Implementing a PID Controller Using a PIC18 MCU

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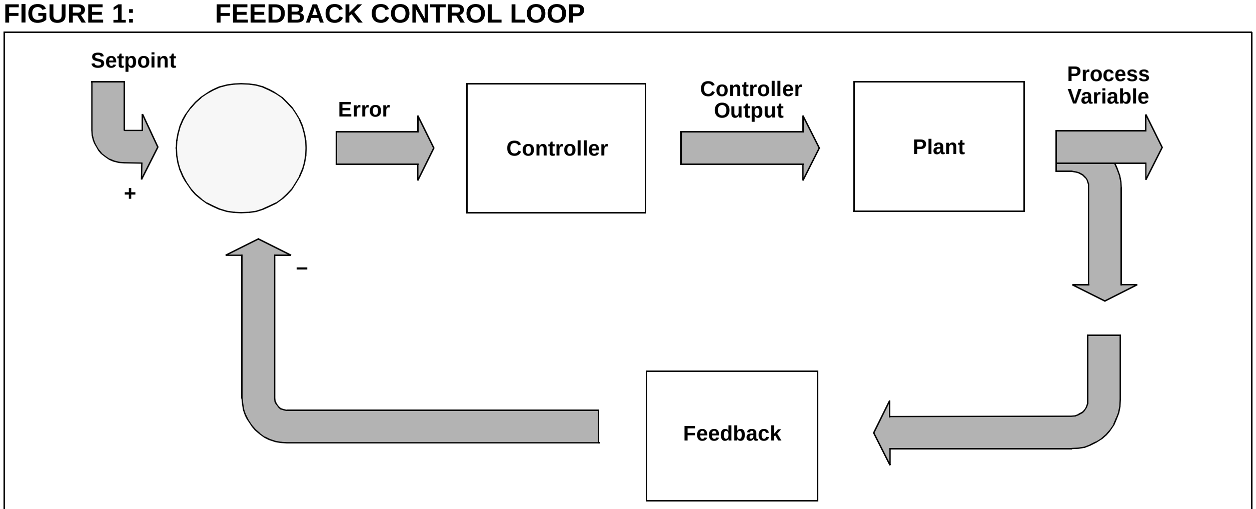
INTRODUCTION

Continuous processes have been controlled by feedback loops since the late 1700's. In 1788, James Watt used a flyball governor on his steam engine to regulate its speed. The Taylor Instrument Company implemented the first fully functional Proportional, Integral and Derivative (PID) controller in 1940. Although feedback control has come a long way since James Watt, the basic approach and system elements have not changed. There are several elements within a feedback system; for discussion purposes, we will use a home heating temperature control system as our model in the descriptions below.

- **Plant** – The physical heating and cooling parts of the system.
- **Sensors** – The devices (thermistors measuring temperature) that measure the variables within the Plant.
- **Setpoint** – This is a value (i.e., 70 degrees), which is converted to a voltage that the process drives towards.
- **Error Signal** – This is the difference between the response of the Plant and the desired response (Setpoint). In a house, the thermostat may be set to 70 degrees, but the temperature is actually 65 degrees, therefore resulting in an error of 5 degrees (Error = Setpoint – Measured).
- **Disturbances** – These are unwanted inputs to the Plant, which can be common. A disturbance would be an open entry door allowing a gust of cold air to blow in, quickly dropping the temperature and causing the heat to come on.
- **Controller** – Intentionally left for last, this is the most significant element of a control system. The Controller is responsible for several tasks and is the link that connects together all of the physical and nonphysical elements. It measures the output signal of the Plant's Sensors, processes the signal and then derives an error based on the signal measurement and the Setpoint. Once the sensor data has been collected and processed, the result must be used to find PID values, which then must be sent out to the Plant for error correction. The rate at which all of this happens is dependent upon the Controller's processing power. This may or may not be an issue depending on the response characteristic of the Plant. A temperature control system is much more forgiving on a Controller's processing capabilities than a motor control system. Figure 1 shows a basic block diagram of a feedback control system.

FIGURE 1: FEEDBACK CONTROL LOOP



OBJECTIVES

The objectives for this application note are to:

- discuss in detail the three elements of a PID Controller: Proportional, Integral and Derivative
- discuss a firmware PID routine on a PIC18 device
- discuss the implementation of a firmware-based PID that has the flexibility of adapting to different systems, but is capable of being specifically tuned later on
- discuss the details of tuning a PID once implementation has been completed

SOURCE CODE OVERVIEW

Before going further, let's discuss how the PID source code is configured. There is no specific way a PID should be implemented in firmware; the methods discussed in this application note only touch upon a few of the many possibilities.

