Automation of a Vacuum Furnace

Robert Lynn Mueller
The Pennsylvania State University
New Kensington Campus

Abstract
A vacuum furnace is a device used in the production of silicon carbide crystals which are used in certain military applications. In order to create these crystals, a source material must first be made by combining silicon and graphite and baking it at temperatures which reach 3000° C in a perfectly uncontaminated environment of argon gas. By heating the crystals in a vacuum, it is possible to reach the necessary temperatures with less lower power as compared to heating at atmospheric pressure. This paper presents the design and implementation of a vacuum furnace automation project that was done as an Electro-Mechanical Engineering Technology capstone senior design project. The automation was designed for a vacuum furnace that previously had only manual controls. The upgrade included additional instrumentation and a LabVIEW HMI for process monitoring and control, data collection, and recipe entry. This project was supervised by the Electro-Optics Center of Penn State University's Applied Research Laboratory.

Senior Project Course

The senior project is a capstone project course taken in the final term of the 4-year Bachelor of Science in Electromechanical Engineering Technology (BSEMET) degree offered at Penn State University New Kensington. The objectives of the course are to train the students in project management, communication skills (both written and oral), budgeting, application of engineering skills, and team building. Each project team consists of 2 students (or one team of 3 if the course has an odd number of students) and the students are allowed to pick their own teams. The team is usually responsible for selecting its project with the condition that the project must contain at least 3 fundamental components: measurements from an electromechanical system, control decisions based on those measurements, and then the control of electromechanical elements to achieve some design criteria.

During the first 2 weeks of the course, the student-teams work with the course instructors to discuss potential projects. For this term, the students were assigned projects. At beginning of the 3rd week each team must make a formal project proposal presentation. This presentation and written report account for 10% of the overall course grade. To accomplish the administrative objectives of the course, the project team must provide biweekly written and oral progress reports on project design-updates, schedule, and budget. This accounts for 25% of the course grade. At the end of the term, each project team is required to write a group project report detailing the project's design and budget; this accounts for 25% of the grade. A formal project presentation that includes a demonstration of the project is also required and this counts for 25% of the grade. Additionally, each student also writes a "journal-style" paper regarding one particular technical aspect of the project. This contributes the remaining 15% of the course grade.

Electro-Optics Center
The Electro-Optics Center (EOC) [1] is a research facility located at Freeport, PA and is devoted to the development of silicon carbide (SiC) crystals for use in military-grade electronics. The EOC had previously used Physical Vapor Transport (PVT) furnaces for the research and development of the crystal growth process. These PVT furnaces are very expensive to operate and require large power consumption not only for the heating process, but also to run the cooling system to keep them from overheating. These furnaces have a large capability, much more than is required for the SiC synthesis process, making them somewhat of an overkill for this process. This overkill situation with the PVT furnaces is what brought about the purchase of the Red Devil vacuum furnace that is manufactured by RD Webb. The Red Devil is a relatively low cost furnace compared to the PVT furnaces, and has considerably lower operating costs. Power consumption is much lower with the Red Devil furnace compared to the PVT furnaces (2kW compared to 25kW), and the Red Devil requires no water cooling, aiding further to the low operating cost. The Red Devil is very user-friendly and its simplicity is better suited to the synthesis process.

One of the students on the two-man team for this project had been hired as an intern at the EOC in the Spring semester of his junior year. The student worked part-time during school semesters and full-time during the summer. This was the campus' first formal internship with local industry. While the internship was a paid position, the student was not paid for the time spent working on this project. Upon graduation, this student was hired full-time by the EOC.

The Process
One of the crystals that the EOC is developing is silicon carbide (SiC). In order to create these crystals, a source material must first be made by combining silicon and carbide powder in an uncontaminated environment and then apply controlled heating that can reach 3000 °C.

Earlier methods for this process used physical vapor transport furnaces which require large amounts of power for heating as well as a cooling system to keep the furnace itself from overheating. They typically require 480 Volt 3-phase with power ratings of around 25 kW. They also have problems keeping the environment uncontaminated. More recently, it has been found that much higher temperatures could be reached while maintaining low power levels by adding a vacuum chamber to the resistive furnace. These furnaces require only 120 Volt single phase with power ratings of around 2 kW. The addition of the vacuum process keeps atmospheric gases from the reaching the growth material. Several vacuum process cycles purge the atmospheric gases and replaces them with argon gas which is a nonvolatile gas that will not contaminate the growth material. The temperature and pressure of the crystal growth process must be controlled according to a recipe in order for proper growth to occur; some of the recipes can takes hours to complete. This can result in less than perfect crystal growth when the operator is the one controlling the temperature and pressure over this long period of time.

