

# Intelligent Monitor and Trigger System

Udanie Salgado

**Abstract**—The primary objective of this project is implementing an intelligent monitoring and trigger system. The chosen application domain was the thermal processing involved in semiconductor manufacturing environments. The solution makes use of an Agilent U2300 series data acquisition card and other temperature sensing circuit elements and the computer software is implemented using Agilent VEE. This system allows monitoring and recording of the temperature of the bake plate and the wafer using eight RTD sensors. The acquired data are observed to make sure that the temperature from each sensor or the variation of the readings between each other does not go beyond critical limits as set by the user. It is also sensitive to any sharp jumps in the temperature from a sensor. If any of these conditions are met notifications will be sent out to the respective engineers to inform of the events via email and SMS using a GSM modem. The system also includes a PI controller that will be used to maintain the temperature of the bake plate. Further more digital outputs from the DAQ card are used to activate emergency systems such as lamps and alarm systems. It was also important to implement a flexible and customizable system. The solution approach adapted in this system can be generalized into real application domains in many industries where intelligent monitoring systems are used to maintain a required process environment.

## I. INTRODUCTION

ALL typical manufacturing processes have to be monitored around the clock and it is not feasible for the engineers or technicians to be always present to accomplish this purpose. Therefore intelligent systems are used to monitor these processes continuously and take necessary action if a situation needs attending to and to aid in maintaining a positive and safe process environment. The monitoring system will watch environmental variables and if they reach certain preset limits or show any undesired patterns, the respective engineer can be triggered via SMS and email and the affected machine can be shutdown or emergency systems can be activated.

Typically intelligent monitoring systems are used in settings where multiple environmental / process variables have to be monitored. For example in a pharmaceutical plant where hundreds of readings are taken of temperature and pressure of chambers, pH levels and flow rates of chemicals, and valve positions. These variables have to be monitored and controlled using various kinds of sensors and other circuit elements. Such large systems can be scaled down to much smaller systems for development purposes.

The bake plate/wafer systems available in the Advanced

Control Technology Lab, National University of Singapore were selected as the test bed for this project which previously has been the test bed for other such experiments [1]. Temperature monitoring and control of the bake plate is a critical factor in lithography, within systems which handle thermal processing of semiconductor wafers.

Another objective of this project is to develop applications which monitor physical variables using Agilent VEE Pro and the Agilent U2300 Series Data Acquisition (DAQ) Hardware.

As per the above description the following three tasks were involved in the completion of this project:

1. Understanding the Agilent VEE Pro or VEE Express and U2300 Series Data Acquisition products.
2. Developing the test bed for the measurement system.
3. Developing the software required for the various subsystems of the project.

The Agilent U2353A 16 channel multifunctional DAQ and Agilent VEE Pro 8.0 Education Version were provided [2]. Other than using Agilent products for data acquisition and processing, other components such as sensors and signal conditioning elements are to be incorporated into the project.

This paper will next include a summary of the background then it will explain the project requirements which were used to come up with the designs for the hardware and software subsystems. Following that it will include a detailed description of the implementation of the subsystems such as acquisition and measurement of the temperature and checking trigger conditions to take appropriate action depending on the situation. It will then conclude with an evaluation of the work done so far and suggestions for further improvement of the project.

## II. PRELIMINARIES

### A. Intelligent Monitoring and Control Systems

Effective Control Systems are the primary components for most mechanisms. Intelligent monitors are extremely useful in facilitating such control mechanisms and at the same time are extremely complex to implement. Intelligent monitors often have real-time constraints i.e. they need to respond to a certain event within a given time period or less [9], [10]. Therefore, Control Systems where constant feedback is received and processed to produce the new output signal are perfect examples of real-time systems that can be enhanced using an intelligent monitor. A major challenge for Intelligent Monitoring is the fast evolving nature of computer systems and particularly in the case of this project; a change in the technologies used could lead to having to

---

This work was supported in part by Agilent Engineering Excellence Programme.