The PID routine is configured in a manner that makes it modular. It is intended to be plugged into an existing piece of firmware, where the PID routine is passed the 8-bit or 16-bit error value (Desired Plant Response – Measured Plant Response). Therefore, the actual error value is calculated outside of the PID routine. If necessary, the code could be easily modified to do this calculation within the PID routine. The PID can be configured to receive the error in one of two ways, either as a percentage with a range of 0 to 100% (8-bit), or a range of 0 to 4000 (16-bit). This option is configured by a `#define` statement at the top of the PID source code with the PID's variable declarations. The gains for proportional, integral and derivative all have a range of 0 to 15. For resolution purposes, the gains are scaled by a factor of 16 with an 8-bit maximum of 255. A general flow showing how the PID routine would be implemented in the main application code is presented in Figure 2.

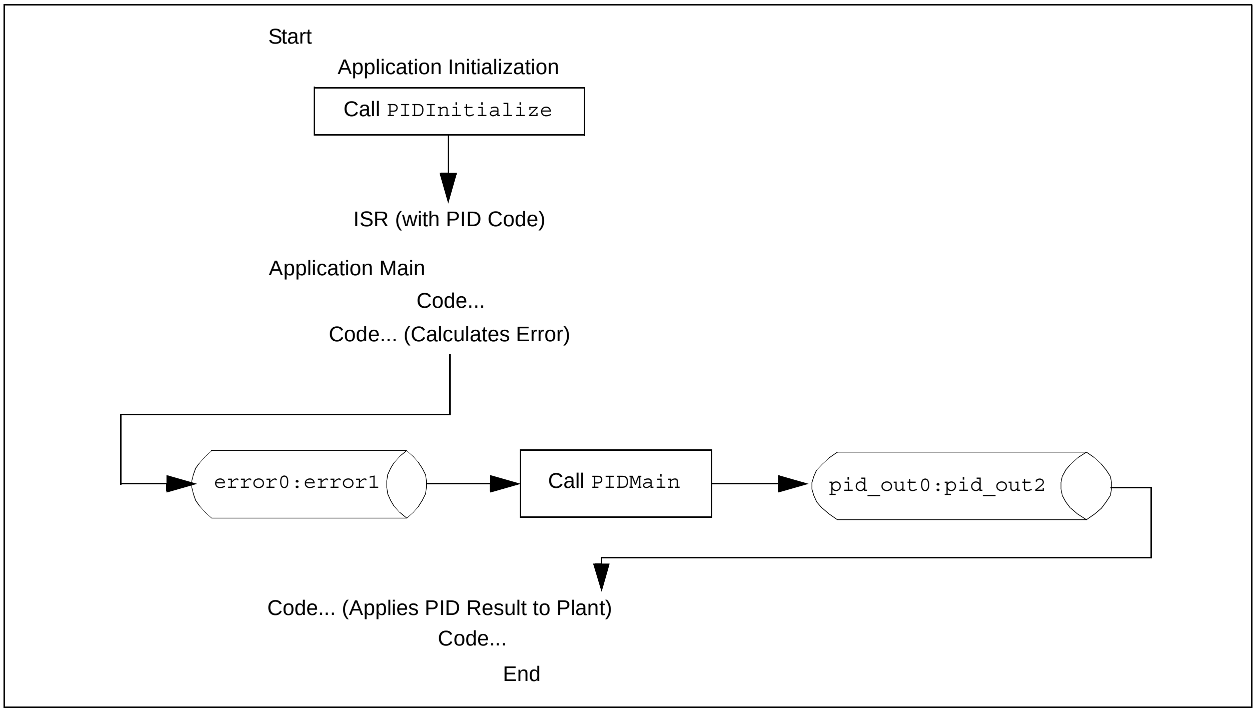
There were two methods considered for handling the signed numbers. The first method was to use signed math routines to handle all of the PID calculations. The second was to use unsigned math routines and maintain a sign bit in a status register. The latter method was implemented. There are five variables that require a sign bit to be maintained:

- `error`
- `a_error`
- `p_error`
- `d_error`
- `pid_error`

All of these sign bits are maintained in the pid_stat1 register (see Register 1).

Although all of the PID status bits are shown in Register 1 and Register 2, the user needs only to be concerned with the error sign bit (err_sign) and the PID final result sign bit (pid_sign). The err_sign bit is inserted into the PID routine along with the error. The user will check the pid_sign bit to determine which direction the Plant must be driven.

FIGURE 2: PID FIRMWARE IMPLEMENTATION



Firmware Variables and Constants

The list of firmware variables and constants and their definitions that are discussed in this application note are shown in Table 1.

