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A New Approach to Implementing a PLC-Based Model Predictive Controller for Application in Industrial Food Processes

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Abstract

Model Predictive Control (MPC) is an advanced control strategy for improving the control of processes that display relatively large variations in system controlled output values in comparison to the system's control set point, for processes with appreciable process variable interactions, and for systems that display a large amount of process deadtime and/or system disturbances This paper reports the implementation of MPC techniques directly on a programmable logic controller (PLC) rather than on a personal computer (PC) for an industrial sugar cooking process. This study implemented and evaluated three PC-based, commercial MPC technologies for the sugar cooking process, and a new model state feedback implementation directly on Rockwell Automation's ControlLogix® PLC. A standard proportional-integral-derivative (PID) control implementation was used as a baseline for comparing the MPC strategies. The comparative analysis focused on the dynamic response of each strategy at startup, including both temperature rise time and overshoot, and the steady-state disturbance rejection capabilities of each strategy.

The test results showed that the MPC strategies controlled the sugar cooking process better than the traditional PID control method in regards to the target parameters. The tests also showed that the PLC-based MPC strategy was comparable to the PC-based commercial MPC applications. This strategy has several benefits such as requiring no external hardware, software, and communications protocols, which may result in a less expensive implementation than the commercial MPC strategies. This is of particular interest for implementation in an educational setting due to the lower cost, use of standard laboratory equipment, and relevance to Electrical Engineering and Engineering Technology curriculum.

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Introduction

The goal of a process control system is to control system changes in order to achieve a specific process characteristic. Changes or variations in raw materials, equipment performance, production rates, utilities, ambient conditions and process set points all necessitate dynamic process control. Properly controlling the results of these changes typically provides economic opportunities. While the PID algorithm is capable of controlling the vast majority of industrial processes, it is due to its lack of ability to control deadtime dominant systems and systems with multiple interacting input and output variables that advanced process control techniques have been a recent major focus of development. "Advanced process control is the intelligent, well-managed, intensive use of technology, systems, and tools based on sound process knowledge, with the objective being to deliver substantial benefits to plant operations in a most cost-effective and timely manner".[1] These solutions seek to extract optimum value from existing assets.

Model predictive control (MPC), a branch of advance process control, is a viable control strategy for production processes that display relatively large variations in system controlled output values, for processes with appreciable process variable interactions, and for systems that display a large amount of process deadtime and/or system disturbances.[2] The objective of using MPC in manufacturing is to reduce overall system variability regardless of measured and unmeasured disturbances such as product raw material changes, variation in production feed rates, wear on process equipment, or random environmental fluctuations. The control set point can then be confidently moved closer to an actual process limit, resulting in a reduction in quality variability and lost product, which can be caused by operating a process at a conservative control set point due to process variability. Additionally, as the set point is moved closer to the system specification control limit, the result is increased process accuracy, precision and efficiency, as illustrated in Figure 1.

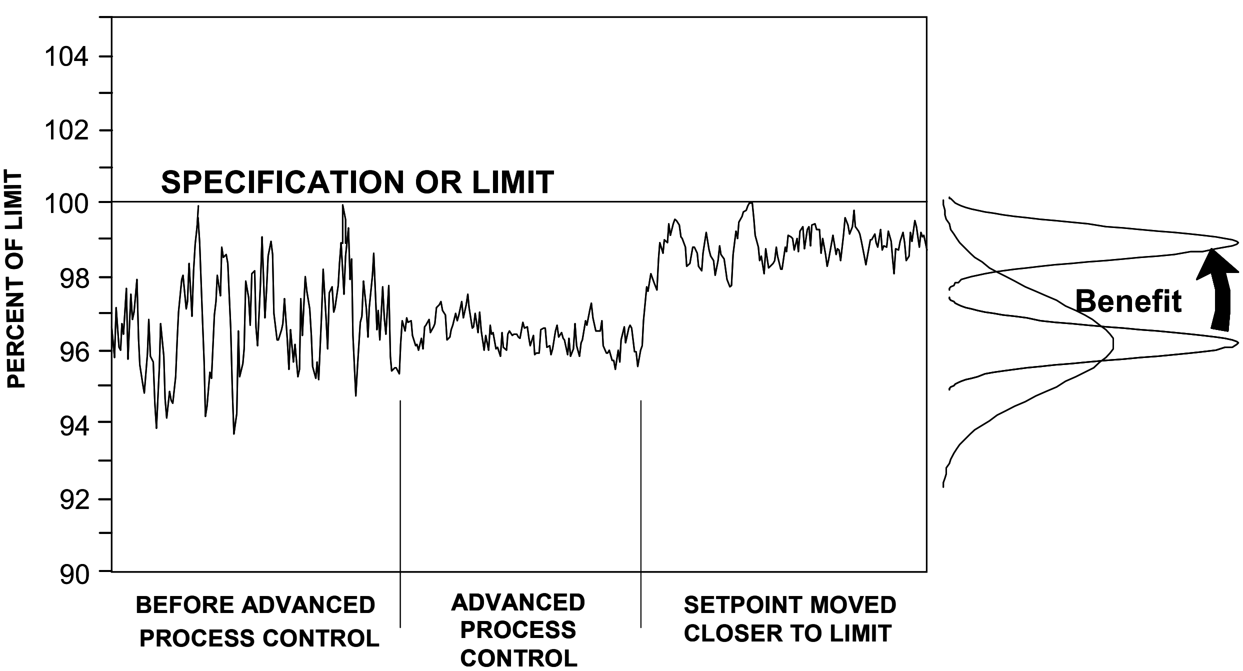

Figure 1. Benefits derived from using advanced process control to reduce variability.