Udanie Salgado is with the Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore (e-mail: udanie@nus.edu.sg).

adapt the monitor accordingly.

### B. Temperature Monitoring in Lithography

Lithography consists of a sequence of steps carried out on a semiconductor substrate such as a wafer that is used for making semiconductor chips in order to transfer a pattern from a mask containing this information to the wafer. These processes involve a number of baking steps such as soft bake, postexposure bake, and postdevelop bake. Baking involves heating the wafer to a given temperature for preset amount of time, and there is a chill step associated with each of these bake steps. These cooling steps prepare the wafer for the next process in the lithography sequence [3]. In lithography these baking steps are performed by mechanically placing the wafer on the bake plate for a given period of time. The preheated bake plates are held at a constant temperature by the use of temperature sensors that are embedded close to the surface of the bake plate. A feedback controller would use the input from them to maintain the temperature if there are any disturbances, such as when the wafer is initially placed on the bake plate. These processes are automated in wafer fabs where the next wafer arrives immediately after the baking of the first wafer [4]. During these bake steps temperature control is critical because the chemical reactions of the photoresist are extremely dependent on the temperature. The post-exposure bake step has the most stringent requirements. It is also expected that the future generations of lithography would require further more precise temperature control and this would be a vital issue [1].

### C. Data Acquisition



Figure 1. A typical DAQ System

A typical data acquisition system consists of four parts; sensors, signal conditioners, DAQ card, PC. In the current bake plate system temperature is read using Platinum Resistance Temperature Detectors (RTD). Benefits of using RTD sensors over other such sensors like thermocouples and thermistors is that RTDs can be more accurate and provides greater stability and repeatability. The variation in the resistance of the RTD with its temperature is documented and therefore a change in resistance can be used to evaluate the temperature. The RTD operates within very low current limits because as the resistance of the RTD increases the power dissipated by the device can cause self-heating and produce an erroneous reading [5] – [7].

The DAQ used is the U2353A, which is a basic multifunction DAQ which can sample 500kSa/s. This includes up to 16 single ended inputs or 8 differential inputs (up to  $\pm 10V$ ), 2 analog output ports, 24-bit TTL compatible programmable digital I/O.

Communication with the DAQ can be handled using VEE,

a graphical programming language developed by Agilent Technologies to work together with test and measurement instruments. This programming language allows the use of the IVI-COM driver when interfacing with the DAQ. IVI (Interchangeable Virtual Instrument) is a new standard put forth by the IVI Foundation in order to promote specifications for programming test instruments and to create a driver standard that allows instrument interchangeability while still providing quality and high performance along with reduced cost of program development and maintenance [8]. Programming the DAQ can also be done using direct I/O transactions written according to SCPI (Standard Commands for Programmable Instruments). It is an ACSII based instruments command language designed for test and measurement instruments.

### D. Controller Design and Tuning

A proportional-integral-derivative controller (PID) is a commonly used control loop feedback mechanism. The process output is read in using sensors and is compared to the set point given by the user. The controller manipulates its output in order to reduce the error between the sensor reading and the set point. The performance of the PID controller depends on the proportional, integral and derivative gains and these values are adjusted until the controller output can make the process reach its set point in the shortest time with the least possible overshoot and oscillation of the output [11]. An open-loop tuning method involves applying a step change to the monitored system when the system is in a stable position and observing the system response to identify the parameters of the process dead time ( $T_d$ ) and the reaction rate ( $R_r$ ) which can then be used to calculate the gains of the controller [12].

## III. DESIGN

The requirements of the intelligent monitor and trigger system can be summarized as shown in Figure 2. This block diagram shows that wafer and bake plate temperatures can be monitored using the sensors that are connected to the DAQ through the signal acquiring circuit. The control signal is sent to the power source which is connected to the bake plate's temperature controller. The software block of the system is the box with the dotted line. The control inputs from the user include the critical limits in the trigger conditions, set point for the controller, mail message settings. The software allows the user to do live monitoring of the system as well as maintain event logs.

