C2000™ Digital Control Library

User's Guide

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About This Manual

This user's guide contains information relating to the C2000 Digital Control Library (DCL). Here you will find technical descriptions of the library functions and how to use them. The user's guide does not contain information on control applications or on the underlying theory of control.

Chapter 1 introduces the library and provides background information. Chapter 2 describes how to use the library. Chapter 3 describes the controller functions and provides detailed information on their use. Chapter 4 describes the utility functions included in the library. Chapter 5 describes the supporting software examples that illustrate the use of the library. A list of useful technical references and training can be found in Chapter 6.

The scope of this user's guide is restricted to description and use of the C2000 Digital Control Library. Information on specific devices and applications is not covered; however, the references listed in Chapter 6 provide a good selection of relevant material and may be of interest.

How to Use This Manual

The reader is advised to begin by reading the library overview in Chapter 1. Chapter 2 provides a useful step-by-step guide of how to add the library code to a C program, and should be read carefully by all users. Once the decision has been made on which type of controller to implement, performance and other important information in the relevant subsection of Chapter 3 should be read carefully. If data array management or performance measurement is required, Chapter 4 describes supporting library functions that may be of interest. Finally, the examples listed in Chapter 5 provide a good starting point for new users of the library.

Related Documentation

For a complete list of related documentation and development tools for the C2000 device, visit the C2000 page on the Texas Instruments website at www.ti.com/c2000.

If You Need Assistance

Technical support for C2000 products is available online via the TI “E2E” Community: e2e.ti.com/support/microcontrollers/c2000.

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Introduction

This chapter contains a brief introduction to the Texas Instruments C2000 Digital Control Library.

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1.1 Supported Devices

The Digital Control Library (DCL) only supports C2000 devices that contain a 32-bit Floating Point Unit (FPU). Among these devices are:

- TMS320F28004x
- TMS320F2837xD
- TMS320F2807x
- TMS320F2833x
- TMS320C2834x
- TMS320F2806x
- TMS320F28M35x
- TMS320F28M36x

The library includes functions that run on the Control Law Accelerator (CLA). This core is only found on certain C2000 devices, including:

- TMS320F28004x
- TMS320F2837xD
- TMS320F2837xS
- TMS320F2807x
- TMS320F2806x

1.2 Overview of the Library

This document describes version 2.0 of the C2000 Digital Control Library (DCL). The DCL provides a suite of robust, open source software functions for developers of control applications using the C2000 MCU platform from Texas Instruments. The library is available for free download at: www.ti.com/c2000.

The DCL functions are intended for use in any system in which a C2000 device is used. The DCL may not be used with any other devices. The DCL is independent of other application specific C2000 software libraries, including “motorWARE” and the “Digital Power Library”, providing attention is paid to data type and range, and integration with these packages should be straightforward.

The library is not extensive. Version 2.0 contains 40 controller functions and 24 supporting functions, all of which are supplied in source code form. Six different types of controller are represented: three PID types, and three “Direct Form” types. The former are typically used to tune transient response properties, while the latter are used in applications where control performance is specified in terms of frequency response properties.

Supporting functions fall into three groups: data logging & buffer management, performance measurement, and transient capture. All supporting functions run on the C28x core only and are supplied in C code form. Some time-critical supporting functions are also supplied in C28x assembly code form.

The library includes a small set of example projects that illustrate how DCL functions might be implemented in user code. All example code was prepared for the F28069 device using the TI peripheral header files for that device.

1.3 Changes to Version 1

1.3.1 New Features

Version 2 of the DCL contains approximately twice the number of controller functions as version 1. The new version of the DCL also adds a number of new utility functions for transient capture and performance measurement. To reflect the broader scope of the library, the name has been changed from Digital Controller Library to Digital Control Library.

The following is a list of features that are new to version 2.0 of the DCL.

- Expanded set of 40 controller functions, compared with 19 in version 1.0
- Controllers coded in C, C28x assembly, and CLA assembly

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- A non-linear PID controller
- Data clamp functions
- A triggered burst data log module for transient capture
- Fast read/write data log functions
- Performance measurement functions

1.3.2 Function Naming

The function naming convention has changed in version 2.0 of the library. The new naming allows several controllers of similar type, but with slightly different implementation, to be included in the library and to be used together in the same program if required.

An example of a function from version 1 of the library is shown in Figure 1-1.

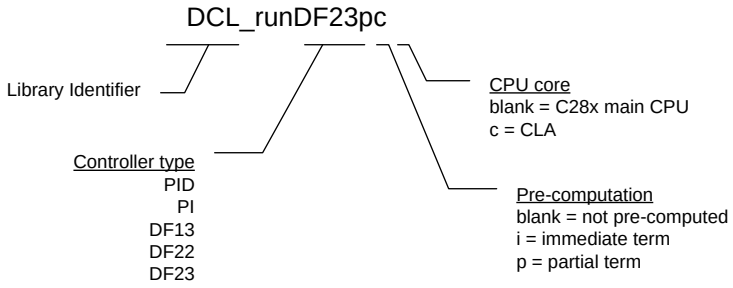

Figure 1-1. DCL Version 1 Function Naming

The corresponding function in version 2 of the library is shown in Figure 1-2.

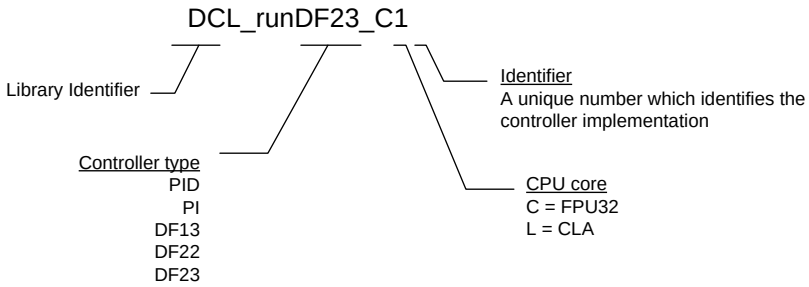

Figure 1-2. DCL Version 2 Function Naming

In the new name format, the controller type, and the CPU on which it runs are explicit. This has been done to allow future expansion of the library with variations of each controller type. An example of this is the PID controller that exists in both “ideal” and “parallel” forms in the new library. The final digit is an arbitrary number that identifies the implementation. Users may add their own controller variations to the DCL controllers by adjusting the final two characters of the function name.

All previous function names have been deprecated in the new library. Previous names are mapped to the new equivalents using the definition list seen near the top of the DCL.h header file. It is not necessary to change any existing code that uses version 1.0 function names.

