by assessing their performance indices [7] [8]. These indices from the pristine system can define the baseline performance of that system and later, the baseline can be used for identifying degradation or failures. Early detection of a problem based on baseline performance will allow preventative action to avoid problems.

To perform prognostics for an electronic product it is necessary to develop an understanding of its performance under various usage and environmental conditions. In this study, notebook computers were used to perform experiments under various environmental and usage conditions. Based on the various notebook manufacturers' suggested operating conditions, a range of environmental conditions was chosen for experiment. Usage conditions were chosen based on the report by the U.S. Department of Commerce [9]. A combination of usage conditions is not considered in this work, with the assumption that often a user does not use certain types of applications concurrently--for example, the user did not open Word and Excel files simultaneously. A user generally only accesses one software application at a time. Performance parameters are monitored and recorded using data collection software. The variability of each performance parameter is addressed by establishing an empirical relationship between the performance parameters. These equations establish the baseline performance of the parameters, which can be used to detect system deviations from normal operation and for determining prognostic distance assessment.

II. Data Collection Software

Software was developed to collect real-time performance parameter information on the notebook computers without any user intervention. The software interacts with the computer's BIOS to retrieve information and periodically writes them to log files (. txt format). Data are grouped into three categories, as shown in Table I. The C1/C2/C3 states are processor performance objects, focused on the power-save modes of the system. CPU usage is a measure of how much time the processor spends on user applications. CPU throttling sets a maximum CPU percentage for any process or service. The memory usage capacity, measured in pages per second, is the number of requested pages needed to run applications that were not available in RAM and that had to be read from or written to the hard disk to make room in RAM for other pages. This information is obtained every five seconds.

Software collects the notebook computer's hardware information, which includes the computer's service tag, the model number, the BIOS version, the maximum CPU speed, the video controller, the size of the hard drive, the hard drive make/model number, and the size of the system RAM. The computer's mechanical usage information, such as the number of times a button/key is pressed, the optical disk drive (ODD) is swapped, a battery is inserted and/or removed, and docking occurs, are recorded as well. Mechanical usage information is obtained every five minutes.

TABLE I
PARAMETERS MONITORED IN NOTEBOOK COMPUTER

Parameter	Unit	Frequency
1. Device Information		
Battery's relative state of charge (RSOC)	%	1 minutes
Battery current	mA	1 minutes
Battery voltage	mV	1 minutes
Fan speed	RPM	1 minutes
LCD brightness	SMBUS value	1 minutes
2. Thermal information		
CPU temperature	°C	30 seconds
GPU temperature	°C	30 seconds
Motherboard temperature	°C	30 seconds
3. Performance management information		
System power state, C1/C2/C3 state	%	5 seconds
CPU usage	%	5 seconds
CPU throttling	%	5 second
Memory usage capacity	pages per second	5 minutes

III. Experimental Setup

Experiments were performed on ten identical notebook computers, representative of the 2007 state of the art in notebook computer performance and battery life (nearly three and half hours on a single battery). The computers were exposed to a set of environmental and usage conditions representative of the normal life-cycle profile and likely extremes. The performance parameters were monitored in-situ during the experiment. Operational temperatures for most notebook computers are in the range of 5°C to 45°C; this experiment was conducted in the temperature range of 5°C to 50°C. For the experiment, six different environmental conditions were tested (see Table II)

The duration for each test was based on the type of power applied. When the computer was powered by an AC adapter (when the battery was fully charged), the test duration was three-and-a-half hours. When the computer was powered by an AC adapter (when the battery was fully discharged), the test duration was determined by the time it took for the battery to fully charge. When its battery powered the laptop, the test duration was determined by the time it took for the battery to fully discharge. Tests were conducted in a temperature-humidity chamber and in the ambient room environment.