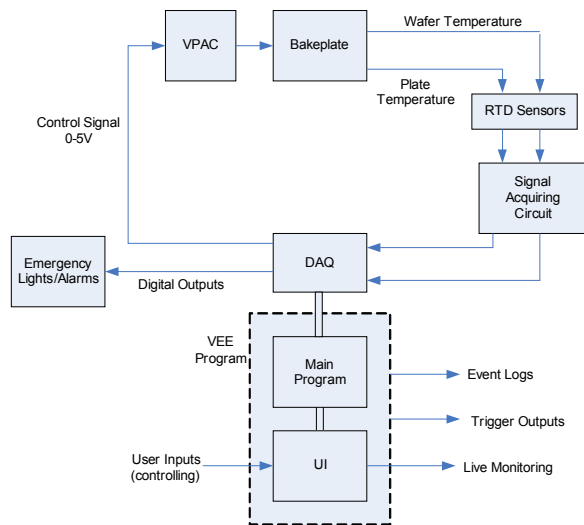


Figure 2. Project block diagram

The power source (VPAC) will have two of its inputs connected to the main power line and the output lines from this power source are connected to the heating element in the bake plate. These hardware connections of the above design are shown in Figure 3.

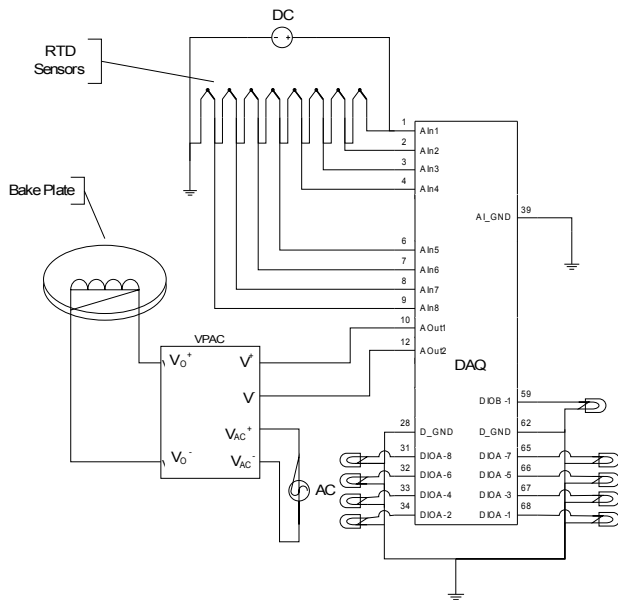


Figure 3. Hardware layout

The analog inputs of the DAQ will be connected to the sensors. The analog output channels will be connected to the control inputs of the power source while the digital outputs will be used to drive a set of LEDs which represent the emergency alarm/ light systems of the process environment. It should be noted to connect the correct ground pins of the DAQ. At the analog inputs a single-ended connection is applicable as they would be referenced to a common ground which is shared between all the inputs. Therefore it will operate in referenced single-ended (RSE) mode with the common ground connected to the AI\_GND

pin and not the AI\_SENSE pin which helps to reject the common mode signal in the inputs.

The software will have five main subsystems as processing and calibration, controller, user interface, triggering and data logging as shown in Figure 4 and will be described in detail in the next section.

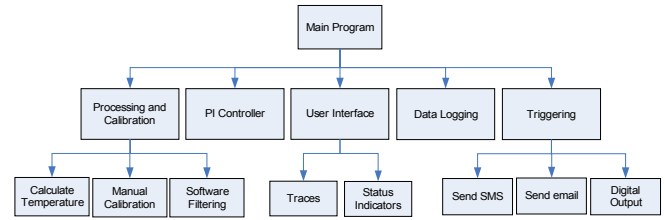


Figure 4. Project block diagram

#### IV. IMPLEMENTATION

RTD sensors were used to read the temperature with some connected to the bake plate and others connected to the wafer. As this is a single zone bake plate only one power controller will be used to send out the temperature control signal.