Red Devil Standard Equipment

The Red Devil vacuum furnace shown in Figure 1 [2]. The furnace chamber is on the left and the control unit is on the right. The basic Red Devil furnace comes standard with a Eurotherm PID process controller that is capable of controlling two process variables (PV) but it is only used to control temperature. Temperature is measured by a thermocouple and a pyrometer. At temperatures up to 1425ºC the PV is 100% from the thermocouple and at temperatures above 1475ºC the PV is 100% from the pyrometer. In between, the measurement is a "mix" of the two and this provides for a bumpless transfer between the two devices; this switchover is done automatically by the Eurotherm PID controller. It is recommended that the thermocouple be removed from the furnace chamber when the temperature is above 1500ºC because high temperatures greatly reduce the thermocouple's life. In fact, when the temperature reaches 1600ºC, the thermocouple acts as an over-temperature device and shuts the furnace down.

The Eurotherm is also capable of having up to 20 recipes programmed into it. A recipe is a group of time-based segments where each segment specifies how the temperature is to be varied during that segment. It can be a "ramp" to a new value or a "hold" at the current value. It is possible for the controller to hold in a segment if the new temperature is not reached by the end of the segment. Before this project, the EOC operators did all of the ramping of temperatures (and pressures) manually and did not use the Eurotherm's recipe feature.

The pressure is controlled manually by turning the rotary vein vacuum pump on and off and is capable of reaching vacuums of 10^{-3}mbar. An active linear Pirani pressure gauge is used to measure pressure and its output is sent for display-only to the display unit for the 2nd process variable on the Eurotherm. The operator then uses the display to control the pressure by turning the vacuum pump on and off. Argon is controlled manually by opening the value on the argon tank "a little bit"; this results in an argon flow that varies with the vacuum in the furnace chamber.

Figure 1. Red Devil Vacuum Furnace

Modifications and Additions for Automation

The goals of this project were to add the following features:

1. A Human-Machine-Interface (HMI) to monitor the process
2. Achieve higher vacuum pressure
3. Recipes that specify both the temperature and pressure
4. Control of argon flow
5. Protection of the thermocouple at high temperatures

Implementation of these items satisfied the technical requirements of the course in that measurements are taken from an electromechanical system, control decisions based on those measurements, and then the control of electromechanical elements to achieve some design criteria.

Please refer to Figure 2 for a control block diagram of the new system.

HMI Interface

LabVIEW [3] was selected as the HMI for this process because it was already in use at the EOC and has all the necessary capabilities to incorporate the other features to be added.

Pressure Control

Part of the automation upgrade was to modify the furnace so that higher vacuum pressures could be achieved. In order to achieve this it was necessary to add instrumentation that could measure higher vacuum pressures as well as a vacuum pump that achieve higher vacuums. The pressure process can be split into two parts: a rough vacuum stage ($>10^{-3}$mbar) and a high vacuum stage ($>10^{-6}$mbar). The rough vacuum stage is now controlled by a newly added throttle valve in conjunction with the standard rotary vein roughing vacuum pump. High vacuum is now controlled by a turbo molecular vacuum pump and a new hot filament ion gauge.