For each temperature/humidity combination, four usage conditions and three power supply conditions were applied. Factorial experiments were designed to study the effect of each factor on the response variable, as well as the effects of interactions between factors. Table III lists all seventy-two experiments. Each computer was turned on for thirty minutes before starting each experiment and the computers were kept at room temperature between each test.

TABLE II
ENVIRONMENTAL CONDITIONS

Temperature- Humidity
1. 5ºC with uncontrolled RH
2. 25ºC with 55% RH (room)
3. 25ºC with 93% RH
4. 50ºC with 20% RH
5. 50ºC with 55% RH
6. 50ºC with 93% RH

TABLE III
EXPERIMENTS PERFORMED

Power Setting	Usage Level	Environmental Condition
AC adapter (when battery is fully charged)	1 - 4	1 - 6
AC adapter (when battery is initially fully discharged)	1 - 4	1 - 6
Battery only	1 - 4	1 - 6

The set of software for the experiments was installed on the computers, along with the Windows XP Professional operating system, Microsoft Office, Front page, WinRunner, Spybot, Winamp, Real Player, Visual Studio, Java 5, Minitab, iTunes, Adobe Photoshop, MATLAB, Winzip and McAfee Antivirus. A script file was written using WinRunner software to simulate user activity. The antivirus application McAfee v8.0 was configured to run on the laptop all the time.

The same environmental and usage conditions were applied to all computers to achieve time synchronization between the computer and the software application responses. The notebook's power mode was always set to ON. The screen saver and hibernation option were disabled to prevent these functions from occurring during the experiment. The wireless capability of the computer was disabled, due to the limited wireless connectivity inside the temperature-humidity chambers. Four levels of computer usage were chosen:

1. Idle system - In this category the operating system is loaded, all windows are closed, and user input from the keyboard or mouse and the optical drive is disabled. The USB or Firewire peripherals are not attached.

2. Office productivity - In this category, the usage condition is designed to simulate an office work environment. The simulator reads a Word document and prepares a new Word document. The simulator opens the file explorer and locates a file to be opened. It opens a "technology benchmark report" Word document of eighty-eight pages. The simulator reads the document, uses arrow keys to page up and page down, and selects a paragraph to copy. The simulator opens a new document from the Word toolbar and pastes the copied section to a new document. The simulator resizes both documents to toggle between them. It switches to the original document, reads pages and copies additional paragraphs, and pastes them into the new document. The simulator also types a new paragraph into the new document. With these activities, the simulator creates a five-page document and saves it. Then it saves the file by invoking the "save as file" explorer and providing a file name for the new document. The simulator does a cleanup by resizing and closing all opened documents. It then removes the new files from the desktop and pastes them into another folder. Finally, the simulator closes all opened file explorer windows.

3. Media center – In this category, the usage condition is designed to simulate entertainment conditions. The Winamp (v5.24) media player is started from the start menu. The file explorer window is opened in Winamp. MP3 music files are stored on the hard drive and selected to play in Winamp. The music is stopped after four minutes, then the Winamp player window is shut down. The Real media player (v10.5) is started from the start menu. The file explorer window is opened to select video files in Real player. Video files from a DVD are selected by maneuvering through the file explorer window and then played in Real player. Movie screens are resized to full screen. The movie is turned off after ninety minutes and Real player is closed.

4. Game mode – In this category, the usage condition is designed to simulate gaming. Quake Arena II was started from the start menu and the single player option was selected to start the game. After an hour of play, the game was stopped and exited.

IV. Data Collection and Analysis Procedure

For each set of test conditions, a time log was maintained. Data were continuously collected in each notebook computer and stored in a separate database. A set of statistical metrics--such as the mean, the median, the mode, the standard deviation, the minimum, the maximum, the kurtosis, the skewness and the ninety-five percent confidence interval--were calculated for each parameter for each set of experiments, with their corresponding environmental, usage, and power-setting conditions. Kurtosis and skewness were used to determine the normality of each dataset. The mean value of the performance parameters was used to calculate the Pearson correlation coefficient.