Advanced processing techniques have historically been achieved using the computational power and speed of PCs and UNIX computers. Traditionally, PLCs have not supported the required mathematical and timing functions to implement advanced algorithms. However, process control technology innovations over the last decade have improved the capabilities of the PLC. Introducing smart sensors used with PLCs and local area networked computers has provided quality and reliability in all types of process control systems. Although implementation of the control has changed steadily, the fundamentals and strategies for the control have not advanced much. This paper demonstrates a novel approach to implementing a PLC-based model predictive controller applied to industrial food processes.

Several recent publications report the use of PLCs in student laboratory exercises. For example, a laboratory module in automation has presented undergraduate students with experience in sensors and data acquisition systems using a PLC-developed man-machine interface.[3] Another reported that a PLC-based process control laboratory with a temperature controlled chamber and fluid mixing tank has increased student interest and enhanced students' ability to visualize simple process control simulators.[4] The design and fabrication of PLC and pneumatic process control modules in a college-based activity that included high school educators and students has resulted in an excellent learning experience for both college and secondary students.[5] Many mechanical engineering and technology curricula now include instrumentation and control courses using PLCs combined with a variety of instrumentation inputs from proximity sensors and other transducers to provide a good learning tool for undergraduate students.[6,7] The work presented in this paper may similarly be applied to a student laboratory exercise for demonstrating the benefits of model-based control techniques.

Confectionery processing requires precise temperature and moisture control of a high-boil, sugar-based formulation product. The system must remain within process specifications even with the presence of various measured and unmeasured disturbances (weather changes, raw material changes, system steam pressure, and so forth). Capability to rapidly increase the sugar-based product's initial temperature to a final temperature, with minimal temperature overshoot, is also required. Standard PLC-based PID control was originally employed as part of the sugar cooking control strategy, but after observing the response of the cooking process due to measured disturbances during normal operation, it was evident that PID control could not meet the desired cooking specifications. It was decided to pursue advanced process control strategies as a means to meet the high-boil sugar cooking specifications.

Research Objectives

The objectives of this advanced process control research study were to successfully implement viable commercial MPC technologies on the sugar cooking process and to develop a new MPC strategy implemented directly on the existing PLC. Existing, commercially available model-based controllers require a personal computer for operation. Typically the existing process control system utilizes an industrially hardened programmable logic controller. As a result, the PC used for the MPC functions is an additional piece of hardware that must be purchased, enclosed, and maintained. The software run on this PC is also additional to the standard process control system. It must be purchased, configured and maintained separately from the base control system. Finally, communication drivers must be purchased and configured. These additional costs required throughout the life cycle of the system reduce the profitability of the process control system. A model-based controller implemented directly on the existing, standard process control hardware (the PLC), with the standard process control software, requires no additional hardware, software or communications drivers.

This study implemented and evaluated three PC-based, commercial MPC technologies for the sugar cooking process, and developed and implemented model predictive functionality directly on a PLC. The options investigated from the range of commercial MPC software packages were ControlSoft, Inc.'s MANTRA®, Universal Dynamics' BrainWave®, and Pavilion Technologies' Process Perfecter®. A model state feedback (MSF) solution was developed and implemented directly on a Rockwell Automation ControlLogix® PLC using ladder logic and function block programming. (It is not the purpose of this paper to examine the details of the MSF algorithm programmed on the PLC, but rather to review its application to an industrial process, and to extend this application into the educational arena. Details on the MSF algorithm can be found in Brosilow & Joseph[8] or Griffen.[9]) The PLC-based solution was validated against the commercial MPC applications. The results of these solutions were compared to the traditional PLC-based PID control solution.