TABLE 1: FIRMWARE VARIABLES AND CONSTANTS

Variable/Constant	Type	Definition
error0:error1	Error Variable	16-bit variable, difference between the Setpoint and measured output of the Plant
a_error0:a_error1	Error Variable	16-bit variable, accumulative error which is the sum of all past errors
d_error0:d_error1	Error Variable	16-bit variable, difference between error0:error1 and p_error0:p_error1
p_error0:p_error1	Error Variable	16-bit variable, value of the last error
a_err_1_lim	Error Variable	8-bit constant defining the accumulative error limits
a_err_2_lim	Error Variable	8-bit constant defining the accumulative error limits
kd	Gains	8-bit variable, derivative gain, max. = 15 (16 levels)
ki	Gains	8-bit variable, integral gain, max. = 15 (16 levels)
kp	Gains	8-bit variable, proportional gain, max. = 15 (16 levels)
pid_stat1	Status Register	8-bit variable, status bit register (see Register 1)
pid_stat2	Status Register	8-bit variable, status bit register (see Register 2)
deriv0:deriv2	Terms	24-bit variable, value of the derivative term
integ0:integ2	Terms	24-bit variable, value of the integral term
pid_out0:pid_out2	Terms	24-bit variable, final PID results
prop0:prop2	Terms	24-bit variable, value of the proportional term
timer1_hi	Time Base	8-bit constant loaded into the TMR1H register
timer1_lo	Time Base	8-bit constant loaded into the TMR1L register

Note: In 16-bit variables, the first variable is the Most Significant Byte (MSB), whereas the second variable is the Least Significant Byte (LSB). For example, in the variable error0:error1, error0 = MSB 8-bit and error1 = LSB 8-bit.

In 24-bit variables, the first variable is the MSB, whereas the last variable is the LSB. For example, in the variable pid_out0:pid_out2, pid_out0 = MSB 8-bit and pid_out2 = LSB 8-bit.

Data Registers

The pid_stat1 and pid_stat2 Data registers contain the individual PID status bits. The following two registers provide brief bit descriptions and their associated values.

REGISTER 1: pid_stat1 DATA REGISTER

pid_sign	d_err_sign	mag	p_err_sign	a_err_sign	err_sign	a_err_zero	err_zero
bit 7							bit 0

bit 7 **pid_sign:** Indicates sign of final PID result
1 = Result was positive
0 = Result was negative

bit 6 **d_err_sign:** Indicates sign of the derivative term
1 = Result was positive
0 = Result was negative

bit 5 **mag:** Indicates which variable is greater in magnitude (AARGB or BARGB)
1 = Result was AARGB
0 = Result was BARGB

bit 4 **p_err_sign:** Indicates sign of the previous error
1 = Result was positive
0 = Result was negative

bit 3 **a_err_sign:** Indicates sign of the accumulative error
1 = Result was positive
0 = Result was negative

bit 2 **err_sign:** Indicates sign of the error (input into the PID)
1 = Result was positive
0 = Result was negative

bit 1 **a_err_zero:** Indicates if the accumulative error is equal to zero or non-zero
1 = Result was zero
0 = Result was non-zero

bit 0 **err_zero:** Indicates if the error is equal to zero or non-zero
1 = Result was zero
0 = Result was non-zero

REGISTER 2: pid_stat2 DATA REGISTER

—	—	—	—	—	d_err_z	—	—
bit 7							bit 0

bit 7-3, 1-0 **Unimplemented**

bit 2 **d_err_z:** Indicates if the data error is equal to zero
1 = Result was zero
0 = Result was non-zero

PID Routine Flowcharts

Flowcharts for the PID main routine and the PID Interrupt Service Routine (ISR) functions are shown in Figure 3 and Figure 4 (see following pages).

The PID main routine is intended to be called from the main application code that updates the `error0:error1` variable, as well as the pid_stat1 error sign bit. Once in the PID main routine, the PID value will be calculated and put into the `pid_out0:pid_out2` variable, with its sign bit in pid_stat1. The value in `pid_out0:pid_out2` is converted by the application code to the correct value so that it can be applied to the Plant.

The PID ISR is configured for the PIC18 device's high priority interrupt at location 0x0008. The instructions within this ISR can be placed into an existing ISR, or kept as is and plugged into the application.

FIGURE 3: MAIN PID ROUTINE (`PIDMain`)