V. Baseline of Performance Parameters

To create a baseline of system performance, each performance parameter was analyzed. Analysis of the performance parameters revealed that they do not necessarily follow any parametric distribution over the range of experiments. Since environmental factors such as temperature, humidity, and applications (software) running on the system have a significant influence on the performance parameters. Therefore, a non-parametric method such as histograms, kernels, orthogonal series estimation, or the nearest neighbor method must be used to estimate the probability density function. Histograms and kernel density have been used for this study.

The strength and direction of a linear relationship between parameters can be expressed by the correlation coefficient. The correlation coefficient between two parameters is given in Table IVand Table V. In the tables, only significantly correlated (p-value less than 0.05) parameters and the corresponding correlation coefficients between those parameters are given.

Table IV shows parameters related to battery performance of notebook computers and Table V contains parameters related to computer performance. Different power supply sources (battery, ac adapter) had no apparent effect on the performance parameters of the system.

An empirical equation for each parameter is given to calculate expected values of the parameters. To construct an empirical equation for each performance parameter, correlated performance parameters, which describe the most variable of dependent parameters, are considered. Abbreviations used for different parameters are given in Table VI.

A. *CPU Temperature*

A histogram for the CPU temperature is presented in Fig. 1. Means, standard deviations, and range of CPU temperatures in different ambient temperature conditions are given in Table VII. An empirical equation for the CPU temperature as a function of fan speed, motherboard temperature, and video card temperature is

$$CT = -21.6 - 0.0025*FS + 0.44*MT + 0.87*VT \quad (1)$$

TABLE IV
CORRELATION COEFFICIENTS FOR BATTERY PERFORMANCE PARAMETERS

	Power source	Battery life	RSOC	Current	Voltage	%C2 state
Power source	1	-0.49	-0.75	0.58	-0.27	-
Battery life	-0.49	1	0.51	-0.88	0.63	0.26
RSOC	-0.75	0.51	1	-0.56	0.75	-
Current	0.58	-0.88	-0.56	1	-0.62	-
Voltage	-0.27	0.63	0.75	-0.62	1	-
%C2 state	-	0.26	-	-	-	1

TABLE V
CORRELATION COEFFICIENTS FOR NOTEBOOK PERFORMANCE PARAMETERS

	Fan speed	CPU temp	Motherboard temp	Videocard temp	%C2 state	%C3 state	%CPU usage	%CPU throttle
Ambient temp	0.92	0.74	0.96	0.67	0.35	-0.63	0.52	0.43
Ambient humidity	0.25	0.26	0.34	0.23	-	-	-	-
Usage level	-	0.36	-	0.44		-0.62	0.74	-0.48
Fan speed	1	0.78	0.95	0.77	0.48	-0.75	0.61	0.22
CPU temp	0.78	1	0.86	0.98	0.60	-0.81	0.66	-0.22
Motherboard temp	0.95	0.86	1	0.81	0.45	-0.70	0.56	0.23
Videocard temp	0.77	0.98	0.81	1	0.61	-0.85	0.70	-0.33
%C2 state	0.48	0.60	0.45	0.61	1	-0.46	-	-0.30
%C3 state	-0.75	-0.81	-0.70	-0.85	-0.46	1	-0.93	0.20
%CPU usage	0.61	0.66	0.56	0.70	-	-0.93	1	-
%CPU throttle	0.22	-0.22	0.23	-0.33	-0.30	0.20	-	1

TABLE VI
ABBREVIATIONS USED FOR PERFORMANCE PARAMETER

CT = CPU temperature	C3 = % C3 state
MT = Motherboard temperature	C2 = % C2 state
VT = Video card temperature	T = Ambient temperature
FS = Fan speed	H = Ambient humidity
CPU = % CPU usage	CTh = % CPU throttle