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1.3.3 Calling Convention

All functions in version 2 of the DCL are designed to be called from a C program. The context save and restore in each function assumes the standard parent register save is performed. If any of the assembly functions are called from an assembly program, additional context save and restore instructions must be added. This differs from version 1.0 in which a full register save and restore was implemented in each function. The new approach has the advantage of fewer instruction cycles when called from a C program, which is the most common use case. For further details, see Section 2.2.2.

1.3.4 Bug Fixes

Only one software bug was known in version 1. This affected the DCL_fillLog() function in the data logger and resulted in the last element in the log not being written. This issue has been corrected in version 2.

1.4 Benchmarks

Table 1-1 lists the performance of each library function by cycle count. In all cases, cycle count benchmarks were measured by logging a free-running PWM timer before and after each function call. Therefore, the measured cycle count includes the function calling overhead from the C environment. Compiler optimization was disabled in all tests. Function sizes are given in units of 16-bit words, as reported in the ".map" file.

Table 1-1. Controller Execution and Code Size Benchmarks

Function	Cycles	Size (W)
DCL_runPID_C1	81	97
DCL_runPID_C2	197	207
DCL_runPID_C3	186	196
DCL_runPID_C4	84	90
DCL_runPID_L1	53	70
DCL_runPID_L2	45	58
DCL_runPI_C1	50	52
DCL_runPI_C2	117	121
DCL_runPI_C3	122	126
DCL_runPI_C4	48	37
DCL_runPI_L1	34	42
DCL_runPI_L2	33	40
DCL_runNLPID_C1	284 (1), (2)	312
DCL_setGamma	2090 (2)	
DCL_runDF13_C1	71	66
DCL_runDF13_C2	20	79
DCL_runDF13_C3	74	
DCL_runDF13_C4	175	162
DCL_runDF13_C5	40	38
DCL_runDF13_C6	121	126
DCL_runDF13_L1	61	86
DCL_runDF13_L2	20	100
DCL_runDF13_L3	58	
DCL_runDF22_C1	44	45
DCL_runDF22_C2	19	48
DCL_runDF22_C3	39	
DCL_runDF22_C4	71	75

(1) All paths operating in linearized error region. For all paths in non-linear operation, total cycle count is approximately 1,433. For more information, see Section 3.3.1.
(2) Measured with run-time library support for the pow() function.

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Table 1-1. Controller Execution and Code Size Benchmarks (continued)

Function	Cycles	Size (W)
DCL_runDF22_C5	29	26
DCL_runDF22_C6	60	67
DCL_runDF22_L1	33	40
DCL_runDF22_L2	20	60
DCL_runDF22_L3	34	
DCL_runDF23_C1	62	64
DCL_runDF23_C2	20	69
DCL_runDF23_C3	54	
DCL_runDF23_C4	98	107
DCL_runDF23_C5	29	26
DCL_runDF23_C6	82	97
DCL_runDF23_L1	44	60
DCL_runDF23_L2	20	80
DCL_runDF23_L3	44	
DCL_writeLog	48	N/A
DCL_readLog	39	N/A
DCL_freadLog	22	11
DCL_fwriteLog	22	14
DCL_runClamp_C1	28	20
DCL_runClamp_C2	71	
DCL_runClamp_L1	25	26
DCL_runITAE_C1		60 (3)
DCL_runIAE_C1		
DCL_runIES_C1		

(3) Cycle count depends on buffer length. For more information, see Section 3.4.1.

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Using the Digital Control Library

This chapter describes how to use the Digital Control Library.

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2.1 What the Library Contains

The DCL library is supplied entirely in open source format. There are no object or ".lib" files in the library. This makes it possible for a user to modify the controller functions if different functionality is required. Controller functions are coded in the following formats:

- Inline C code
- C28x (FPU32) assembly code
- CLA assembly code

2.1.1 Header Files

The four header files shown in Table 2-1 are included in the library.

Table 2-1. List of DCL Header Files

Filename	Type	Description
DCL	h	Library functions
DCL_fdlog	h	Data logger functions
DCL_NLPID	h	Non-linear PID functions
DCL_TCM	h	Transient capture functions

2.1.2 Source Files

The source files shown in Table 2-2 are included in the library.

Table 2-2. List of DCL Source Files

Filename	Type	CPU	Description
DCL_PID_C1	asm	C28x	Ideal linear PID
DCL_PID_C4	asm	C28x	Parallel linear PID
DCL_PID_L1	asm	CLA	Ideal linear PID
DCL_PID_L2	asm	CLA	Parallel linear PID
DCL_PI_C1	asm	C28x	Ideal linear PI
DCL_PI_C4	asm	C28x	Parallel linear PI
DCL_PI_L1	asm	CLA	Ideal linear PI
DCL_PI_L2	asm	CLA	Parallel linear PI
DCL_DF13_C1	asm	C28x	Full DF1 (3rd order)
DCL_DF13_C2C3	asm	C28x	Pre-computed DF1 (3rd order)
DCL_DF13_L1	asm	CLA	Full DF1 (3rd order)
DCL_DF13_L2L3	asm	CLA	Pre-computed DF1 (3rd order)
DCL_DF22_C1	asm	C28x	Full DF2 (2nd order)
DCL_DF22_C2C3	asm	C28x	Pre-computed DF2 (2nd order)
DCL_DF22_L1	asm	CLA	Full DF2 (2nd order)
DCL_DF22_L2L3	asm	CLA	Pre-computed DF2 (2nd order)
DCL_DF23_C1	asm	C28x	Full DF2 (3rd order)
DCL_DF23_C2C3	asm	C28x	Pre-computed DF2 (3rd order)
DCL_DF23_L1	asm	CLA	Full DF2 (3rd order)
DCL_DF23_L2L3	asm	CLA	Pre-computed DF2 (3rd order)
DCL_frwlog	asm	C28x	Fast read/write log functions
DCL_clamp_C1	asm	C28x	Data clamp
DCL_clamp_L1	asm	CLA	Data clamp
DCL_index	asm	C28x	Performance measurement

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2.1.3 Examples

Six examples are supplied with the Digital Control Library. These were prepared using CCS version 6 and run without modification on the F28069 device. The examples include linker command files that show how to allocate device memory when using the DCL. For more details, see Chapter 5.

2.2 How to Add the DCL to your Code

The Digital Control Library is intended to be used with a project written in the C programming language. Typically, the controller functions for the C28x would be inserted into an Interrupt Service Routine (ISR) triggered by a hardware event, which ensures they are executed at a fixed rate and their timing is synchronized with the availability of incoming control data. Control functions for use on the CLA would be called from a CLA task, which again, would typically be triggered by a hardware event.