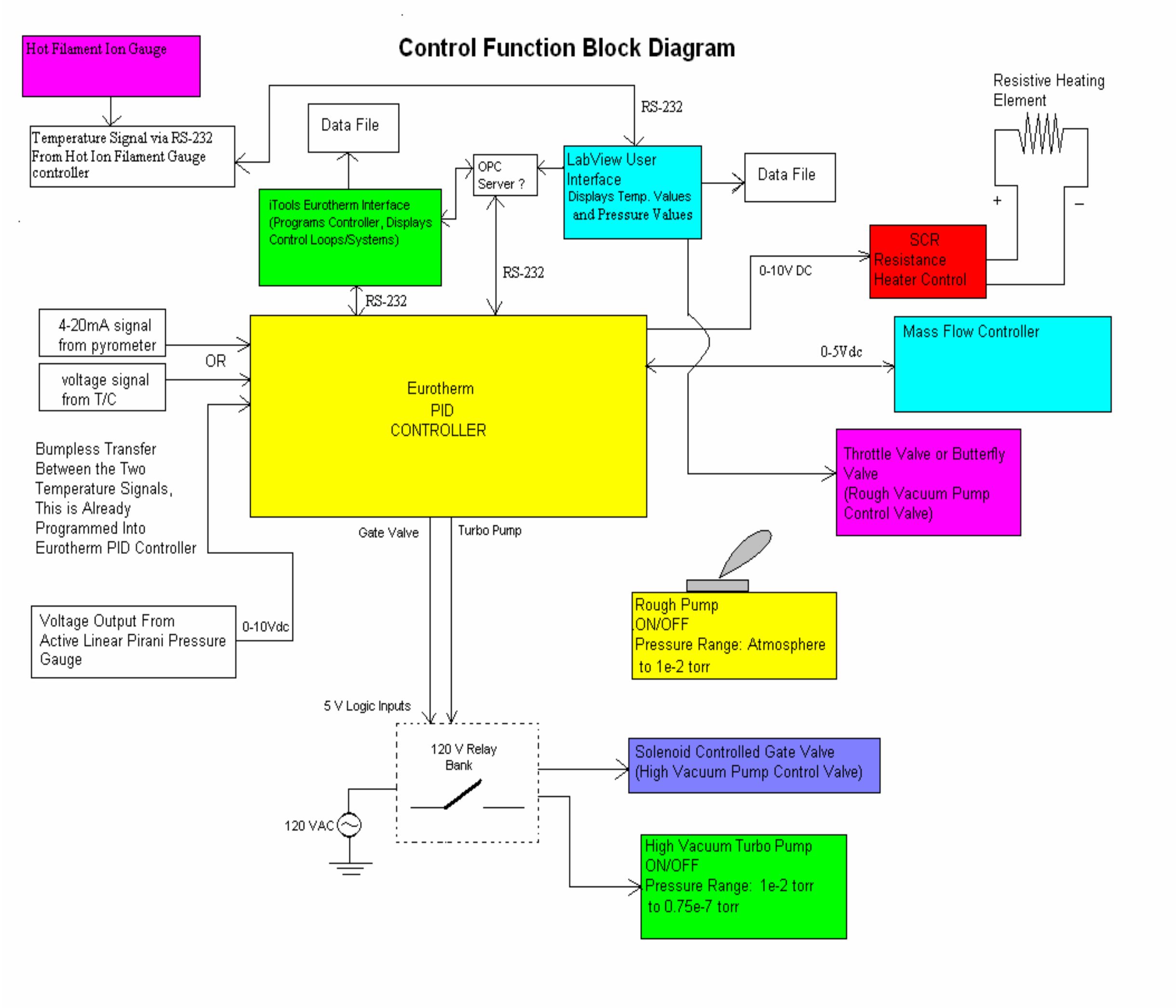

Figure 2. Control Block Diagram of the Automated Furnace

The new throttle valve PID controller processes a 0-10 Volt DC feedback signal from the Pirani pressure gauge. The new recipe feature contains a time-based setpoint corresponding to a percentage of full-scale 0-10 Volt DC output to the controller. The controller adjusts throttle position to regulate the exhausting of gases from the chamber by reducing or increasing the amount of gas the rough pump is allowed to pump.

The high vacuum process consists of three major components that require control: the turbo molecular vacuum pump, the solenoid controlled gate valve, and the hot filament ion gauge.

The new turbo molecular vacuum pump is used to pump the chamber from low vacuum pressures of 10^{-3} mbar down to pressures of 10^{-6} mbar. In order to prevent damage to the turbo pump, a backing pump is required to lower the turbo molecular pump's pressure to around 10^{-3} mbar before it is started. The turbo molecular pump and its backing pump are controlled with a digital output from the Eurotherm. This backing pump is controlled by a self-contained relay supplied with the turbo pump controller.

When the turbo pump is not in use, it is isolated from the system by an air-powered solenoid gate valve. This valve is controlled with a digital output from the Eurotherm.

The hot filament ion gauge is used to measure vacuum pressure during the high vacuum stage. This gauge can only be energized during the high vacuum stage because damage can occur to the filament if used at higher pressures. This gauge's controller automatically senses a high pressure condition and then de-activates the gauge under such conditions. The gauge uses an external controller controlled via LabVIEW with RS232 logic.