TABLE VII
STATISTICS FOR CPU TEMPERATURE

	All data points	5°C	25°C	50°C
Mean	46.7	29.6	43.3	54.8
Std Dev	12.7	5.0	4.1	3.5
Minimum	9.0	9.0	22.0	29.0
Maximum	70.0	70.0	70.0	70.0

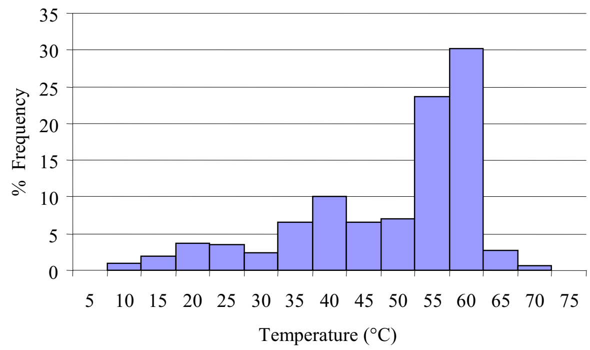

Fig. 1 Frequency chart for CPU temperature

A. *Motherboard Temperature*

A histogram for the motherboard temperature is presented in Fig. 2. Means, standard deviations, and range of motherboard temperatures in different ambient temperature conditions are shown in Table VIII. An empirical equation for the motherboard temperature as a function of ambient temperature, fan speed, CPU states C2 and C3, and CPU temperature is

$$MT = 9.59 + 0.22*T + 0.005*FS + 0.53*CT - 0.22*C2 + 0.10*C3 \quad (2)$$

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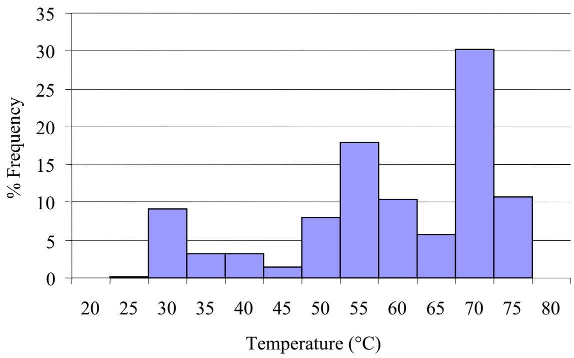

Fig. 2 Frequency chart for motherboard temperature

TABLE VIII
STATISTICS FOR MOTHERBOARD TEMPERATURE

	All Data Points	5°C	25°C	50°C
Mean	56.8	32.7	53.0	67.4
Std Dev	13.1	5.2	3.2	1.9
Minimum	25.0	25.0	28.0	35.0
Maximum	74.0	52.0	62.0	74.0

B. Videocard temperature

A histogram for the video card temperature is presented in Fig. 3. Means, standard deviations, and range of videocard temperatures in different ambient temperature conditions are shown in Table IX. An empirical equation for the videocard temperature as a function of CPU state C3, CPU temperature, and CPU throttles is

$$VT = 24.6 + 0.81*CT - 0.06*C3 - 0.08*CTh \quad (3)$$

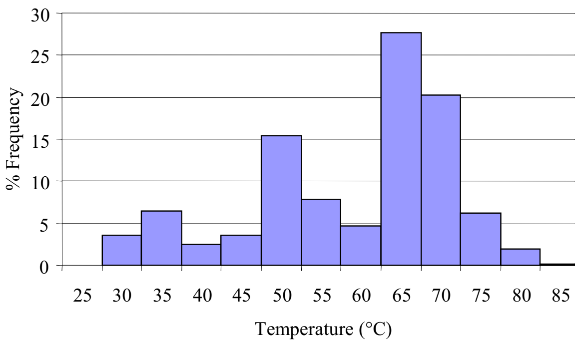

Fig. 3 Frequency chart for video card temperature

TABLE IX
STATISTICS FOR VIDEO CARD TEMPERATURE

	All Data Points	5°C	25°C	50°C
Mean	57.0	42.0	53.9	66.1
Std Dev	12.1	19.0	8.8	2.4
Minimum	26.0	26.0	35.0	41.0
Maximum	83.0	76.0	80.0	83.0