2.2.1 Steps to Add the DCL to Existing C Code

The following is a sequence of steps that can be followed when adding the DCL to an existing C program. For a set of code examples that illustrates configuration and use of the DCL, see Chapter 5.

1. Specify the include file(s)

   Before you can begin using the library you must add the library header file to your project.

   ```
   #include    “DCL.h”
   ```

   This must be done in such a way that the DCL header file is visible to all program source files that reference controller variables or functions. The include file search options in CCS allow users to specify header file paths. The project properties can be found by right-clicking on the project name, selecting “Properties”, and navigating to the “Include Options” section.

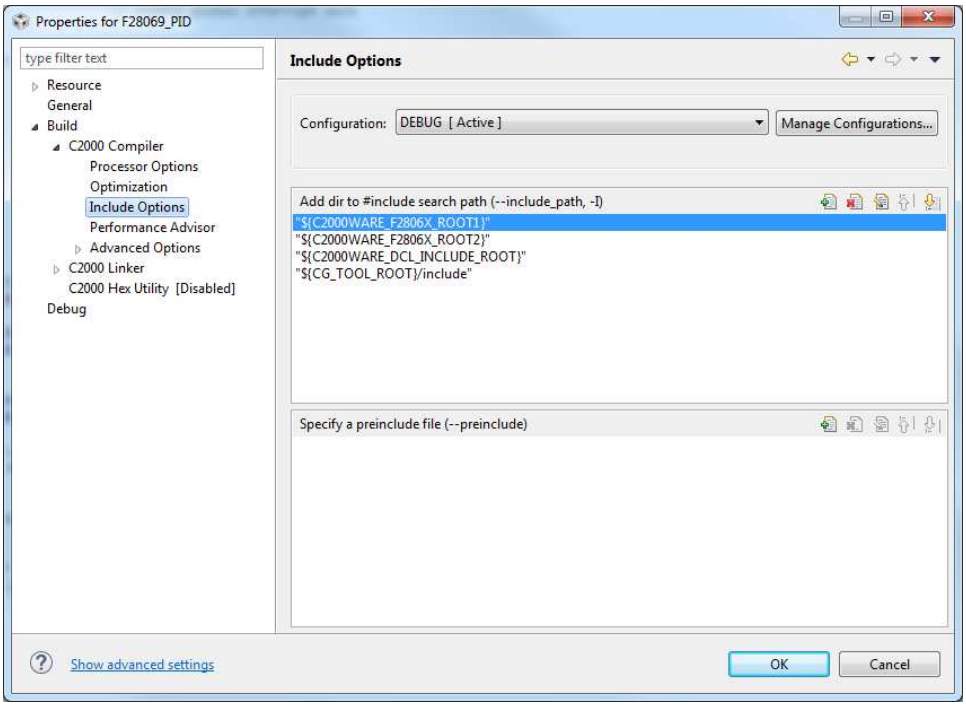

Figure 2-1. CCSv6 Include Options

If you want to include the data logger or functions in the TCM, you must also include those respective header files. Note that the TCM includes the data log header file.

If you want to use the non-linear PID functions, the header file “DCL_NLPID.h” must be included in your program. Note that the NLPID does not run on the CLA and the header file should not be included in any CLA files.

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2. Add the source files to the project.

   The source files for the controllers that you want to use must be added to your CCS project. You can manually copy the files into your project directory, or specify the library pathname in the CCS compiler options. It is only necessary to add those source files for the functions that you want to use.

3. Allocate the controller functions in the linker command file.

   DCL functions that execute on the C28x core can be allocated to a specific memory block in the linker command file. It is common to place the controller functions in internal zero wait state RAM, since this allows them to run at the maximum speed of the device. Note that all CLA functions must run from internal zero wait state RAM.

   C28x library functions are placed in the user defined code section “dclfuncs”. An example showing how this section might be mapped into the internal L4 RAM memory block is shown below.

   ```
   dclfuncs        : > RAML4,        PAGE = 0
   ```

   See also the linker command file “F28069_DCL.cmd” in the project examples.

   In a stand-alone application, code must be stored in non-volatile memory (such as internal flash) and copied into RAM at run-time. For information on how to do this, see *Running an Application from Internal Flash Memory on the TMS320F28xxx DSP* (SPRA958).

   More details on the linker section allocation can be found in the *TMS320C28x Assembly Language Tools User’s Guide* (SPRU513).

4. Create an instance of the controller

   You must declare an instance of the controller you wish to use. Examples can be found for each controller type in the corresponding chapter that describes it. For example, to create an instance of a PID controller named “pid1”, you would add the following line to the variable list in your C source.

   ```
   PID pid1 = DCL_PID_DEFAULTS;
   ```

   This creates a variable of type “PID”, the elements of which are initialized to those default values specified in the “DCL.h” header file. Like any C variable, the structure must be visible to any source files that reference it.

   Note that CLA variables must be initialized at run-time by user code (they cannot be initialized at the variable declaration). Typically, this is done using a separate CLA task.

5. Declare variables

   In addition to a pointer to the controller structure, each controller function requires certain input variables to be passed as arguments to the function. You should declare instances of these variables in your code and ensure they can be referenced by all files that call the controller functions. For example:

   ```
   float uk;        // control
   float rk = 0.0f;    // reference
   float yk = 0.0f;    // feedback
   float lk = 1.0f;    // saturation
   ```

   Again, CLA variables cannot be initialized at the variable declaration.

6. Initialize the controller

   The elements of the (CPU) controller structure were initialized to default settings in step 3. The user program must configure any controller elements with specific values before the function is called. For example:

   ```
   pid.Kp = 9.4f;      // set proportional gain to 9.4
   pid.Umax = 10.0f;   // upper output clamp limit = 10
   ```

   If a CLA based controller is being used, its parameters must always be initialized using a separate task. For more information on the CLA C compiler, see the *CLA Compiler* chapter of the TMS320C28x Optimizing C/C++ Compiler v16.12.0.STS User's Guide.

   Direct Form control structures incorporate one or two delay lines that hold previous controller output data. These must be initialized to zero before calling the controller functions. It is possible that uninitialized delay line data, especially in the recursive path, might cause the controller to saturate or deliver unreliable results. The initialization of the delay line elements is the responsibility of the user. For examples of delay line initialization, see the code examples 1 and 2 described in Chapter 5.