##### A. Signal Acquisition and Calibration

The Honeywell HRTS-5760-B-T-0-12 Platinum RTD sensors are used to measure the temperature. Once the resistance of an RTD is obtained, this value can in turn be used to calculate the temperature.

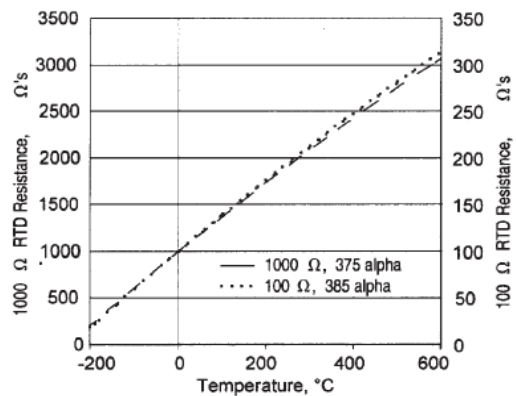


Figure 5. Resistance vs. Temperature curve of the sensor [13]

According to the datasheet of the RTD sensor the recommended operating current is 1mA and the maximum is 2mA. Obtaining a very low accurate current source was a difficult task as the power sources available in the lab were not precise enough. Therefore the following sensor arrangement which uses the potential divider principle was designed. The resistor in series with the sensor should be in the same range as the sensor (to reduce noise) and 147Ω resistors were added to the circuit. Then for a resistance range of 100Ω to 150Ω from the sensors, the current in the circuit with a 0.3V source will be between a minimum of 1.01mA (0.3/297) and a maximum of 1.21mA (0.3/247)

which satisfies the operating conditions of a RTD sensor.

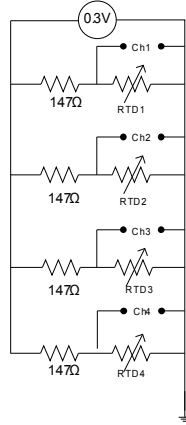


Figure 6. Final circuit for the RTD Sensors

The readings from analog input channels can be used in the following formula to calculate the resistance of the RTD where  $r$  is the resistor in series with the RTD,  $V_i$  is the voltage measured at channel  $i$ , and  $V=0.3V$ .

$$R = \frac{rV_i}{V - V_i} \quad \text{The datasheet [13] of the RTD describes}$$

its functional behaviour using the following formula,

$$R_T = R_0 (1 + AT + BT^2) \quad \text{for } T > 0^\circ\text{C}$$

$R_T$  is resistance at temperature  $T$ , with  $A=3.908 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$ ,  $B=-5.775 \times 10^{-7} \text{ } ^\circ\text{C}^{-2}$ , for RTDs with the temperature coefficient  $\alpha = 0.000385$  and resistance at  $0^\circ\text{C}$  is  $R_0 = 100\Omega$ .

By substituting these values into the equation and simplifying it we can obtain the following equation which can be used to calculate the temperature  $T$  for a given resistance,  $R_T$ .

$$T = \frac{-0.3908 + \sqrt{0.1758 - 0.000231R_T}}{-0.0001155}$$

The behaviour of four sensors was monitored at preset temperatures using a heat bath and the results were then used to identify four characteristic equations which describe the relationship between the temperature and sensors' resistance. First order polynomials were used to obtain a good fit with the actual values. When comparing the actual temperature of the heat bath to the result that can be obtained using formula from the data sheet; the general relationship for all sensors, the difference is minimal and therefore the general formula will be used in place of individual formulae in the software.

### B. Controller Design

A PI controller is implemented for the single zone bake plate system and  $K_p$  the proportional gain of the controller,  $K_i$  is the integral gain, and the set\_point are variables that can be set by the system user.