C. Fan speed

A histogram for the fan speed is presented in Fig. 4. Fan speed is a parameter that increases and decreases in steps. Fan speed predominantly depends on motherboard temperature but is fine-tuned based on the CPU temperature. Fan speed is categorized and shown in Table X. An empirical equation for fan speed as a function of ambient temperature, CPU temperature, motherboard temperature, percentage CPU usage, CPU state C3 and CPU throttle is

$$\text{Fan speed} = 0 \quad \text{when } T < 25°C$$
$$= 1506+26.2*T - 81.4*CT + 113*MT- 10.9*CPU -19.5*C3-25.8*CTh \quad \text{when } T \geq 25°C \quad (4)$$

Fan speed can be grouped into four categories based on motherboard temperature, and is given in Table X. In each category, the startup fan speed depends on the CPU temperature.

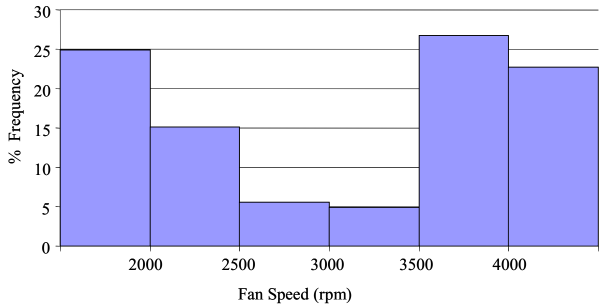

Fig. 4 Frequency chart for fan speed

TABLE X
FAN SPEED CHARACTERIZATION

Category	Motherboard temperature (°C)		Fan speed (RPM)		CPU temperature (°C)		Sub speed in group
	min	max	min	max	min	max	
1	15	50	0	0	7	64	NA
2	51	55	2422	2561	33	63	12
3	56	58	2859	3463	41	62	12
4	59	72	3903	4031	41	64	3

D. C2 State

A histogram for the CPU state (C2) is presented in Fig. 5. Means, standard deviations, and range of the CPU states C2 in different ambient temperature conditions are shown in Table XI. An empirical equation for CPU state C2 as a function of ambient temperature, fan speed, CPU state C3, CPU temperature, motherboard temperature, and videocard temperature is

$$C2 = 0.52*T + 0.01*FS + 0.97*CT - 2.56*MT + 0.72*VT + 0.35*C3 \quad (5)$$

TABLE XI
STATISTICS FOR CPU STATE 2 (C2)

	All Data Points	5°C	25°C	50°C
Mean	7.5	4.6	6.1	9.3
Std Dev	6.1	7.3	5.8	5.8
Minimum	0	0	0	0
Maximum	62	59	62	57

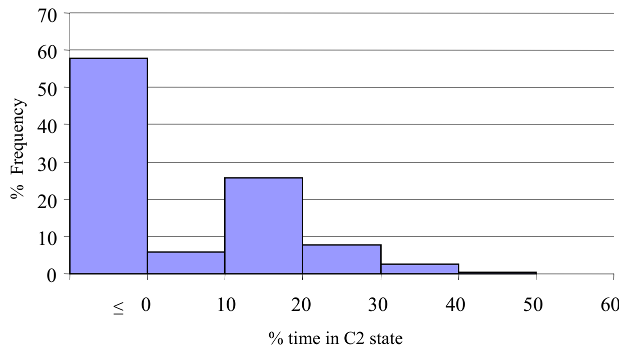

Fig. 5 Frequency chart for C2 state

E. C3 State

A histogram for the CPU state (C3) is presented in Fig. 6. Means, standard deviations, and range of CPU states, C3, in different ambient temperature conditions are shown in Table XII. An empirical equation for the CPU state C3 as a function of ambient temperature, fan speed, CPU state C2, CPU usage, CPU throttle, motherboard temperature, and videocard temperature is

$$C3 = 109 - 0.007*FS + 1.15*MT - 1.09*VT - 1.34*C2 - 0.83*CPU - 0.34*CTh \quad (6)$$