Process Description

1. The high-boil sugar cooking process starts with a high viscosity sugar syrup mixture that is blended and heated to a temperature of 170°F in an 1800-pound mixer (see Figure 2).
2. Product is gravity fed to a positive displacement Waukesha pump (product feed pump). The product feed pump delivers the sugar syrup mixture at a rate of 8.5 pounds per minute through a small shell and tube heat exchanger (preheater). The product reaches a temperature of approximately 220°F (±4°F) at the discharge of the preheater.
3. Product enters the bottom of the sugar cooker shell and tube heat exchanger section at a constant flow rate of 8.5 pounds per minute, the product residence time in the heat exchanger is approximately 31.5 seconds. The Hohberger cooker consists of two main sections: (a) a heat exchanger is used to elevate the product temperature to the desired set point, and (b) a vacuum chamber is used to assist in removing product moisture.
4. Product exits the top of the heat exchanger and flows down a transition duct (bridge) that is at atmospheric pressure. A resistive temperature device (RTD TT4) positioned in the bridge provides feedback regarding the product's discharge temperature from the cooker.
5. The control loop modulates a proportional steam supply valve to regulate the sugar cooker's internal vessel pressure, thus controlling the cooking temperature.
6. The desired cooking process maintains a discharge product temperature at the bridge (TT4) of 274°F ±1°F. If product temperature is too low the resulting sugar mixture will not caramelize, and will need to be reprocessed. If the product temperature gets too high the cooker will foul and the product will be unusable. Therefore, the usable control limits are ±5°F over short (less than 30 second) periods.
7. The product feed rate varies by a maximum of approximately ±25%, as determined by downstream equipment. Typical feed rate variations are held between 5% and 10%. As the feed rate increases the product residence time in the heat exchanger decreases. The opposite is the case as the feed rate decreases. The control system has to maintain the discharge product temperature at the bridge regardless of feed rate (within the ±25% range).

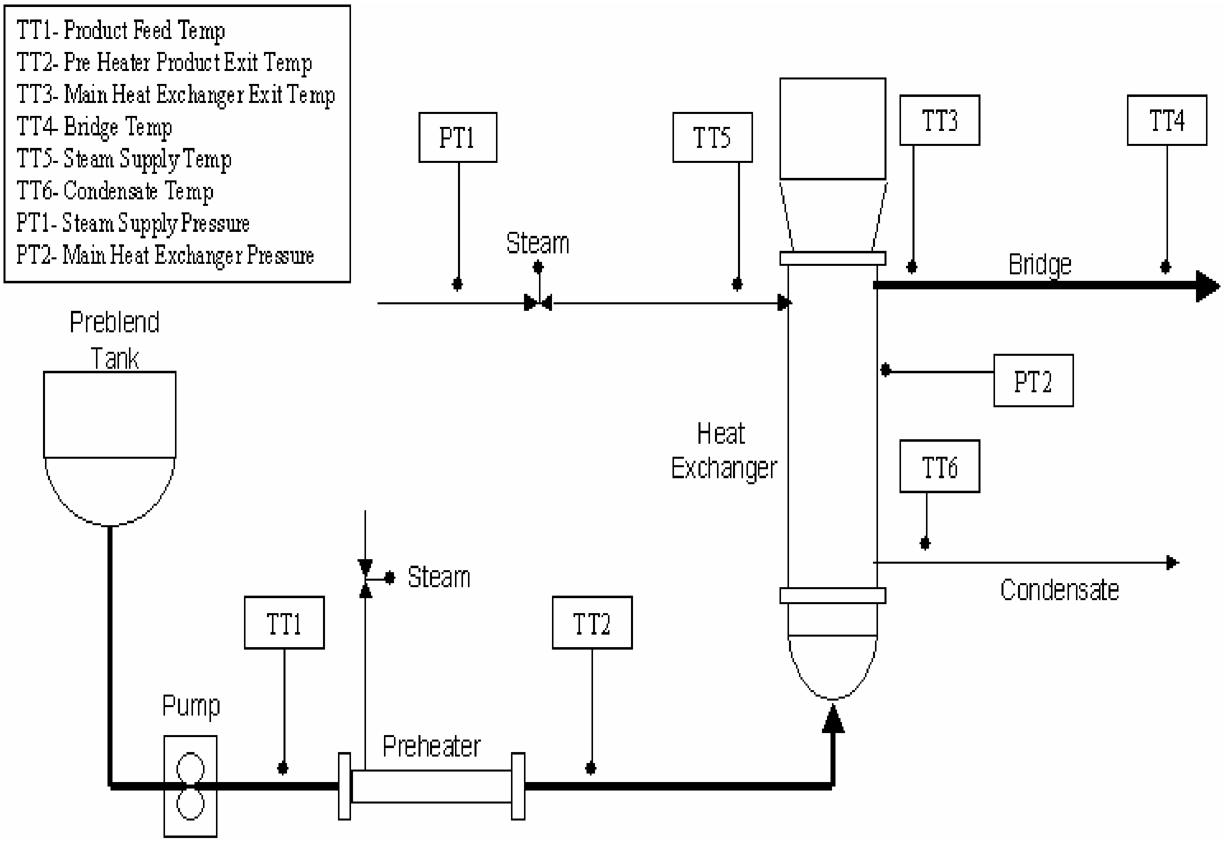

Figure 2. Sugar cooker process flow diagram.