Since the hot ion gauge and throttle valve use RS232 data communication, these components could not be controlled through the PID controller. In this case, LabVIEW is used to send and receive information to and from these components. LabVIEW virtual instruments (VI) are used to control the hot ion gauge and the throttle valve controller.

Recipe Based Control

A recipe builder was part of the new LabVIEW program. It provides the operator with a mechanism to build time-based segments that specify the desired temperatures and pressures along with their corresponding ramp-rates. This program also generates an Excel file the can be used as a recipe in the future.

Argon Control

Argon gas flow is now regulated using a new mass flow controller (MFC). This MFC uses a self-contained PID controller to regulate mass flow according to user input. The operator enters the controller's setpoint at the beginning of a new recipe and the Eurotherm controller is used to send a 0-5VDC setpoint signal to the MFC.

In order to control the on/off functions of the solenoid controlled gate valve, molecular vacuum turbo pump, and MFC with the PID controller's digital outputs it was necessary to add a relay bank to act as an electronic switch.

Temperature Control

The LabVIEW program sends temperature setpoints to the Eurotherm PID controller based on the operator-entered recipes. These recipes specify time-based temperature setpoints and ramp rates. The Eurotherm uses feedback from a Type C thermocouple for low temperatures and an infrared pyrometer for higher temperature. Since the life of the thermocouple will degrade quickly at temperatures above 1500˚C, it is necessary to pull the thermocouple away from the hot process core when temperatures exceed this amount. The LabVIEW program automatically holds all functions when the process reaches 1500˚C, and waits for a user input indicating that the thermocouple has been removed.

The final furnace with the added hardware is shown in Figure 3.

Figure 3. Final Automated Furnace

HMI Operation

Operation of the furnace is via the LabVIEW Main Operator Screen shown in Figure 4. This screen displays all pertinent operating values as well as alarm notification. The operator starts the process by clicking "Run". The program then directs the operator to the Recipe Builder Screen shown in Figure 5. The operator can then choose to load a previously saved recipe from an Excel spreadsheet or the operator can choose to construct a recipe using the Ramp Editor Screen shown in Figure 6. After the segments are loaded, the operator selects "Done" and the program automatically uploads the recipe and starts the process. This process also builds an Excel file that can be reused. If there are any errors detected in the ramps, the program holds in the Ramps Editor Screen and instructions are given to correct the problem.