TABLE XII
STATISTICS FOR CPU STATE 3 (C3)

	All Data Points	5°C	25°C	50°C
Mean Std Dev	47.3 32.8	72.5 35.2	65.6 33.4	26.7 16.4
Minimum Maximum	0 100	0 99	0 100	0 99

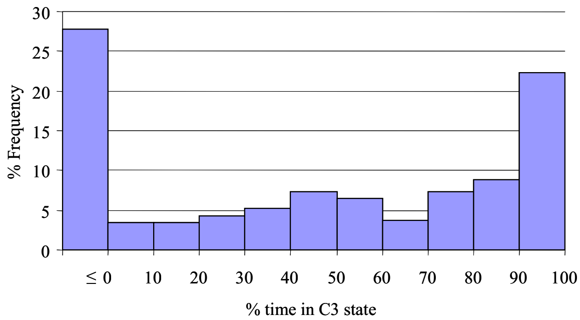

Fig. 6 Frequency chart for C3 state

F. CPU Usage

A histogram for the CPU usage is presented in Fig. 7. Means, standard deviations, and range of percentage CPU usage in different ambient temperature conditions are shown in Table XIII. An empirical equation for the percentage CPU usage as a as function of the CPU states C2 and C3 and CPU throttle is

$$\%CPU\ usage = 96.2 - 2.09*C2 - 0.94*C3 - 0.15*CTh \quad (7)$$

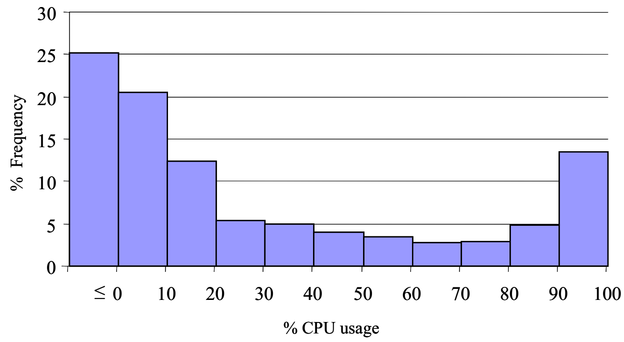

Fig. 7 Frequency chart for CPU usage

TABLE XIII
STATISTICS FOR PERCENTAGE CPU USAGE

	All Data Points	5°C	25°C	50°C
Mean Std Dev	31.2 28.7	14.2 22.2	17.8 22.5	45.8 28.3
Minimum Maximum	0 100	0 100	0 100	0 100

G. Usage Level

The usage level for a notebook computer did not show a strong linear relationship with any individual performance parameter, but showed a weak correlation with several parameters. Therefore, for usage level a non-linear empirical relationship is defined as a function of various performance parameters. It was also found that the usage load on the computer cannot be established by just knowing the name of the application running on the system. Characterization of the usage level is based on ambient temperature, humidity, and CPU parameters such as CPU states C2 and C3, CPU usage, and CPU throttle. The empirical equation for the usage level in non-linear in nature and can be expressed as

Usage Level =

$$62.4 - 0.008*H - T*(6.23- 0.25*CPU- 0.07*T*c3 - 0.004*CTh + 0.005*C2*C3 + 0.006*C2*CPU - 0.01*C2*CTh - 0.002*C3*CPU) + T^2*(0.09 - 0.001*C3 - 0.003 *CPU- 0.0002*C2*CTh + 0.00002*C3*CPU +0.00007*C2*C3 + 0.00008*C2*CPU) - CPU*(2.61- 0.116*C2+ 0.02*CPU+ 0.00206*C2^2 - 0.0003*C3*CPU- 0.0002*C3^2 - 0.0001*CPU^2) + C2*(0.07*C3 - 0.20*CTh + 0.09*C2 - 0.002*C2*C3+ 0.001*C2*CTh) - 0.01*C3^2 - 0.002*CTh^2 \quad (8)$$