There are several process parameters that define the control system. The process set point (SP) is the target for the process variable. For the cooker in this application the SP was 274°F. The process variable (PV) is the variable being controlled by the system, which was temperature in degrees Fahrenheit for this application. The steam valve position (in percent open) was the process control variable (CV), which is the output from the control system to the actuator. The measured process disturbance variables (DV) are parameters that are measured and included as feed forward variables to the process controller. The feed rate (measured as pump speed) in RPM was used as such a feed forward variable. The unmeasured process disturbance variables (dV) are the parameters that are typically not measured by the system controller, and thus not accounted for in the control system. Attempts were made to hold all potential disturbance variables, such as product moisture and operational constraints, constant throughout the trials.

Controller Implementations

The PID control algorithm is ubiquitous in today's process industries. It is a simple and easy to implement regulatory control algorithm that uses feedback to generate a control output which causes a corrective effort to be applied to a process to reduce the error between the desired process value and the actual process value. However, there are certain conditions for which a PID controller is ill suited and cannot be adequately tuned to meet the system control objectives. Tzovla and Mehta[10] point out that it is "difficult to adequately control multiple-input/multiple-output processes, processes with constraints and/or disturbances, and processes with associated complex dynamics using conventional PID-based approaches". There are numerous well-developed techniques for improving the effectiveness of a PID controller, such as gain scheduling for set point dependent processes, cascaded loops for interacting variables, and the Smith predictor for deadtime-dominant processes.[11, 12, 13] However, even with these enhancements and proper tuning, the PID controller is typically incapable of controlling processes with large variability, highly interactive variables, or long deadtimes.

Model-based controllers are of particular interest for use on complex processes with significant deadtimes. Improved control performance is achieved through basing the control action on the mathematical model of the process, including deadtime, so that the control action takes into consideration the effects of past control actions that have not yet appeared in the process variable (due to deadtime), as well as the long-term consequences of the currently calculated action. The mathematical model is adjusted to compensate for changes in the process characteristics so that the controller can maintain control under various operating conditions.[14]

One of the most common models used to describe real industrial processes is a combination of a first-order lag and time delay model called a first-order plus deadtime (FOPDT) model. It describes the open-loop response of many processes. Equation 1 shows this model.

$$PV = \frac{Ke^{-\theta s}}{\tau s + 1} CV \tag{1}$$

where,

K:	process gain
θ:	process deadtime
τ:	process time constant
s:	Laplace operator

For a first-order plus deadtime process, the process model is based on the following three parameters (illustrated in Figure 3):

1. Deadtime is the elapsed time from when the control variable is modified until the initial reaction to that modification is seen in the process variable.
2. The time constant is defined as the amount of time required for the process variable to reach 63.2% of its steady-state value as a result of a change to the control variable. It is a measurement of how fast the process variable will approach steady-state after the initial deadtime period.
3. Process gain is the ratio of the magnitude of the resultant steady-state change in the process variable to a step change in the control variable (Equation 2).

$$\text{Gain}(K) = \frac{\%\Delta PV}{\%\Delta CV} \tag{2}$$

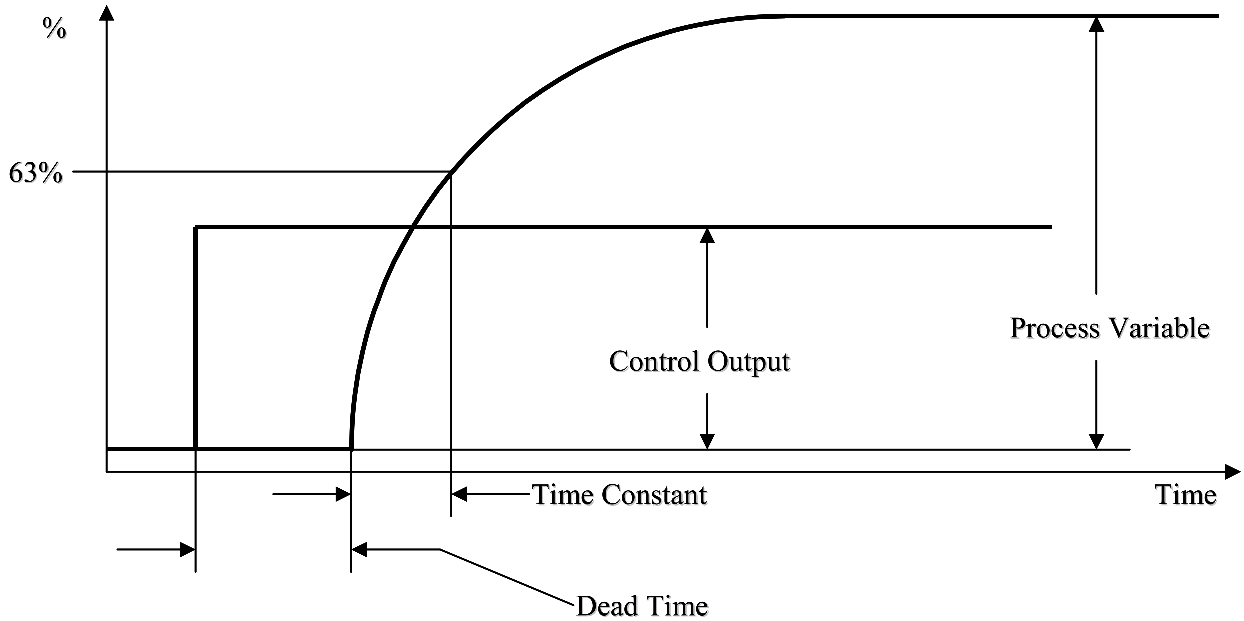

Figure 3. Parameters for a first-order plus deadtime process model.