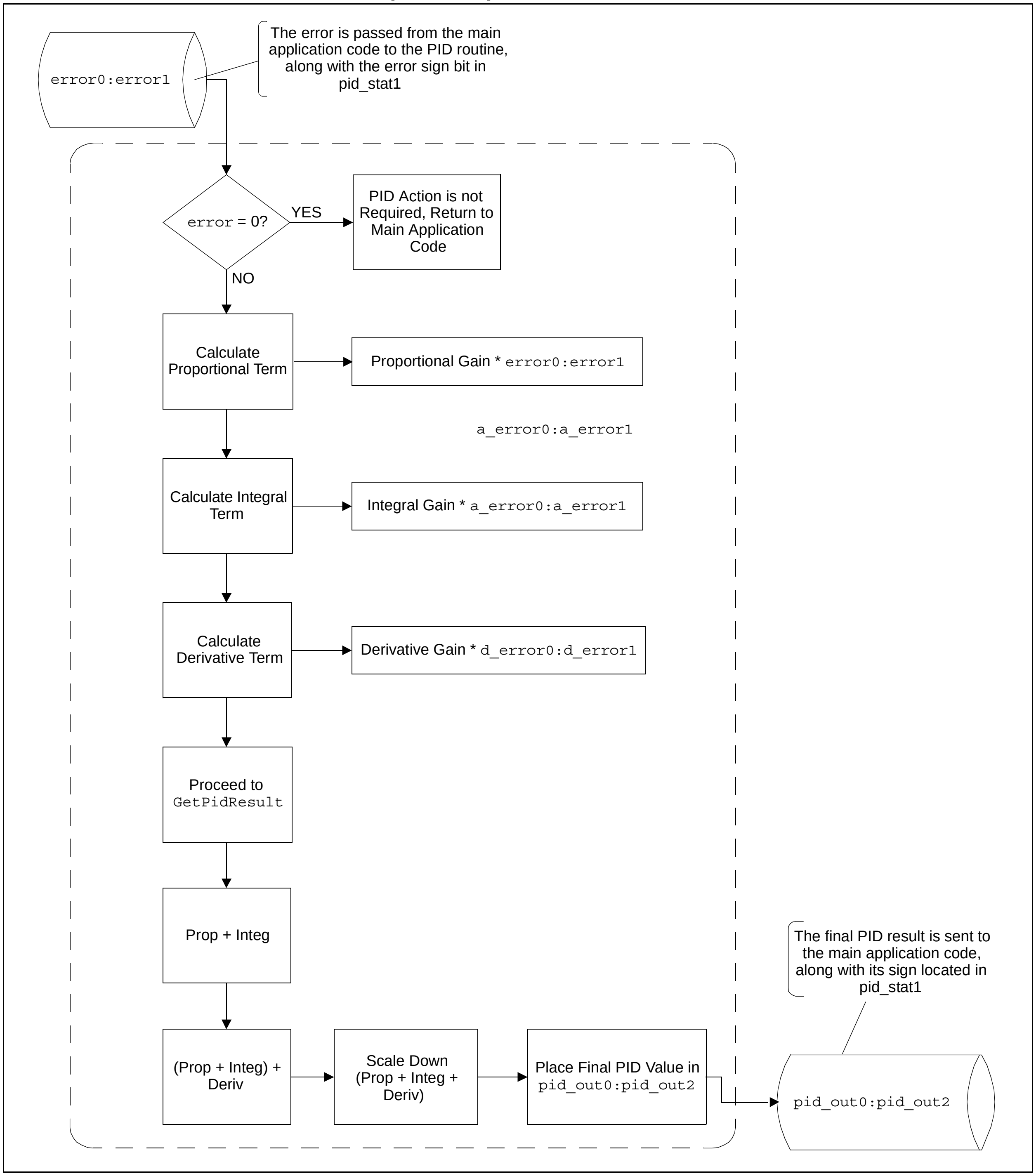
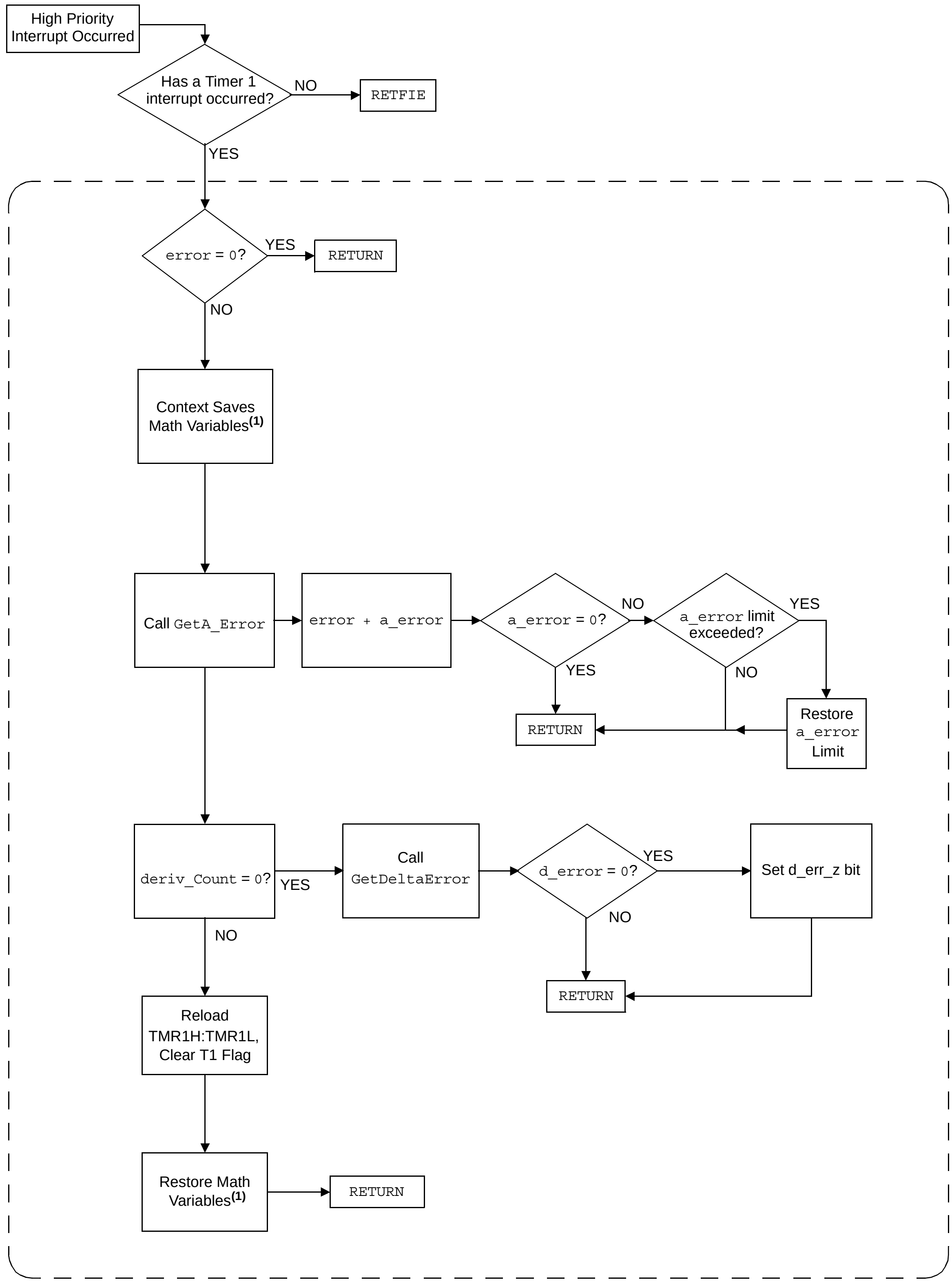