VI. INFLUENCE OF ENVIRONMENTAL, USAGE AND POWER SETTING ON % CPU USAGE

Systems performance parameters will often respond uniquely to environmental factors. Analysis was performed on the experimental data to determine the effects of different environmental and usage conditions on performance characteristics. Total CPU usage is a measure of how much time the CPU spends on user applications and high-level operating system (Windows) functions. Even when the CPU usage is zero percent the CPU is still performing basic system tasks, like responding to mouse movements and keyboard input. The total CPU usage measures the amount of time the CPU spends on all tasks, including Windows. This is very useful when evaluating system performance problems based on a specific program. CPU usage in this study was measured by the operating system and collected by monitoring software.

The notebook computers were powered by one of the three possible power sources (AC adapter while battery was fully charged, battery, and AC adapter while battery was initially discharged). To neutralize the effect of different environmental and usage conditions, data from all those conditions were considered together to observe the effect of the power source. Variations in average CPU usage among different power states were not more than three percent, and fell within one standard deviation for each power state. The mean and one standard deviation are plotted in Fig. 8. The figure shows that average CPU usage (%) does not depend on the power source of the computer, although spread in CPU usage (%) in the AC adapter condition is greater. To capture more variability in the performance parameter, data corresponding to the AC adapter power setting conditions were analyzed.

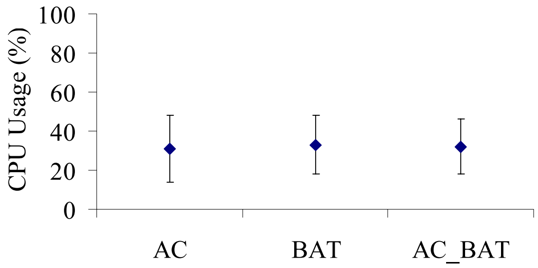

Fig. 8 Variability of % CPU usage with different power source

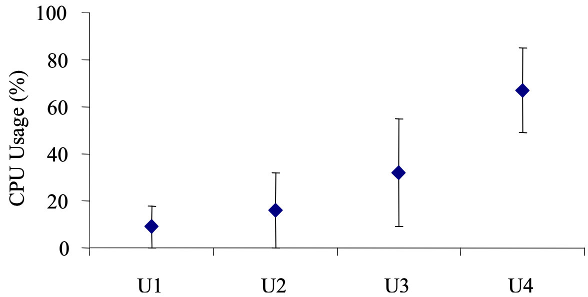

Fig. 9 Variability of % CPU usage with different usage levels

Fig. 9 shows the CPU usage metric mean and standard deviation as a function of the usage level. This validates our assumption that it is necessary to have different usage/load conditions to baseline the health of the product. However, since the spread is larger for certain use conditions, it may be possible to select preferred conditions to baseline healthy conditions.

Fig. 10 shows the CPU usage metric mean and standard deviation as a function of different environmental conditions. Similarly, this validates our assumption that it is necessary to have different environmental conditions to baseline the health of the product. Again, because the spread is larger for certain use conditions, it may be possible to select preferred conditions to baseline healthy conditions.

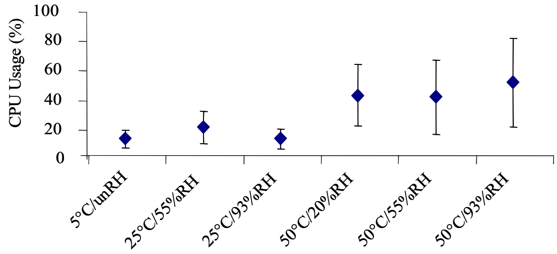

Fig. 10 Variability of %CPU usage with different environmental conditions

The combined effect of different usage levels under various environmental conditions on percentage CPU usage is presented in Fig. 11. Use level 4 is significantly different than other usage levels, regardless of environmental conditions. Except for high temperature and humidity condition, all the use conditions show results very close to each other. Our finding is that we can use 50°C/20%RH as a baseline for the CPU usage test to cover the full range of environmental and usage conditions of the notebook computer.