An analog output channel of the DAQ is used to send out the control signal to the power controller. The Watlow DIN-

A-MITE Style C is used for this application and the control signal sent to it should be maintained between 0-5V for proper and safe operation of the whole system. To implement this requirement into the system, if the output of the PI algorithm falls outside of 0-5V then the respective minimum or maximum value is presented as the output.

Once the controller is designed a loop tuning method described in Section II was used to get its parameters optimized. This is very important in this application because even though the heating of the bake plate can be fast in response to a change in the set point but the cooling of the system is a much slower process. Therefore the overshoot of the system should be minimized in order to have a faster settling point. The controller is designed with a 2% tolerance between the steady state temperature and the set point given by the user.

### C. Trigger Subsystem

The triggering subsystem is responsible for checking the data read in through the DAQ for conditions that are not favourable to the wafer/bake plate system, send out notifications regarding these events to the respective engineers and also to maintain a record of them within the system. The conditions that the program will respond to are,

1. If a temperature reading from any input channel is greater than a preset value as this would be harmful to the process environment.
2. If the maximum difference between any two readings is more than a preset value as this would indicate that the temperature variation across the wafer is too much.
3. If there are any unusual trends in the input data; sharp jumps.

Checking for the first condition is relatively easy and it only requires the user to provide the maximum tolerable and safe temperature for the system. For the second condition the program should obtain the maximum and the minimum of the set of readings from the channels and compare the difference between these two values to a limit given by the user. The output from this stage (the absolute difference) will be available for the user to view in a trace placed in the user interface. The third condition needs a more complex implementation where the gradient of the temperature variation through a number of sampling points (as set by the user) will be used to detect these sharp jumps. The user is allowed to set the maximum gradient at a given point, and the number of consecutive times this maximum gradient should occur in order to classify a sharp jump. A counter is used to accomplish this and if a maximum gradient does not occur enough times consecutively the counter will be cleared.

Once a trigger condition and the input channel is identified as described above the set of functions which handle sending out notifications will be called. These are organised into a library of user functions. They need to be called with details such as which message to send out and

which digital output channel to activate for the LEDs that show the status of channels. It will be undesirable for the program to keep sending out notifications about the same channel for example if a channel's temperature goes above the desired limit. Therefore the program maintains a global list of channel numbers whose status has changed. Only if a channel number is not already in the global list and if so the channel will be added to the list before calling the other functions. The details of the persons that are to be notified such as the name, phone number and email address will be stored in a file that will be accessed by the program when a notification needs to be sent out. These steps are summarised in the flow chart shown below.