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7. Call the controller function

   Typically, the controller functions would be inserted into an ISR, which is triggered by a hardware timer. This ensures that the control law is executed at a deterministic and fixed time interval. Each control function returns a single floating-point variable that represents the controller output. An example of a controller function call is shown below.

```
uk = DCL_runPID(&pid1, rk, yk  lk);
```

2.2.2 Calling the Library Functions From Assembly

The assembly coded functions in the DCL have been written to be called from a C program. The context save and restore sections within each function protect only those core registers that are not already protected by the C environment. In applications where the DCL controller functions must be called from an assembly program, the user must place additional register save and restore instructions near the start and end of each called function.

For the C28x, see the *Register Conventions* and *Function Structure and Calling Conventions* sections of the TMS320C28x Optimizing C/C++ Compiler v16.12.0.STS User's Guide for detailed information on register usage and calling conventions. For the CLA, see the *Function Structure and Calling Conventions* section of the same document.

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Controllers

This chapter provides detailed information on the controller functions in the Digital Control Library.

The DCL contains six basic types of controller.

- Linear PID
- Linear PI
- Non-linear PID
- Direct Form 1 (third order)
- Direct Form 2 (second order)
- Direct Form 2 (third order)

In this guide, the three direct form types are referred to as “compensators”. This reflects a situation typical in power supply design, where the objectives are to compensate some feature of the open loop frequency response, such as phase shift. In such cases the controller is specified using a set of pole and zero frequencies, which leads naturally to a transfer function description. The “Direct Form” nomenclature comes from different implementations of digital filters having transfer function descriptions.

Each controller type is coded in C, and in assembly using two different instruction sets (FPU32 and CLA). There are therefore three different functions for each controller. For more information on function names, see Section 1.3.2. Additionally, each of the three Direct Form compensators is implemented in both full and pre-computed forms.

An exception is the non-linear PID controller that is only available in C coded form. At the present time, support for the pow() function used in the control law is only available in the standard C run-time support library. Note that this controller is not supported on the CLA.

The description of each controller in this chapter is broken down into three subsections.

- A general description of the controller
- Information of the implementation of the controller
- A detailed list of functions

The implementation subsection always includes a block diagram showing the variables used in the code. Local variables, which do not need to be preserved between functions, are pre-fixed with the letter “v”. Variables that are part of the controller structure and, therefore, preserved between functions, are pre-fixed with some other letter according to their purpose. For example, “i10” refers to a variable used in the PID integrator. These same variable names are used in the library source code, so it is straightforward to correlate the source code with the diagrams.

All functions in the DCL are re-entrant.

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3.1 Linear PID Controllers

3.1.1 Description

The basic controller described here is a linear PID type. The PID implementations in the DCL include several features not commonly found in basic PID designs, and this complexity is reflected the benchmark figures. Applications that do not require derivative action, or are more sensitive to cycle efficiency, may be better served by the simpler PI controller structure described in Chapter 4.

PID control is widely used in systems that employ output feedback control. In such systems, the controlled output is measured and fed back to a summing point where it is subtracted from the reference input. The difference between the reference and feedback corresponds to the control loop error (or servo error) and forms the input to the PID controller.

The PID controller output is the parallel sum of three paths that act on the error, error integral, and error derivative, respectively. The relative weight of each path is adjusted by the user to optimize transient response.

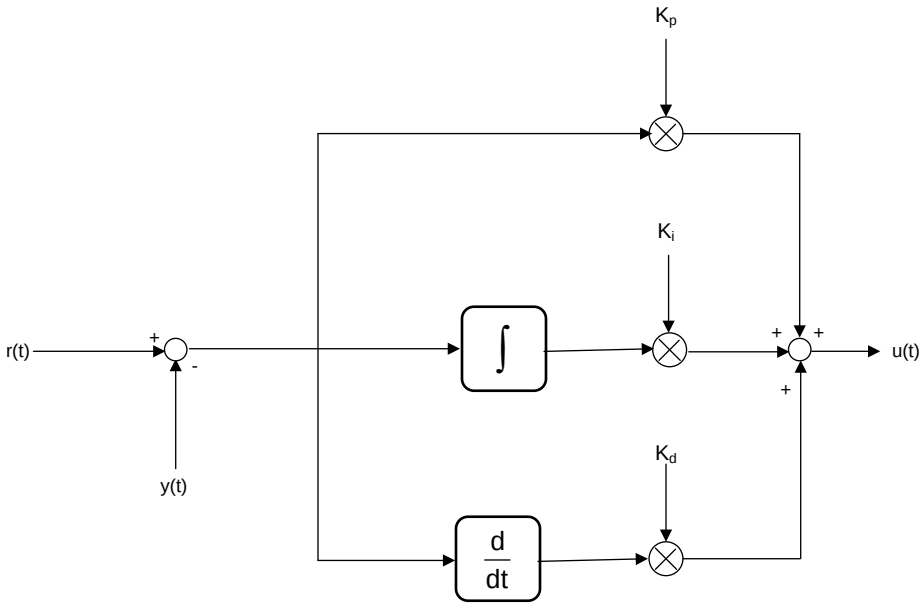

Figure 3-1. Parallel Form PID Controller

The diagram above shows the structure of a continuous time “parallel” PID controller. The output of this controller is captured in Equation 1.

$$u(t) = K_p e(t) + K_i \int_{-\infty}^{t} e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

Conceptually, the controller comprises three separate paths connected in parallel. The upper path contains an adjustable gain term (K_p). Its effect is to fix the open loop gain of the control system. Since loop gain is proportional to this term, K_p is known as proportional gain.

A second path contains an integrator that accumulates error history. A separate gain term acts on this path. The output of the integral path changes continuously as long as a non-zero error (e) is present at the controller input. A small but persistent servo error has the effect of driving the output of the integrator such that the loop error will eventually disappear. The principal effect of the integral path is therefore to eliminate steady state error. The effect of the integral gain term is to change the rate at which this happens. Integral action is especially important in applications such as electronic power supplies, which must maintain accurate regulation over long periods of time.

The third path contains a differentiator. The output of this path is large whenever the rate of change of the error is large. The principal effect of the derivative action is to damp oscillation and reduce transients.

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The operation of the PID controller can be visualized in terms of the transient error following a step change of set-point.