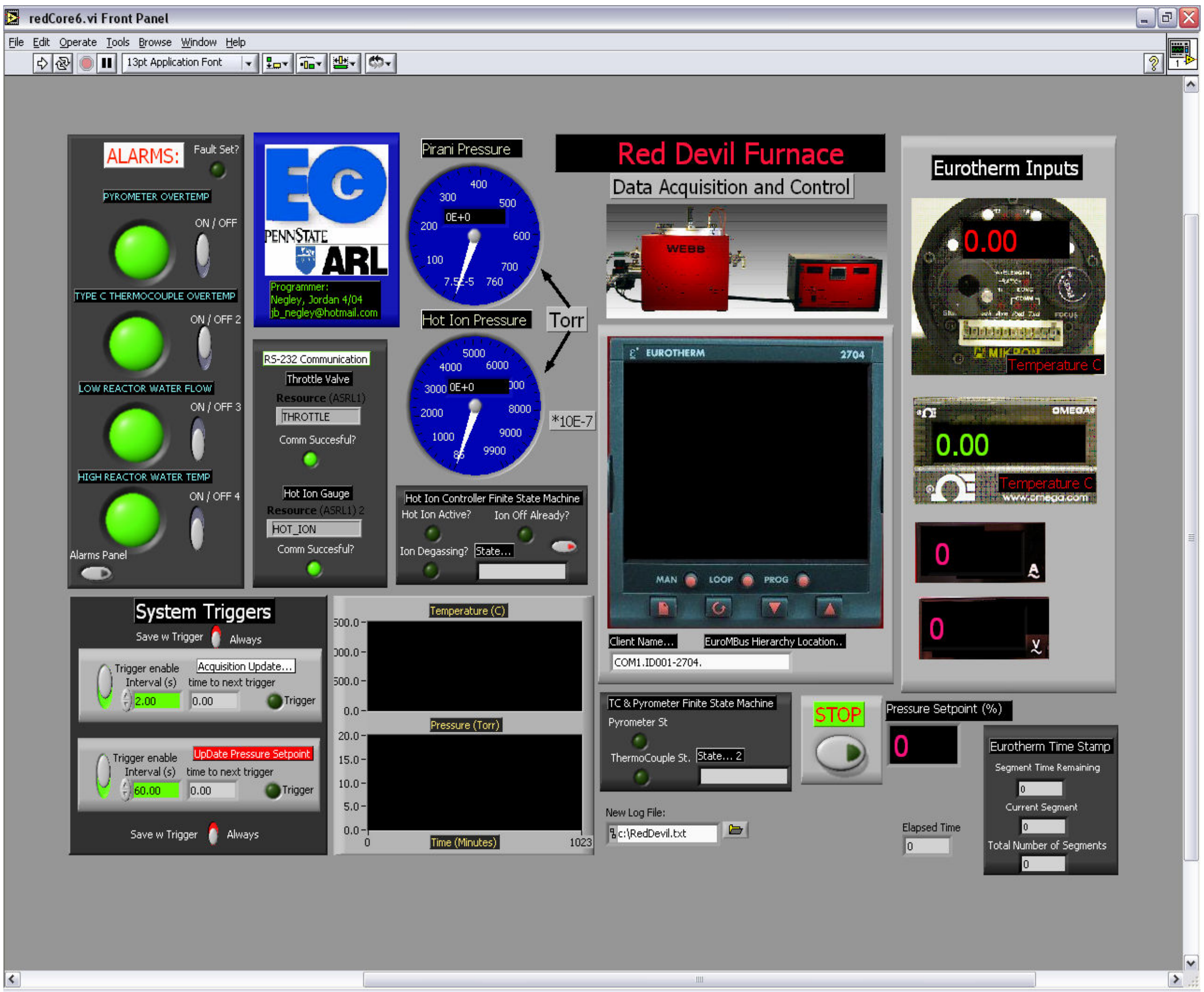

Figure 4. Main Operator Screen

When the upload is done and the program starts executing the recipe, LabVIEW returns to the Main Screen where all input parameters are displayed, including temperature, pressure, voltage and current of the heater, current segment number, and time remaining in segment. The operator can stop the program at any time by clicking the "Stop" button and the system will reset to initial conditions.

The system also incorporates the normal data collection and alarming capabilities of LabVIEW.