The temperature control loop for the sugar cooking process that was the focus of this research follows this model. For most processes this model is simply developed using empirical data gathered from historical data or step tests performed on the process. Additional details on model-based algorithms can be found throughout the literature.[15, 16, 17]

Two sets of step tests were performed in this study to generate the necessary mathematical model of the system. The first set of step tests was performed to discover the relationship between the product temperature and steam valve position. This test resulted in an average process gain of approximately 3, an average process deadtime of approximately 30 to 40 seconds, and a process time constant of approximately 100 to 120 seconds.

The second set of step tests determined the relationship between the product temperature and the feed forward disturbance expressed as a feed rate in RPM. This resulted in a gain of approximately –0.8, with a deadtime for the feed forward model of approximately 50 seconds, and a time constant of approximately 75 seconds.

Using the data from the step tests of the sugar cooker, the transfer functions in Equations 3 and 4 were identified to model the process. These transfer functions represented all model information available to design, tune and integrate the controllers.

$$T_{SP} = \frac{2.9}{(100s+1)} e^{-25s} P \tag{3}$$

$$T_{FF} = \frac{-0.8}{(75s+1)} e^{-40s} PS \tag{4}$$

where,

T_{SP}: set point temperature control
T_{FF}: feed forward disturbance temperature control
P: steam pressure
PS: pump speed
s: Laplace operator

The mathematical model of the process was then used to configure the various model predictive controllers that were implemented in this research. Figure 4 shows the overall system block diagram for the sugar cooking process. The system is comprised of a PLC used for basic control, PID control and/or model state feedback control; an operator interface; an industrial PC used for each of the three commercial MPC controllers, programming, and data acquisition; and the sugar cooker as depicted in Figure 2. The various communication protocols used throughout the system are also shown.

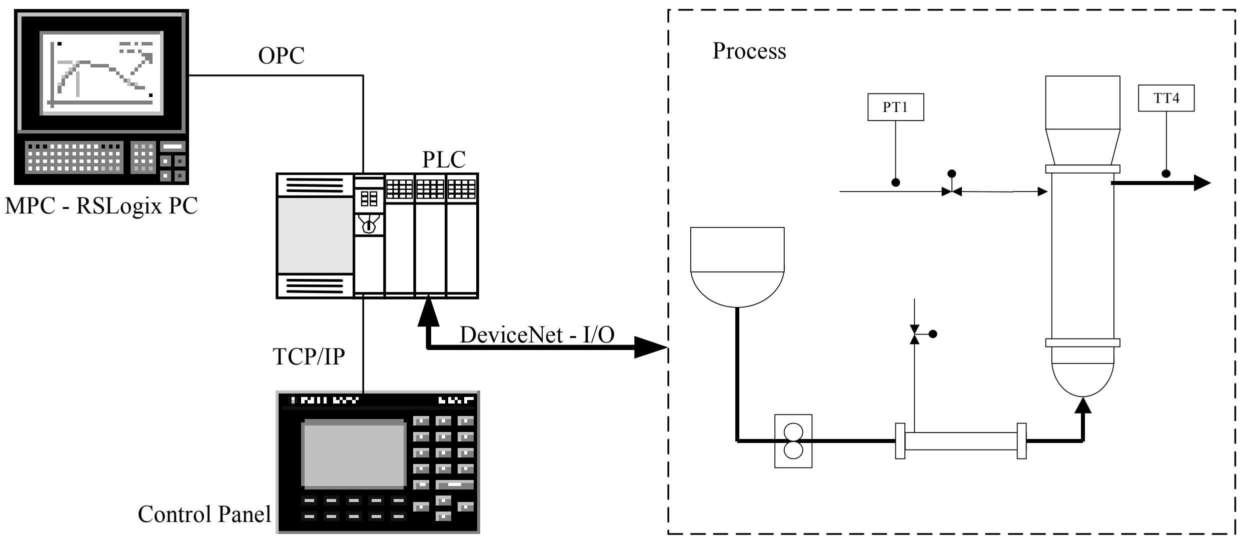

Figure 4. Sugar cooking process system diagram.