FIGURE 4: PID INTERRUPT ROUTINE (`PidInterrupt`)



Note 1: These instructions are options; they are dependant upon how the ISR is configured. The ISR code referenced in this application note is set up with context save/restore and is within the main application code ISR.

Proportional

The proportional term is the simplest of the three and is also the most commonly found control technique in a feedback system. The proportional gain (`kp`) is multiplied by the error. In this application note, the error is a 16-bit value, `error0:error1`. The amount of correction applied to the system is directly proportional to the error. As the gain increases, the applied correction to the Plant becomes more aggressive. This type of Controller is common for driving the error to a small, but non-zero value, leaving a steady state error. This is the reason for proportional control not being enough in some systems, thereby requiring integral and derivative control to come into play, separately or together (i.e., PI, PD or PID Controller).

IMPLEMENTATION

As mentioned earlier, the proportional is the simplest term. The error is multiplied by the proportional gain, `error0:error1 * kp`. This is accomplished by the 16 * 16 multiplication routine. The result is stored in the 24-bit variable, `prop0:prop2`. This value will be used later in the code to calculate the overall value needed to go to the Plant.

EQUATION 1: PROPORTIONAL TERM

$$prop0:prop2 = kp * error0:error1$$

Integral

Unlike proportional control, which looks at the present error, integral control looks at past errors. Given this, the accumulative error (sum of all past errors) is used to calculate the integral term, but at fixed time intervals. Basically, every time the fixed interval expires, the current error at that moment is added to the `a_error` variable. A temperature system would require a longer sample period than a motor system because of the sluggish response in a temperature controlled environment. If the integral sample period was too fast in the temperature system, the accumulative error would add too quickly to give the system a chance to respond, thereby not allowing it to ever stabilize. Another element in integral control to consider is 'wind-up'. Wind-up occurs when the accumulative error keeps increasing because the Plant output is saturated. This event can be avoided by setting limits to the accumulative error. It can also be eliminated by not executing the integral term when the Plant output is saturated. Another characteristic is excessive gain, that can create an unstable condition within the system, causing it to oscillate. The integral gain must be thoroughly tested for all possible situations to find the best overall value. In conclusion, as the accumulative error increases, the integral term has a greater effect on the Plant. In a sluggish system, this could dominate the value that is sent to the Plant.

IMPLEMENTATION

To obtain the integral term, the accumulated error must be retrieved. The accumulated error (`a_error0:a_error2`) is the sum of past errors. For this reason, the integral is known for looking at a system's history for correction. Refer to Table 2 for details on how `a_error` is accumulated.

Each time the PID routine receives an error, it may or may not be added to the accumulated error variable. This is dependant upon the Timer1 overflow rate. If Timer1 overflowed, then the error at that moment will be added to the accumulated error variable. The Timer1 overflow rate is interrupt driven and is configured as a high priority interrupt. The TMR1H:TMR1L registers are loaded with values defined by the constants, `timer1_hi` and `timer1_lo`. The values for these constants should be based on the Plant's response. The accumulated error will be multiplied by the integral gain, `a_error0:a_error2 * ki` and the result is stored in `integ0:integ2`.