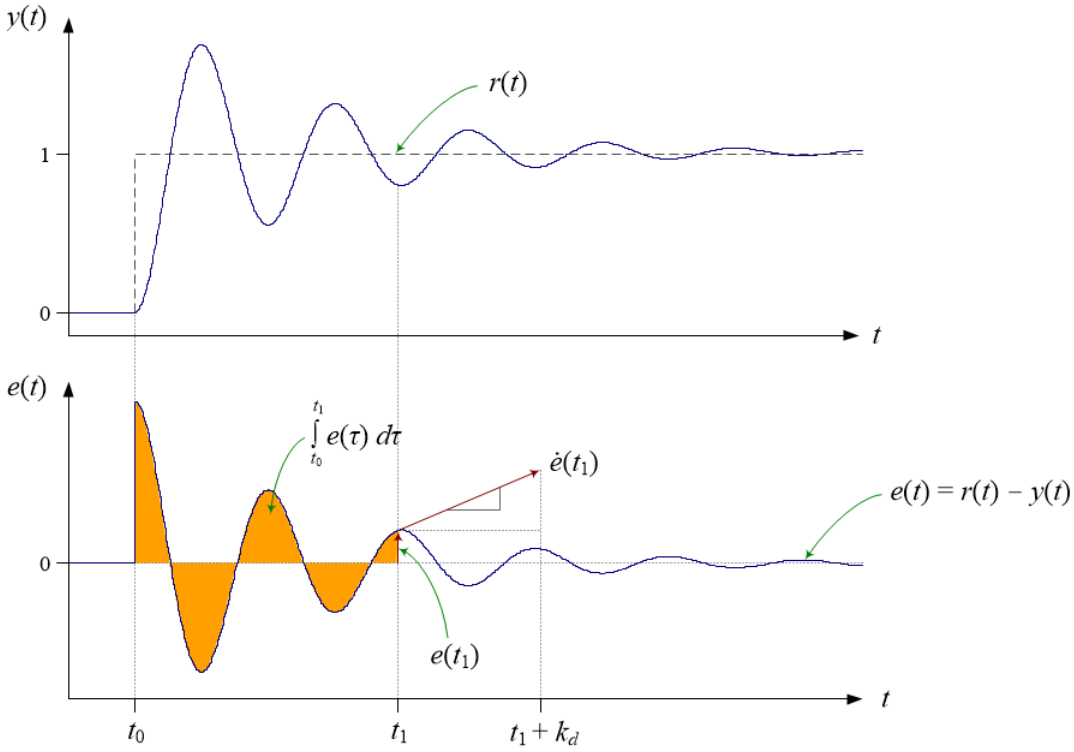

Figure 3-2. PID Control Action

Figure 3-2 shows the action of the PID controller in terms of the control loop error at time t1. The proportional term contributes a control effort that is proportional to the instantaneous loop error. The output of the integral path is the accumulated error history: the shaded area in the lower plot. The contribution of the derivative path is proportional to the rate of change of the loop error. Derivative gain fixes the time interval over which a tangential line to the error curve is projected forward in time.

Tuning the PID controller is a matter of finding the optimum combination of these three effects. This in turn means finding the best balance of the three gain terms. For more information on PID control and tuning, see Section 6.1.

The PID shown above is known as the “parallel” form because the three controller gains appear in separate parallel paths. A different PID architecture in which the proportional gain is moved into the output path (that is, after the summing point), so that the proportional path becomes a direct connection between the controller input and the summing point, is known as the “ideal” form. In the ideal form, the open loop gain is directly influenced by the proportional controller gain, and there is less interaction between the controller gains. However, the proportional gain cannot be zero (since the loop would be opened), and to maintain good control cannot be small. The parallel form allows the proportional gain to be small; however, there is slightly more interaction between the three controller gains. The DCL contains both ideal and parallel PID functions.

3.1.2 Implementation

The linear PID controllers in the DCL include the following features:

- Parallel and ideal forms
- Programmable output saturation
- Independent reference weighting on proportional path
- Anti-windup integrator reset
- Programmable low-pass derivative filter

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- External saturation input for integrator anti-windup
- Adjustable output saturation

All PID type controllers in the library implement anti-windup reset in a similar way. A clamp is present at the controller output that allows the user to set upper and lower limits on the control effort. If either limit is exceeded, an internal floating-point controller variable changes from 1.0f to 0.0f. This variable is multiplied by the integrator input, such that the integrator accumulates successive zero data when the output is saturated, avoiding the well-known wind-up phenomenon.

The PID controllers in the library make provision for anti-windup reset to be triggered from an external part of the loop. This is useful in situations where a component outside the controller mat be saturated. The floating-point variable “lk” is expected to be either 1.0f or 0.0f in the normal and saturated conditions respectively. If this feature is not required, the functions should be called with the “lk” argument set to 1.0f. External saturation is not provided on the PI controllers.

The derivative PID path includes a digital low-pass filter to avoid amplification of un-wanted high frequency noise. The filter implemented here is a simple first order lag filter with differentiator, converted into discrete form using the Tustin transform. Referring to Figure 3-3, the difference equation of the filtered differentiator is:

$$v_4(k) = v_1(k) - d_2(k) - d_3(k) \tag{2}$$

The temporary storage elements d2 & d3 interval must be preserved from the (k - 1)th interval, so the following must be computed after the differentiator update.

$$d_2(k) = v_1(k-1) \tag{3}$$

$$d_3(k) = c_2 v_4(k-1) \tag{4}$$

The derivative filter coefficients are:

$$c_1 = \frac{2}{T + 2\tau} \tag{5}$$

$$c_2 = \frac{T - 2\tau}{T + 2\tau} \tag{6}$$

Both the sample period (T) and filter time constant (τ) are required for definition of this filter. The time constant is the reciprocal of the desired filter bandwidth in radians per second.

All linear PID controller functions use a common C structure to hold coefficients and data, defined in the header file “DCL.h”.

```
typedef volatile struct {
    float Kp;       //!< Proportional gain
    float Ki;       //!< Integral gain
    float Kd;       //!< Derivative gain
    float Kr;       //!< Set point weight
    float c1;       //!< D-term filter coefficient 1
    float c2;       //!< D-term filter coefficient 2
    float d2;       //!< D-term filter intermediate storage 1
    float d3;       //!< D-term filter intermediate storage 2
    float i10;      //!< I-term intermediate storage
    float i14;      //!< Intermediate saturation storage
    float Umax;     //!< Upper saturation limit
    float Umin;     //!< Lower saturation limit
} PID;
```


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The memory address offsets of the structure elements are shown in Table 3-1.