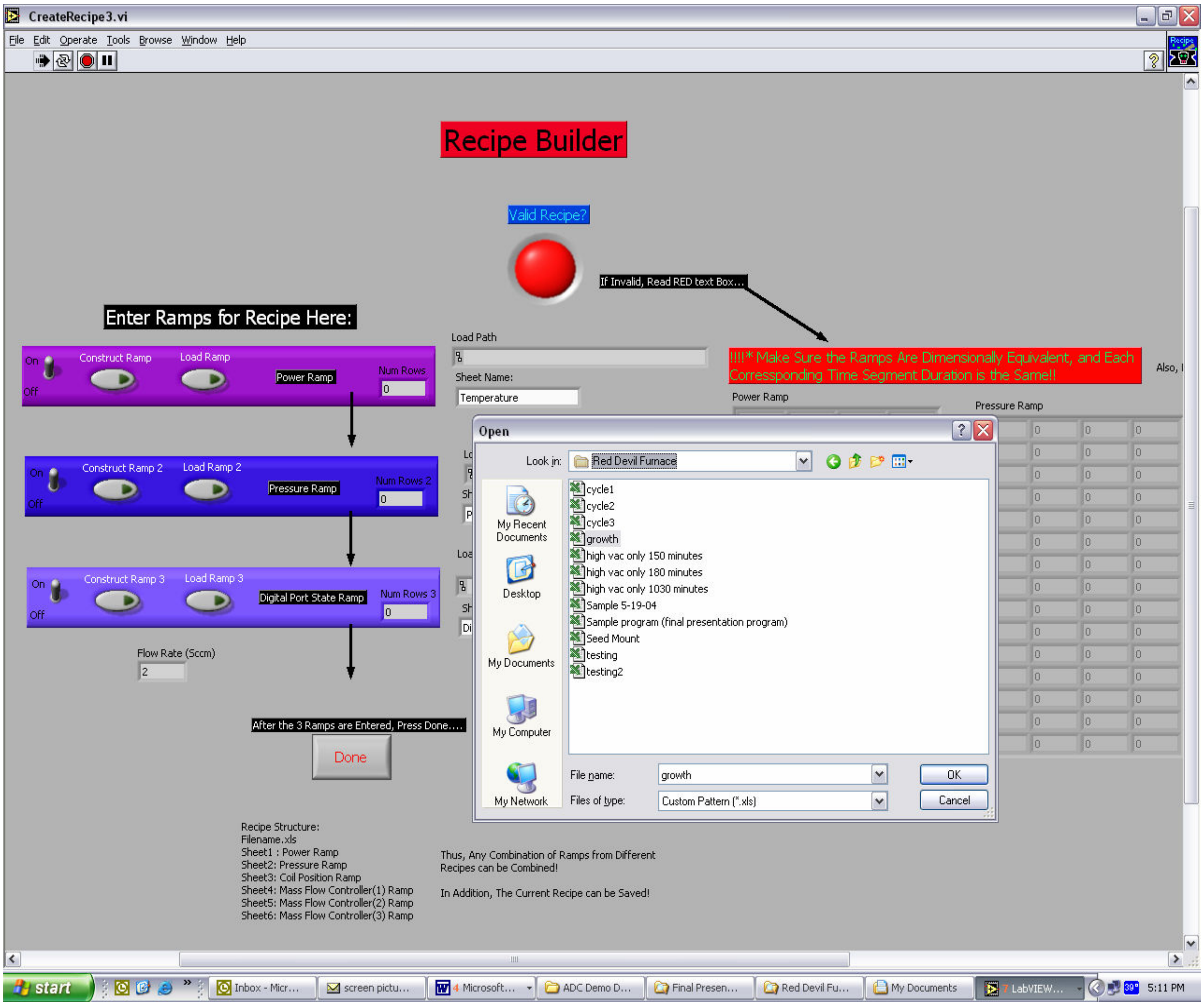

Figure 5. Recipe Builder Screen

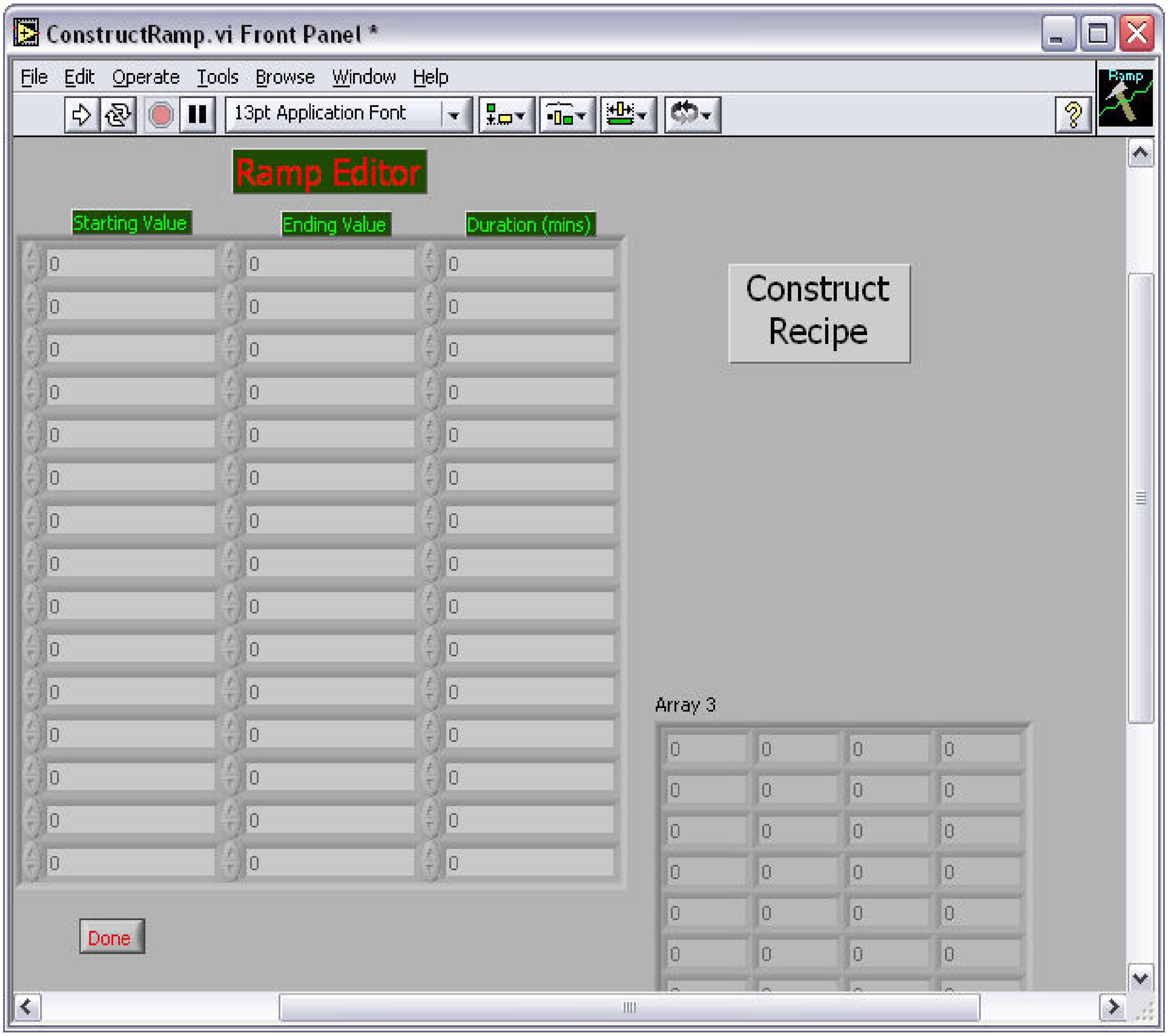

Figure 6. Ramp Editor Screen

Journal Papers

Each student produced a journal-style paper. One was entitled "Pressure Measurement in High Vacuum Applications" and it covers the two main methods for measuring pressure in high vacuums: the active linear pirani guage and the hot filament ion gauge. The paper describes the method by which each measures pressure, the effective pressure range in which the gauges operate, what types of gases they are meant to read, the environmental effects on readings, and safety issues for the device related to pressures. It also describes the criteria used to select the appropriate pressure gauge based on the application, and explains the operating advantages and disadvantages of each. It ends with an explanation of how all of this theoretical information was applied to the automation of the vacuum furnace. The other paper was entitled "Infrared Pyrometer: Theory of Operation and Application". This paper explains the basic theory of operation of an infrared (IR) pyrometer, including information on emissivity and wavelength of light as it applies to the temperature of an object. It also contains application information including benefits and drawbacks related to using an IR pyrometer. It ends by using the pyrometer that was used in this project as an example to illustrate the importance of the various IR characteristics and features.

Learning Points for Students

This project accomplished all of the objectives of the course as outlined in the beginning of this paper. However, there were other additional learning points that were achieved because the project was done in collaboration with industry. Budget and schedule are much more important when working with industry; the customer expects the project to be completed within the specified budget and the project must be done by the end of