TABLE 2: `a_error` ACCUMULATION EXAMPLE

Time	Error	Timer1 Overflow	Accumulated Error
t = n	10%	No	x%
t = n + 1	8%	No	x%
t = n + 2	12%	Yes	x + 12%
t = n + 3	9%	No	(x% + 12%)
t = n + 4	6%	No	(x% + 12%)
t = n + 5	4%	Yes	(x% + 12%) + 4%
t = n + ...			

To avoid integral wind-up, accumulative error limits were installed (a_err_1_Lim:a_err_2_Lim). When the accumulative error is calculated, the result is compared against the limit variables. If the calculated value exceeds the limits, the accumulative error is made equal to the value that is determined by the user in the variable definition at the beginning of the code.

EQUATION 2: INTEGRAL TERM

integ0:integ2 = ki * a_error0:a_error1 (a_error0:a_error1 = error0:error1 + error0:error1 + …error0:error1)

Derivative

As previously mentioned, the proportional term works on the present error, the integral term works on past errors and the derivative term works on the present and past error to forecast a future response of the system. The derivative term makes an adjustment based on the rate at which the Plant output is changing from its Setpoint. A notable characteristic in this type of control is when the error is constant, or at the maximum limit, the effect is minimal. There are some systems where proportional and/or integral do not provide enough control. In these systems, adding in the derivative term completes the control requirements.

IMPLEMENTATION

The derivative term is calculated in similar fashion to the integral term. Considering that the derivative term is based on the rate at which the system is changing, the derivative routine calculates d_error. This is the difference between the current error and the previous error. The rate at which this calculation takes place is dependant upon the Timer1 overflow. The derivative term can be extremely aggressive when it is acting on the error of the system. An alternative to this is to calculate the derivative term from the output of the system and not the error. In this application note, the error will be used. To keep the derivative term from being too aggressive, a derivative counter variable has been installed. This variable allows d_error to be calculated once for an x number of Timer1 overflows (unlike the accumulated error, which is calculated every Timer1 overflow).

To get the derivative term, the previous error is subtracted from the current error (d_errro0:d_error1 = error0:error – p_error0:p_error1). The difference is then multiplied by the derivative gain (kd) and this result is placed in deriv0:deriv2, which is added with the proportional and integral terms.

Tuning

There are several different ways to tune a PID Controller for system optimization. The code in this application note is loosely defined, giving it the flexibility to be tuned for a specific application (i.e., motor control, temperature, actuator, etc.).

Tuning a PID Controller can be somewhat difficult and time consuming and should be completed in a systematic fashion.

1. Run the system in an open loop and measure its response over time. Based on the measured response, you will get an idea for which PID term is needed most.
2. Determine the application requirements: Plant response time, which PID term will have the most affect and accumulative error limits.
3. Determine how often the a_error and d_error terms should be calculated; this will dictate the values loaded into the Timer1 and derivative counter registers.

In the current configuration, d_error is calculated once for every a_error calculation. Should this be less or more, or vice versa? Finally, once these variables are decided, the PID gains can be experimented with. Start with the smallest gains (i.e., kp = 1 * 16, ki = 1 * 16, kd = 1 * 16), slowly increasing these values until the desired output is reached. With a few code modifications, it is possible to make the Controller a proportional only Controller and tune this to an optimal value. Then it is possible to add the other terms one at a time, optimizing each time.

EQUATION 3: DERIVATIVE TERM

deriv0:deriv2 = kd * d_error0:d_error1 (d_error0:d_error1 = error0:error – p_error:p_error1)

The system response of a temperature controlled environment is shown in Figures 5 through 7. Figure 5 shows the graphic response for a proportional only feedback loop. As shown, none of the gain values can reach the input signal and maintain that level. All four gain values have settled at a non-zero value, as previously discussed.