Table 3-1. List of PID Structure Elements and Address Offsets

Element	Offset (Hex)	Offset (Dec)	Description
Kp	0	0	Proportional gain
Ki	2	2	Integral gain
Kd	4	4	Derivative gain
Kr	6	6	Set point weight
c1	8	8	D-term filter coefficient 1
c2	A	10	D-term filter coefficient 2
d2	C	12	D-term filter intermediate storage 1
d3	E	14	D-term filter intermediate storage 2
i10	10	16	I-term intermediate storage
i14	12	18	Intermediate saturation storage
Umax	14	20	Upper saturation limit
Umin	16	22	Lower saturation limit

The ideal form PID implementation is shown in Figure 3-3.

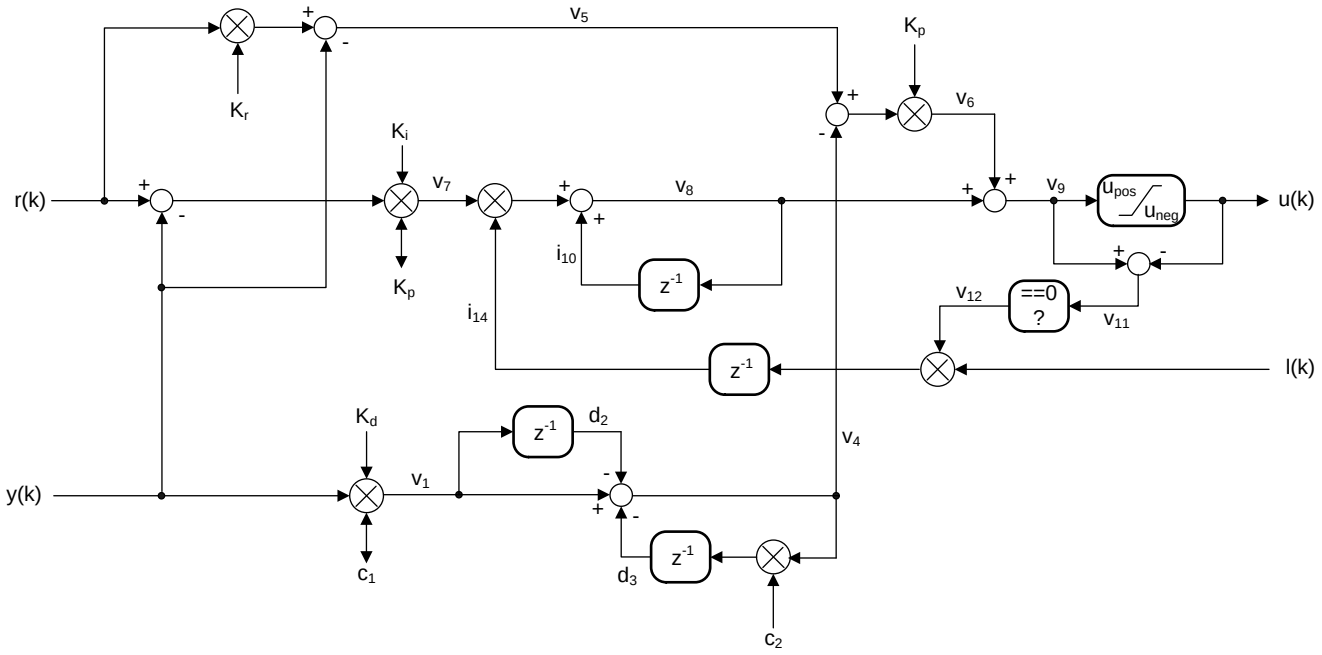

Figure 3-3. DCL_PID_C1 Architecture

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The parallel form PID is shown in Figure 3-4.

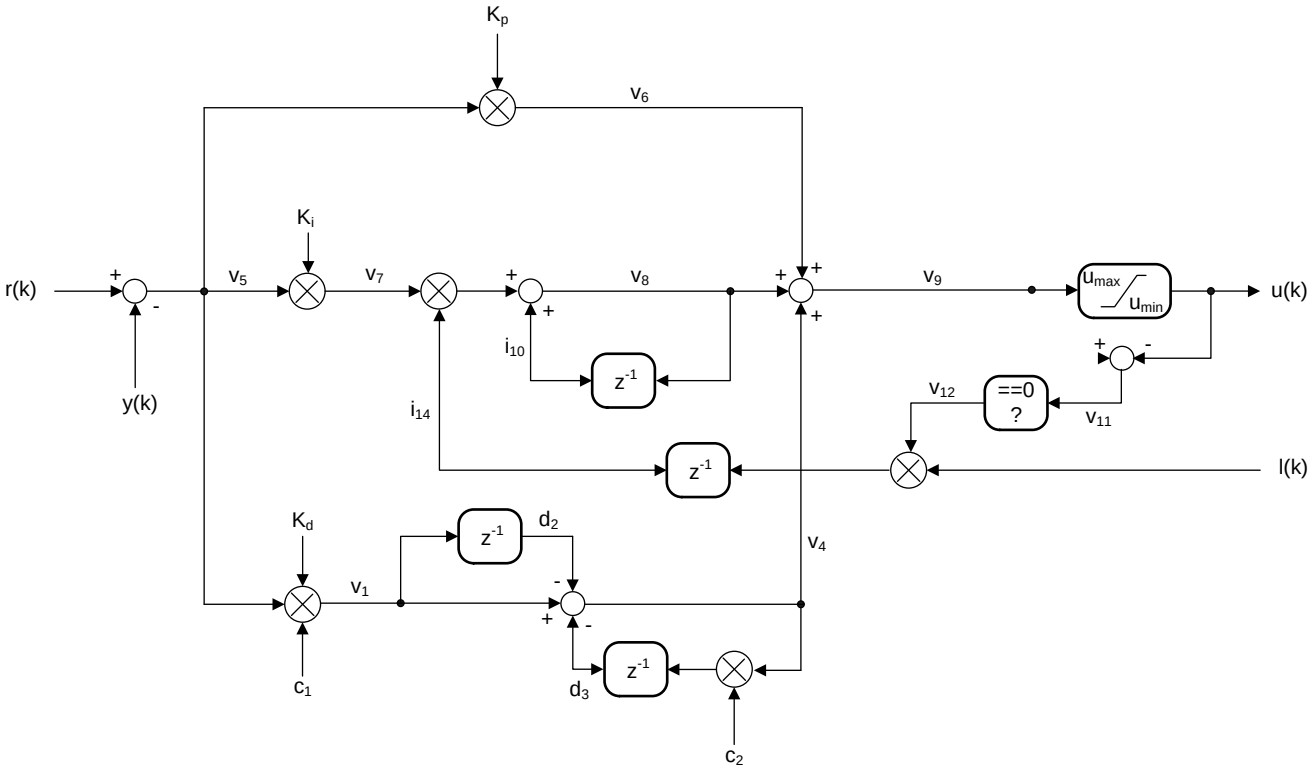

Figure 3-4. DCL_PID_C3 Architecture

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3.1.3 PID Functions

Table 3-2. Summary of PID Functions

Title	Page
DCL_runPID_C1 —Run the Ideal Form PID Controller	23
DCL_runPID_C2 —Run the Ideal PID Form Controller	23
DCL_runPID_C3 —Run the Parallel Form PID Controller	24
DCL_runPID_C4 —Run the Parallel Form PID Controller	24
DCL_runPID_L1 —Run the Ideal Form PID Controller	25
DCL_runPID_L2 —Run the Parallel Form PID Controller	25