the semester. Also, the normal senior project is demonstrated in the lab and then it is forgotten. However, the industry-based project is put into service after the demonstration. This brings other considerations to bear. The first is that the product must be designed for easy maintenance after it is placed into operation. It also makes it necessary to address product liability concerns. That is, the project must be designed in such a way so that it is not possible for the operator or maintenance personnel to be injured by the project.

Results

This project resulted in two successes: First, the project fulfilled the requirements of the course and both the students and faculty advisors learned a lot. Secondly, the EOC was very pleased with the project; it meant all of their expectations and is still in operation. The success of this project led the EOC to hire 2 of our junior-level students as interns in the semester following this project. They also sponsored another senior project in the following year and plan on doing the same in the future.

Acknowledgements

The author would like to thank newly graduated engineers Eric Franz and Tim Stotler for their efforts in this project.

Bibliography:

[1] EOC website, URL www.electro-optics.org

[2] RD Webb website, URL www.rdwebb.com

[3] LabVIEW website, URL www.ni.com

ROBERT LYNN MUELLER
Robert Lynn (Doc) Mueller is an assistant professor of Electro-Mechanical Engineering at the New Kensington Campus of the Pennsylvania State University. He received his B.S. in Electrical Engineering from Wichita State University and his Ph.D. in Electrical Engineering from the University of Pittsburgh. He is a registered professional engineer in the state of Pennsylvania and a member of several professional societies. Dr. Mueller spent 30 years working with industrial control systems before joining Penn State and still continues to work as a consultant providing advice regarding industrial automation.