Model State Feedback Implementation

The objective of the model state feedback controller was to demonstrate the capabilities of the ControlLogix® PLC to apply model-based control functionality using the standard function block library. The implementation consisted of two function block diagrams, one main ladder code routine, and input and output ladder routines. The function block diagrams provided the control output calculations in automatic and manual (tracking) modes. The main ladder routine addressed internal parameter calculations, initializations, bumpless transfer and standard interface to the controller configuration parameters. The input and output routines provided interface to the process variables. See Griffen[9] for details on the coding algorithms.

The advanced control routines were programmed as subroutines in the ControlLogix® program and were set up as periodic tasks. Periodic tasks in ControlLogix® execute program subroutines deterministically. Deterministic execution of a program assures that the elapsed time between two subsequent executions of the program is kept constant by the processor. Deterministic execution is assumed in the implementation and must be assured when the program is executed so that the deadtime array timing is maintained.

Experimental Trials

The experimental trials followed a procedure whereby the sugar cooker was individually controlled by each of the MPC control paradigms, as well as by a standard PID control algorithm. The PID control response was used as a baseline for comparison against the four model-based controllers. During each trial, a predefined sequence of process tests was performed. The process temperature set point, the steam valve position, the actual process temperature, and the product feed rate were collected, recorded, and stored for each trial at a one second acquisition rate.

The cooking process started from an established steady-state condition for each trial, and was ramped up to the cooking temperature as quickly as possible without experiencing excessive temperature overshoot. The controller was then required to maintain the cooking temperature while the process was operated through a preset sequence of tests that introduced disturbances into the cooking process.

To evaluate controller performance, the following objectives were established and measurable parameters were recorded:

1. Each controller was required to ramp up the product temperature in 15 minutes or less. (The system was not ramped up to temperature in less than five minutes, as doing so would have caused the product to burn.)
2. Each controller was to maintain a steady-state discharge product temperature at the bridge (TT4) of 274°F (±1°F on average) for a period of 10 minutes. (A constant product feed rate was assumed.)
3. Each controller was to maintain a discharge product temperature at the bridge of 274°F (±1°F on average, with a maximum deviation of ±5°F) while the product feed rate was varied by approximately ±25% in a prescribed test pattern.

Analysis

There were three main areas on which the overall comparative analysis focused. These were the dynamic response of each strategy at start-up (temperature rise time and initial temperature overshoot), and the steady-state disturbance rejection capabilities of each strategy based on process feed rate changes. Summary statistics were calculated for each of these parameters based on the production trials.

Figure 6 is a compilation of the individual performances for each of the control strategies, using a typical production run for each. This graphical comparison shows that the four MPC strategies significantly outperformed the standard PID control with gain scheduling. It additionally shows that the four MPC strategies performed similarly, and that each of them would be an acceptable strategy for the sugar cooker.

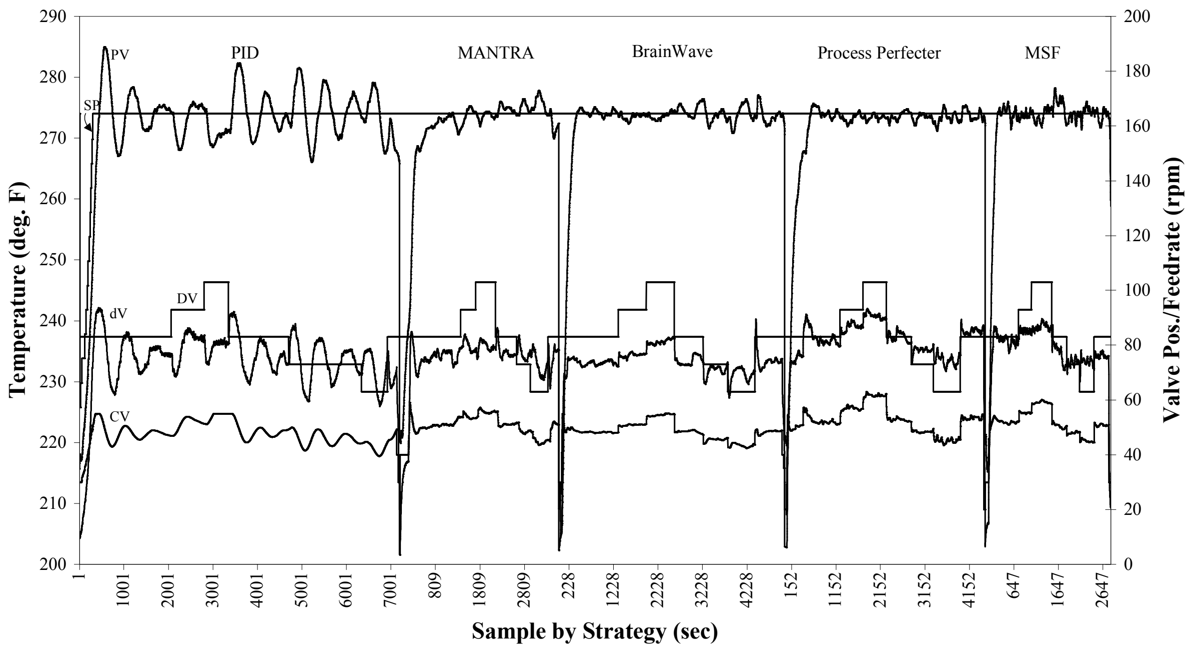

Figure 6. Overall system response comparison.