DCL_runPID_C1 *Run the Ideal Form PID Controller*

Header File DCL.h

Source File DCL_PID_C1.asm

Declaration float DCL_runPID_C1(PID *p, float rk, float yk, float lk)

Description This function executes an ideal form PID controller on the C28x. The function is coded in C28x assembly.

Parameters

p	The PID structure
rk	The controller set-point reference
yk	The measured feedback value
lk	External output clamp flag

Return The control effort

DCL_runPID_C2 *Run the Ideal PID Form Controller*

Header File DCL.h

Source File N/A

Declaration float DCL_runPID_C2(PID *p, float rk, float yk, float lk)

Description This function executes an ideal form PID controller on the C28x, and is identical in structure and operation to the C1 form. The function is coded in inline C.

Parameters

p	The PID structure
rk	The controller set-point reference
yk	The measured feedback value
lk	External output clamp flag

Return The control effort

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DCL_runPID_C3 *Run the Parallel Form PID Controller*

Header File DCL.h

Source File N/A

Declaration float DCL_runPID_C3(PID *p, float rk, float yk, float lk)

Description This function executes a parallel form PID controller on the C28x. The function is coded in inline C.

Parameters

p	The PID structure
rk	The controller set-point reference
yk	The measured feedback value
lk	External output clamp flag

Return The control effort

DCL_runPID_C4 *Run the Parallel Form PID Controller*

Header File DCL.h

Source File DCL_PID_C4.asm

Declaration float DCL_runPID_C4(PID *p, float rk, float yk, float lk)

Description This function executes a parallel form PID controller on the C28x, and is identical in structure and operation to the C3 form. The function is coded in inline C.

Parameters

p	The PID structure
rk	The controller set-point reference
yk	The measured feedback value
lk	External output clamp flag

Return The control effort

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DCL_runPID_L1 *Run the Ideal Form PID Controller*

Header File DCL.h

Source File DCL_PID_L1.asm

Declaration float DCL_runPID_L1(PID *p, float rk, float yk, float lk)

Description This function executes an ideal form PID controller on the CLA. The function is coded in CLA assembly.

Parameters

p	The PID structure
rk	The controller set-point reference
yk	The measured feedback value
lk	External output clamp flag

Return The control effort

DCL_runPID_L2 *Run the Parallel Form PID Controller*

Header File DCL.h

Source File DCL_PID_L2.asm

Declaration float DCL_runPID_L2(PID *p, float rk, float yk, float lk)

Description This function executes a parallel form PID controller on the CLA. The function is coded in CLA assembly.

Parameters

p	The PID structure
rk	The controller set-point reference
yk	The measured feedback value
lk	External output clamp flag

Return The control effort

3.2 Linear PI Controllers

3.2.1 Description

The continuous time parallel PI control equation is shown in Equation 7.

$$u(t) = K_p e(t) + K_i \int_{-\infty}^{t} e(\tau) d\tau \tag{7}$$

The linear PI controllers in the DCL differ from the PID in the following respects:

- Removal of derivative path
- Removal of set-point weighting
- No provision for external saturation input

In all other regards the PI controllers are similar to the PID controllers described in the previous subsection.

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3.2.2 Implementation

All linear PI controller functions use a common C structure to hold coefficients and data, defined in the header file “DCL.h”.

```
typedef volatile struct {
    float Kp;     //!< Proportional gain
    float Ki;     //!< Integral gain
    float i10;    //!< I storage
    float Umax;   //!< Upper saturation limit
    float Umin;   //!< Lower saturation limit
    float i6;     //!< Saturation storage
} PI;
```

The memory address offsets of the structure elements are shown in Table 3-3.

Table 3-3. List of PI Structure Elements and Address Offsets

Element	Offset (Hex)	Offset (Dec)	Description
Kp	0	0	Proportional gain
Ki	2	2	Integral gain
i10	4	4	I storage
Umax	6	6	Upper saturation limit
Umin	8	8	Lower saturation limit
i6	A	10	Saturation storage

The ideal form PI implementation is shown in Figure 3-5.

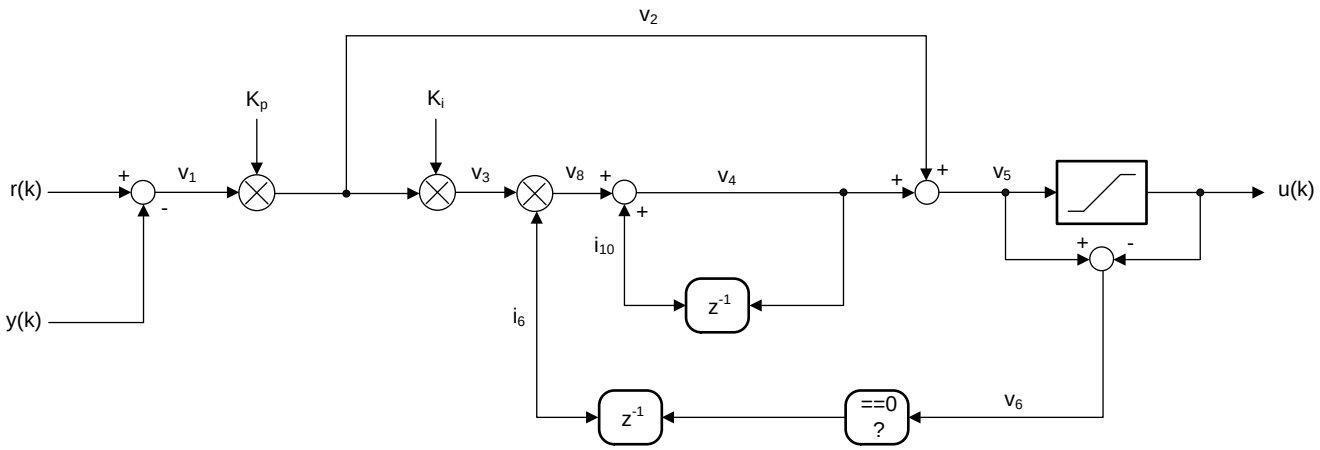

Figure 3-5. DCL_PI_C1 Architecture

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The parallel form PI implementation is shown in Figure 3-6.