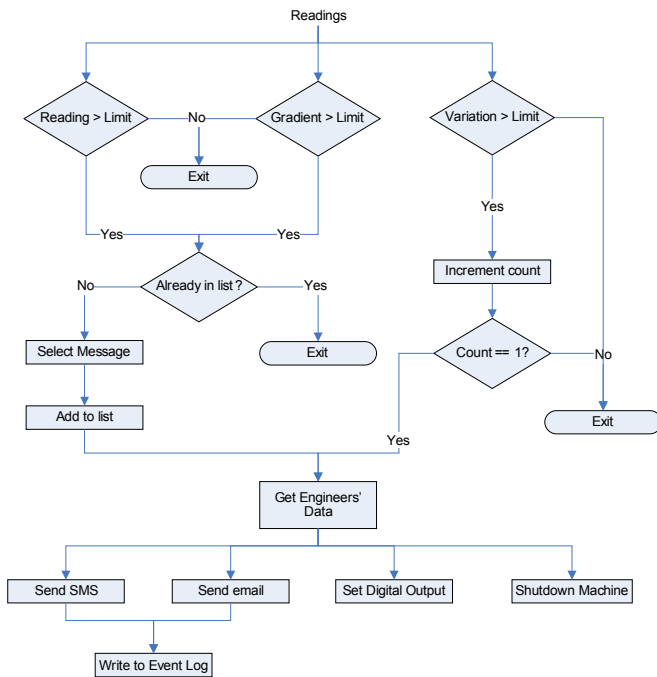


Figure 7. Trigger System flowchart

When sending out the SMS the software should communicate with the program SendsMS [14], which is the intermediate program that will communicate with the GSM modem. This instruction is executed when calling the program to pass the recipients numbers and the message to be sent.

```
sendsms.exe /port:com2 /baudrate:115200 /safe
<rec> "<Title><message><Timestamp>"
```

An email is sent using the Simple Mail Transfer Protocol (SMTP) that is supported by Agilent VEE. The System.Web.Mail namespace classes don't expose an API for providing credentials to an SMTP server but most modern servers require this action [14]. This has to be achieved by defining configuration settings for the Configuration object associated to the Message CDO. The settings for connecting to the SMTP server such as the server address, username and password should be set by the user. Further more if any of these trigger conditions are met

the system will set its bake plate control signal to zero effectively switching off the system by adjusting the analog output to zero.

#### D. User Interface

The main feature of the user interface (UI) will be to display the current temperature reading for the eight input channels connected to eight RTDs. It will also have two other plots which show the variation between the readings and the output of the controller. The 'start' button will allow the user to start the data acquisition while the 'pause' button will allow them to stop reading the temperature temporarily. Pressing the exit button will stop the process of data acquisition and send the closing instructions to the DAQ as well as close all the open libraries such as Microsoft Excel. Using this button to exit the program is important to make sure that all the sub threads of the program exit normally and all the data logged is saved properly.



Figure 8. The Front Panel

The UI allows users to select which plots are displayed currently by using a set of tick boxes. Other than showing the current temperature on the trace, it is also shown as a number. The column next to these labels is a set of elements which allow manual adjustment of the readings from the DAQ since there could be discrepancies between the readings at the start of the experiment where all the RTDs are actually at the same temperature. The readings can be different due to many reasons such as performance and characteristics of the sensors and other circuit elements not being constant over time. The results of the trigger condition checks are available with the use of a set of elements resembling nine LEDs, eight for each channel and

one for the status of the overall variation of temperature across the wafer. The colour of these elements will be set to green at the start of the program and will turn to red if any of the trigger conditions are satisfied. All the plots have an auto scale button and also allow the user to select the range of the display area at run time. It also lets them zoom in on any area on the plot. The last section is related to the PI controller. The text box allows the user to give the set point. Users can select which input channel should be used as the input to the controller. These two inputs can be adjusted while the program is running.

#### *E. Data Logging*

All the data that are being read in by the eight sensors are written to a Microsoft Excel work book. This is done through the use of the excel library available within the VEE programming environment. The output filename will be created using the time that the process was started. Example: `bakePlateOutputAt_01_04_2008_10_50_25_AM.xls`.

#### *F. SMS Request*

The system handles temperature queries in the form “? temperature” sent to the modem. This is done by polling the modem every 15 seconds and replies are sent with the readings from the DAQ. This feature can be extended to allow other data to be queried as well as remote controlling.

### V. FURTHER IMPROVEMENTS

The system can be further improved by incorporating the following features. A more verbose email can be sent out which includes dynamic data such as the channel readings leading up to it in the form of tables or charts, rather than the current static message describing which event occurred. A new admin panel could be added which allows access to all user defined variables in the system. This will centralize these variables as well as improve user efficiency, reduce mistakes and abstract away from the program details. More buttons could also be added to give more control over the program. Some of them are a record button which will indicate when data logging should be started, a reset button to clear data structure such as the list of triggered channels, and an on/off switch for the controller which will give the user an option of using the system only for monitoring and triggering.