FIGURE 5: PROPORTIONAL ONLY GRAPHIC RESPONSE

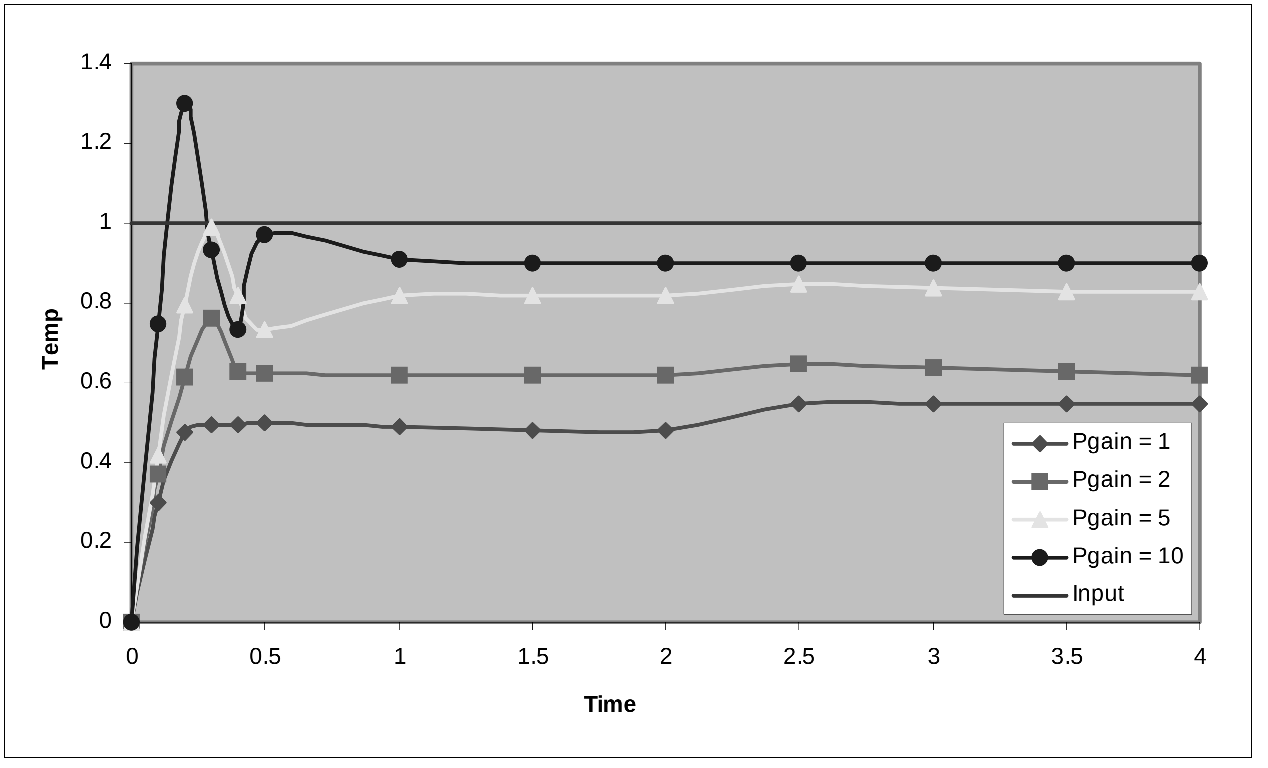


Figure 6 shows the graphic response of a Proportional/Integral (PI) Controller. The high integral gain dominates the response (see line with diamond shapes).

With a tuned proportional and integral gain, the system does settle to its Setpoint, which is why PI control is adequate in many systems. The disadvantage is the time required for it to settle (t = 3), which brings us to PID control.