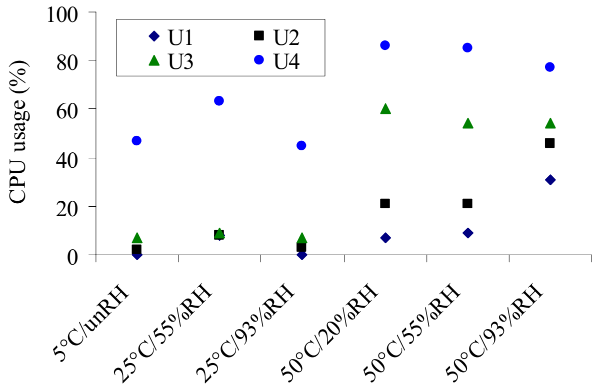

Fig. 11 Percentage CPU usages in different range

Based on the characterization and behavior of each performance parameter under various environmental and usage conditions, the system diagnostic can be performed using univariate techniques, such as time series, or by a go/no-go decision based on the differences in the parameters or by using a multivariate distance-based approach, such as Mahalanobis distance method. The multivariate approach mentioned above considers the correlation of parameters and transforms the multivariate problem into univariate problem, which is easier to interpret for decision-making and prognostic purposes. For the system prognostic, multivariate methods in conjunction with the time series technique can be used.

VII. Summary and Conclusions

This article outlines a new approach that demonstrates how to baseline a commercial electronics product by considering an electronic product's life-cycle profile. This approach could be applied to any system and emphasizes utilizing embedded sensors. It also highlights the need to understand the correlation and the variability of performance parameters.

To assess environmental and usage conditions associated with electronic products for prognostics, automated program scripts were written to perform a typical user's activity. These scripts also provided an opportunity to expose all the computers to a similar workload during the experiment. This reduced the uncertainty that could have arisen due to variations in a user's activity in terms of response time. The user's activity was simulated by defining different usage levels.

The experiments were designed to evaluate variations and trends as well as the extreme value a parameter can attain in various usage and environmental conditions. The variability of performance parameters was defined using an empirical relationship, as a function of other performance parameters.

Using external sensors could have been detrimental for the electronics product, due to such reasons as the possibility of electromagnetic interference, electrostatic discharge, and a change in failure mechanism. Therefore, software was built to collect data from the system BIOS, where information from different embedded sensors was collected to optimize system operation and its cooling requirements. This software interfered only minimally with system performance. Analysing the experimental data reveals that several computer performance parameters are significantly correlated, but that battery performance parameters are not significantly correlated to notebook computer performance parameters. Various performance parameters are dependent on the ambient temperature, humidity, and product usage. The performance parameters are multi-modal in nature, and a parametric method cannot be used for density estimation for performance parameters over the entire range of experiment. A non-parametric method can be used to estimate the probability density function (PDF), such as histograms, kernels, orthogonal series estimation, and the nearest neighbor method. This underlines the need for extreme care when assuming a certain PDF for the component or system for the entire range of applications under various environments.

A linear empirical relationship for each performance parameter is defined in the text. This explains the contribution of individual independent parameters in the definition of dependent parameters. This relationship can assist in system diagnostics. The measure of difference between expected and observed parameters can give an indication of the severity of an abnormality. This difference in parameters can be used for the system state determination based on a time-series and the Markov state model. Thus, this baseline approach is useful not only for diagnostics but also sets a platform to perform prognostics.

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