Figure 7 compares the normal distribution of error for each of the control strategies evaluated. When comparing recorded data it is apparent that PID control was much less precise than the MPC strategies. It is also seen that the MPC strategies exhibited much tighter control than PID, resulting in less overall system error.

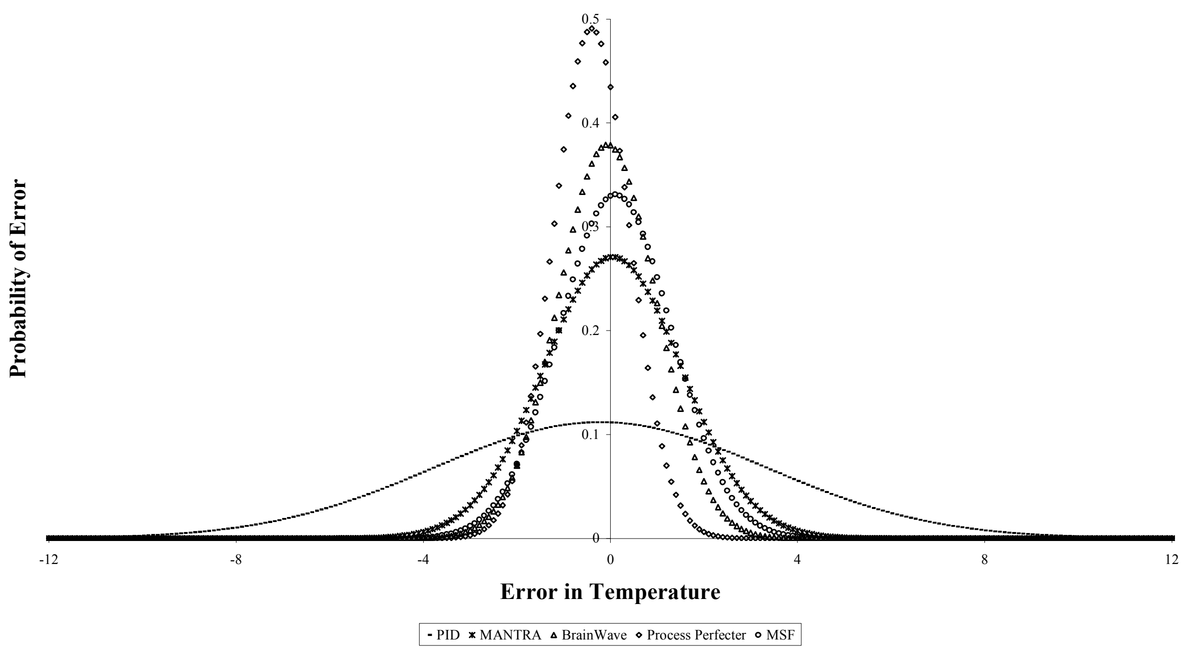

Figure 7. Error distribution comparison.

Table 1 lists the dynamic control summary statistics calculated based on the production trials for each control strategy. The steady-state control summary statistics are shown in Table 2.

Table 1 Application Strategy Dynamic Control Results and Comparison

Method	$M_{Rise\ Time}$	$SD_{Rise\ Time}$	Max. Initial Overshoot	$M_{Overshoot}$	$SD_{Overshoot}$
PID	28.8 min.	2.5 min.	11.0°F	8.6°F	2.7°F
MANTRA®	14.5 min.	1.0 min.	0.4°F	0.2°F	0.12°F
BrainWave®	5.5 min.	0.29 min.	3.0°F	1.7°F	0.82°F
Perfecter®	8.4 min.	0.29 min.	1.7°F	1.4°F	0.45°F
MSF	6.6 min.	0.54 min.	2.9°F	2.3°F	0.39°F

Table 2 Application Strategy Steady-State Results and Comparison

Method	M_{Temp}	SD_{Temp}	$M_{Abs\ Err}$	$SD_{Abs\ Err}$	Max. Deviation
PID	273.8°F	3.6°F	2.1°F	1.1°F	8.3°F
MANTRA®	274.0°F	1.5°F	1.2°F	0.52°F	4.1°F
BrainWave®	273.9°F	1.0°F	0.96°F	0.39°F	3.2°F
Perfecter®	273.6°F	0.8°F	0.78°F	0.24°F	2.8°F
MSF	274.1°F	1.2°F	0.86°F	0.36°F	4.2°F

Analysis of the data showed that the PID control strategy was not able to meet the defined performance criteria. The PID controller did not successfully bring the product to the set point temperature without significant overshoot within the required time. Additionally, the PID controller was not able to maintain the process set point within the required deadband during system disturbances. Conversely, all of the implemented MPC control strategies did meet the defined performance criteria. The analysis shows that there was not a significant difference in the operational results of the different MPC control strategies with regard to temperature overshoot or disturbance rejection during feed rate changes. A significant difference was demonstrated in rise time for the MANTRA® controller, even though the controller did meet the required criteria. (See Griffen[9] for a detailed statistical analysis.)