### VI. CONCLUSION

At the beginning this paper has presented the motivation for creating this intelligent monitor and trigger system and background information on related topics. Then the current design and implementation of this design was discussed. Understanding and learning the Agilent VEE programming language was essential in building a useful and effective program. Along with successfully building a working

program, the hardware required for supporting the bake plate test bed was also designed and implemented after many iterations. In the design presented in this paper the goal of building an intelligent monitoring and trigger system, described at the beginning, has been met.

### ACKNOWLEDGMENT

The author would like to thank Dr. Arthur Tay, Agilent Technologies, Ms. Wathi and Ms. Yuheng for their kind support.

### REFERENCES

- [1] Ho, W. K., Tay, A., and Schaper, C. D., “Optimal Predictive Control with Constraints for the processing of Semiconductor Wafers on Bake Plates,” *IEEE Transactions On Semiconductor Manufacturing*, Vol. 13, No. 1, pp. 88–96, 2000.
- [2] Agilent U2300A Series Multifunction USB Data Acquisition, User’s Guide, Agilent Technologies Inc. 2006.
- [3] El-Awady, K., Schaper, C. D., and Kailath, T., “Programmable Thermal Processing Module for Semiconductor Substrates,” *IEEE Transactions On Control Systems Technology*, Vol. 12, No. 4, pp. 493–509, 2004.
- [4] Tay, A., Ho, W. K., Schaper, C. D., Lee, L. L., “Constraint feedforward control for thermal processing of quartz photomasks in microelectronics manufacturing,” *Journal of Process Control*, 14, pp. 31–39, 2004.
- [5] Omega Engineering, “RTDs,” [omega.com](http://www.omega.com/rtd.html), 2007. [Online]. Available: <http://www.omega.com/rtd.html>. [Accessed Oct. 23, 2007].
- [6] Nave, C. R., “Resistance: Temperature Coefficient,” *HyperPhysics*, Georgia State University, 2005. [Online]. Available: <http://hyperphysics.phy-astr.gsu.edu/hbase/electric/restmp.html>. [Accessed Oct. 25, 2007].
- [7] National Instruments, “Resistance-Temperature Detectors,” *Developer Zone – National Instruments*, 2006. [Online]. Available: <http://zone.ni.com/devzone/cda/ph/p/id/208>. [Accessed Oct. 23, 2007].
- [8] IVI Foundation, “IVI Overcomes Industry Challenges,” *IVI Foundation*, 2007. [Online]. Available: <http://ivifoundation.org>. [Accessed Sep. 27, 2007].
- [9] Factor, M., and Gelenter, D. H., “The Process Trellis: A Software Architecture for Intelligent Monitors,” *IEEE International Workshop on Tools for Artificial Intelligence Architectures, Languages and Algorithms*, 1989.
- [10] Xu, M., Shen, S., and Mukkamal, R., “An Approach to Intelligent Monitoring,” *IEEE /ACM International Conference on Developing and Managing Expert System Programs*, 1991.
- [11] Franklin, G. F., Powell, J. D., Workman, M. L., “*Digital Control of Dynamic Systems*”, 3rd edition, Prentice Hall 1998.
- [12] Ishak, A. A., and Ahmad, A., “Application of Numerical Technique in Tangent Analysis of a Discrete Step Response Data,” *Student Conference on Research and Development*, 2002.
- [13] Honeywell, *Temperature Sensors – Platinum RTDs – HRTS Series [Data Sheet]*, Microswitch Sensing and Control.
- [14] Mayr, S., “Sending short messages (SMS) via GSM mobile phones,” 2007. [Online]. Available: <http://www.scampers.org/steve/sms/index.htm>. [Accessed: Mar. 13, 2008].
- [15] Microsoft Corporation, “How to enable SMTP Authentication using System.Web.Mail,” *Microsoft Help and Support*, 2005. [Online]. Available: <http://support.microsoft.com/kb/555287>. [Accessed: Feb. 3, 2008].