FIGURE 6: PROPORTIONAL/INTEGRAL (PI) CONTROLLER GRAPHIC RESPONSE

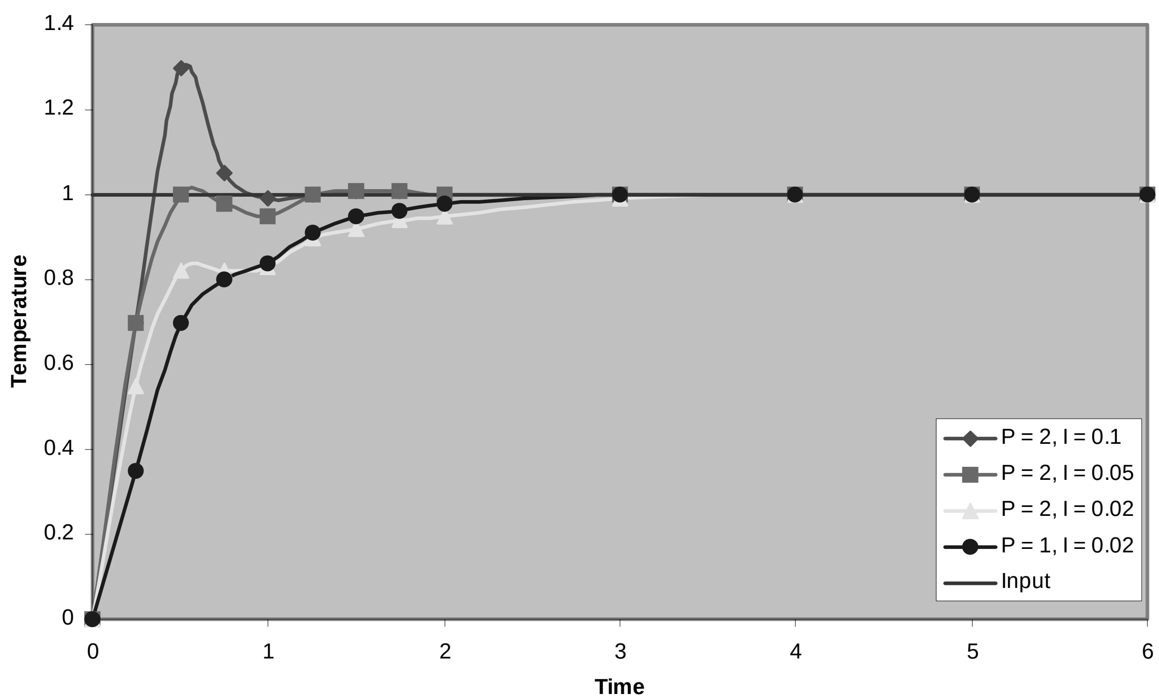
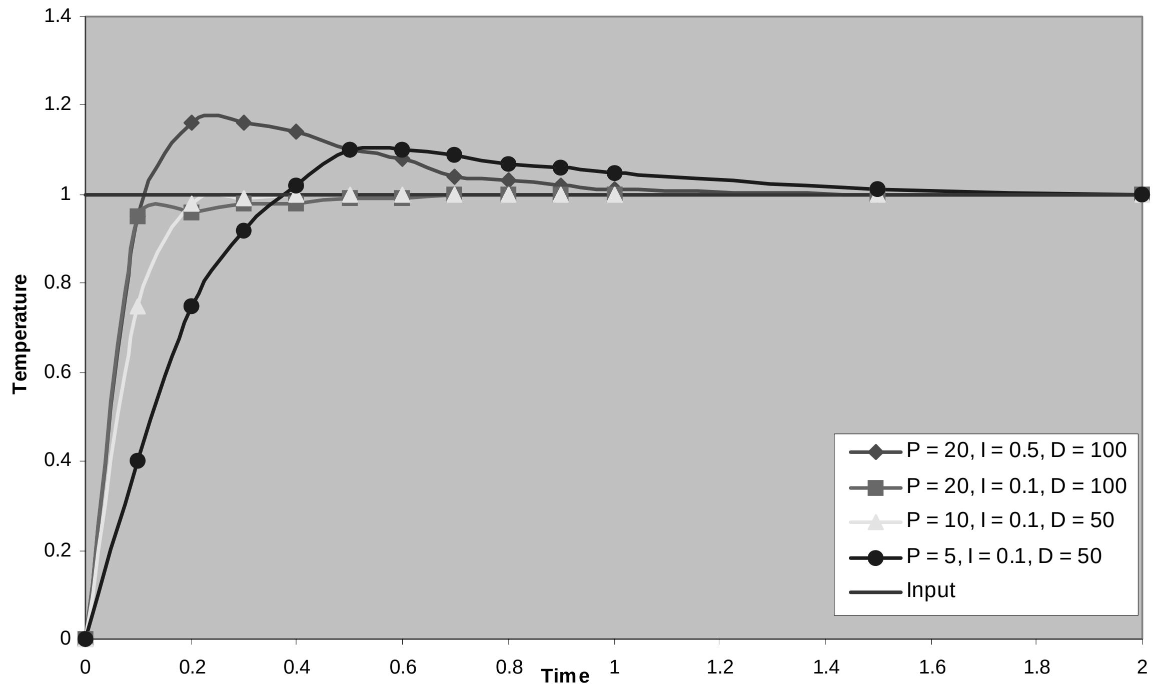


Figure 7 shows the graphic response of a PID Controller. This graph is very similar to the PI graph (Figure 6), except that the PID control takes half as long as the PI control to settle (t = 1.5) as the Setpoint.

FIGURE 7: PID CONTROLLER GRAPHIC RESPONSE



PID Output

The PID output is calculated after the proportional, integral and derivative terms have been determined. In addition to this calculation is the pid_sign bit, which the user must check to decide which direction the Plant will be driven. This bit is located in pid_stat1. The sum of all these terms is stored in `pid_out0:pid_out2`.

EQUATION 4: PID ROUTINE

PID Output = prop0:prop2 + integ0:integ2 + deriv0:deriv2

CONCLUSION

As mentioned in the introduction, the Controller's processing capabilities will dictate the system's ability to respond to the error. Table 3 shows a list of PID functions, each with the amount of instruction cycles and time required. In cases where the Plant response is sluggish, it may be possible to decrease the processor speed and save on power, but still be able to execute the PID routine in acceptable time.

TABLE 3: PID FUNCTIONS

Function	Instruction Cycles	Elapsed Time (µS) (T_{CY} at 40 MHz)
`PID Main`	437	43.7
`Proportional`	50	5.0
`Integral`	52	5.2
`Derivative`	52	5.2
`GetPidResult`	270	27
`GetA_Error`	70	7.0
`PID Interrupt`	184	18.4

The measurements shown in Table 3 can vary, depending on the size of the error and how much of the math routines will be used. The measurements also reflect an error of 6% sent to the PID routine.

After the code development for this application note was completed, the PID routine was implemented on the PIC18F4431 Motor Control board (PICDEM™ MC). For the initial start of the motor, the PID gains were: `kp` = 96, `ki` = 80 and `kd` = 16. These were scaled values. After starting the motor and running it close to its set speed, the integral gain was changed to 144. The accumulated error was calculated every millisecond, initiated by a Timer1 overflow. The delta error (`d_error`) was calculated every 4 ms (derivative counter = 4).

APPENDIX A: SOURCE CODE

The complete source code, including the PID Application Maestro™ module, any demo applications and necessary support files, are available for download as a single archive file from the Microchip corporate web site at:

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