While not part of the statistical analysis, the cost of the developed system needs to be taken into account. The most cost effective control solution is one that can be applied directly on the PLC where no additional hardware or software is required, such as with PID control and the MSF algorithm in this research, and thus no additional system costs are incurred. The cost of other MPC solutions tends to vary in direct proportion to the strategy's scope of control and capabilities. This aspect of the development is of particular importance in an educational setting where the ability to keep laboratory costs low is essential. There is significant value in the opportunity to use the existing PLC laboratory equipment for advanced experimentation.

Curricular Implications

This paper presents an application-oriented control system implementation that is relevant to technology education. The results of this research have value for Electrical Engineering, Electrical Engineering Technology and, perhaps, Manufacturing Engineering Technology programs, depending on the level of immersion in PLC applications and available laboratory equipment. The ability to emulate the industrial environment in the electronics laboratory is a determining factor in the applicability of the model. Assuming a small-scale food process (or simulation) exists, it would be of particular interest for implementation in an educational setting due to its low cost, use of standard laboratory equipment, and relevance to Electrical Engineering and Engineering Technology curriculum. The MPC strategy and MSF algorithm applied to a food manufacturing process may be the most appropriate for a senior level and/or graduate level instrumentation and data acquisition course in either Engineering or Engineering Technology programs.

For an existing sugar cooking process facility, the MPC strategy and MSF algorithm successfully implemented in a PLC setting have shown that the following enhancements are achieved: (1) energy conservation due to reduced fluctuations in the overall control; (2) quality, stability, reliability, and overall process efficiency have been improved. Further research and experimentation in this area may prove additional benefits to the manufacturing process. Potential areas of further study include adapting the algorithm for other process models, such as second-order and integrating systems; targeting additional process parameters for true multivariable applications; adapting the implementation to other manufacturing processes and industries; or developing a man-machine interface for design and operation.

The authors accept that the implementation of a similar educational control system requires at least a small-scaled cooking process, which may require an initial capital cost. However, educational institutions located close to food manufacturing plants may utilize the advantages of an industry-university partnership. In particular, industrial plants with existing food processes can employ the strategy efficiently and economically using local engineering and/or engineering technology program seniors or graduate students since the strategy does not require any external hardware, software, and communications protocols in contrast to commercial MPC strategies. Other manufacturing processes with similar characteristics (i.e., a first-order plus deadtime process model) should also be considered for implementation of these advanced control techniques.

The authors believe that an alternate quick and economical approach for educational institutions may be modeling and implementation of the MPC strategy and MSF algorithm through PLCs and a LabView™ interface (or similar simulation environment). This may eliminate the necessity of an actual, and expensive, manufacturing process. Assuming more and more institutions are now using simulation tools, this may bring an excellent enhancement to their instrumentation and data acquisition curriculum. Students with basic control system theory may gain useful pedagogical skills by applying the MPC strategy and MSF algorithm either through a small-scaled food process as demonstrated in this paper, or a simulation-based data acquisition system as a next step to this work.

Conclusion

Based on the results of the study, it is concluded that the model state feedback algorithm may be successfully implemented on a ControlLogix® PLC to control an industrial shell and tube style heat exchanger applied to cooking sugar syrup used in confectionary products. The MSF controller exhibited superior operational results compared to the standard PID-based controller in regards to reduced temperature rise time, overshoot minimization, and feed rate disturbance rejection. The MSF model predictive controller compared favorably to the commercially available MPC strategies studied for these same parameters.

Using an advanced control solution for the sugar cooking process resulted in several benefits, both financial and product related. The advanced solutions resulted in a more stable process control. The tighter control limits achieved with advanced control reduced the amount of product wasted due to improper processing. A more consistent product was produced that was closer to the target recipe. Lastly, the process efficiency was increased.

Additional benefits were realized by implementing the advanced control solution directly on the ControlLogix® PLC. By leveraging the existing control platform, no external hardware (such as a PC) was required, no additional programming software was required, and no special communications protocols (such as OPC) were required. This makes it easier to maintain the advanced solution at the plant level. Additionally, the cost of implementation is significantly reduced.

Ingredient cooking is one of the most common manufacturing processes within the food and beverage industry. By properly leveraging the knowledge gained from this research study, multiple sectors within the food and beverage industry may be able to reduce production costs while improving the quality of many manufactured goods.

Additionally, educational institutions seeking to implement advanced laboratory exercises within engineering and engineering technology curriculums may realize benefit from this study. The foundation for the laboratory curriculum may arise from industry-university collaboration, from on-site manufacturing equipment exhibiting appropriate mathematical behavior, or from the utilization of simulation tools.

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