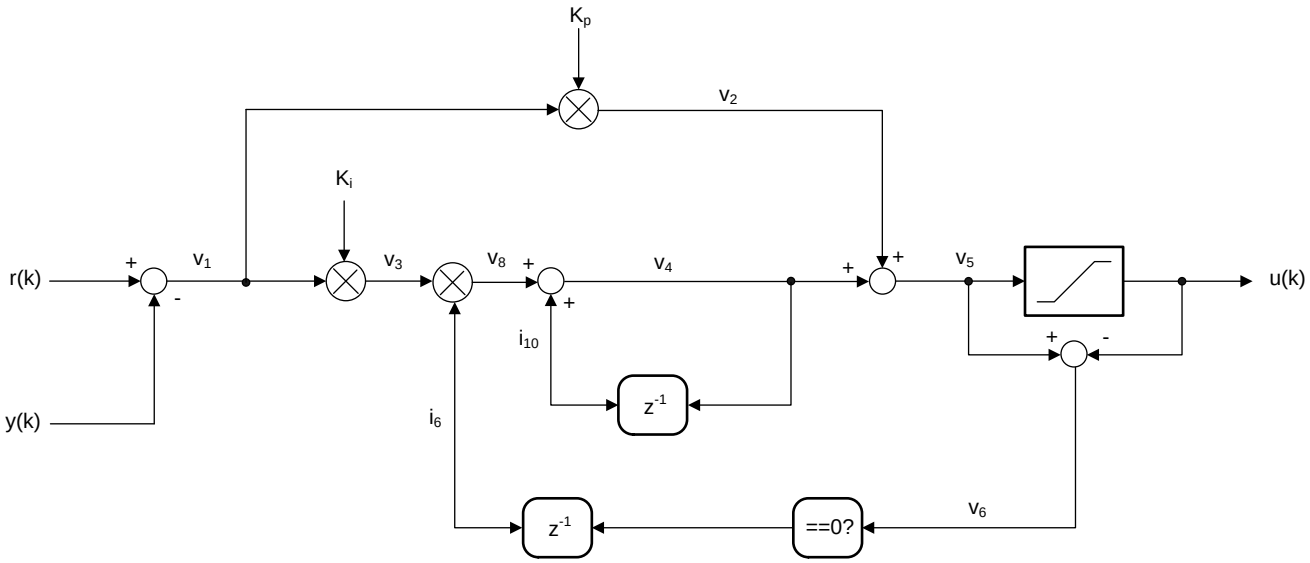

Figure 3-6. DCL_PI_C3 architecture

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3.2.3 Summary of PI Functions

Table 3-4. PI Functions

Title	Page
DCL_runPI_C1 —Run the Ideal Form PI Controller	28
DCL_runPI_C2 —Run the Ideal PI Form Controller	28
DCL_runPI_C3 —Run the Parallel Form PI Controller	29
DCL_runPI_C4 —Run the Parallel Form PI Controller	29
DCL_runPI_L1 —Run the Ideal Form PI Controller	30
DCL_runPI_L2 —Run the Parallel Form PI Controller	30

DCL_runPI_C1 *Run the Ideal Form PI Controller*

Header File DCL.h

Source File DCL_PID_C1.asm

Declaration float DCL_runPI_C1(PI *p, float rk, float yk)

Description This function executes an ideal form PI controller on the C28x. The function is coded in C28x assembly.

Parameters

p	The PI structure
rk	The controller set-point reference
yk	The measured feedback value

Return The control effort

DCL_runPI_C2 *Run the Ideal PI Form Controller*

Header File DCL.h

Source File N/A

Declaration float DCL_runPI_C2(PI *p, float rk, float yk)

Description This function executes an ideal form PI controller on the C28x, and is identical in structure and operation to the C1 form. The function is coded in inline C.

Parameters

p	The PI structure
rk	The controller set-point reference
yk	The measured feedback value

Return The control effort

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DCL_runPI_C3 *Run the Parallel Form PI Controller*

Header File DCL.h

Source File N/A

Declaration float DCL_runPI_C3(PI *p, float rk, float yk)

Description This function executes a parallel form PI controller on the C28x. The function is coded in inline C.

Parameters

p	The PI structure
rk	The controller set-point reference
yk	The measured feedback value

Return The control effort

DCL_runPI_C4 *Run the Parallel Form PI Controller*

Header File DCL.h

Source File DCL_PI_C4.asm

Declaration float DCL_runPI_C4(PI *p, float rk, float yk)

Description This function executes a parallel form PI controller on the C28x, and is identical in structure and operation to the C3 form. The function is coded in inline C.

Parameters

p	The PI structure
rk	The controller set-point reference
yk	The measured feedback value

Return The control effort

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DCL_runPI_L1 *Run the Ideal Form PI Controller*

Header File DCL.h

Source File DCL_PI_L1.asm

Declaration float DCL_runPI_L1(PI *p, float rk, float yk)

Description This function executes an ideal form PI controller on the CLA. The function is coded in CLA assembly.

Parameters

p	The PI structure
rk	The controller set-point reference
yk	The measured feedback value

Return The control effort

DCL_runPI_L2 *Run the Parallel Form PI Controller*

Header File DCL.h

Source File DCL_PI_L2.asm

Declaration float DCL_runPI_L2(PI *p, float rk, float yk)

Description This function executes an ideal form PI controller on the CLA. The function is coded in CLA assembly.

Parameters

p	The PI structure
rk	The controller set-point reference
yk	The measured feedback value

Return The control effort

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3.3 Non-linear PID Controller

3.3.1 Description

The DCL includes one implementation of a non-linear PID controller, denoted NLPID. The controller is similar to the DCL implementation of ideal PID, except that there is no set-point weighting and the derivative path sees the servo error instead of the feedback. A non-linear gain block appears in series with each of the three paths.

To improve computational efficiency, the non-linear law is separated into two parts: one part that is common to all paths, and a second part that contains terms specific to each path. The non-linear part of the high-level controller structure is shown in Figure 3-7.

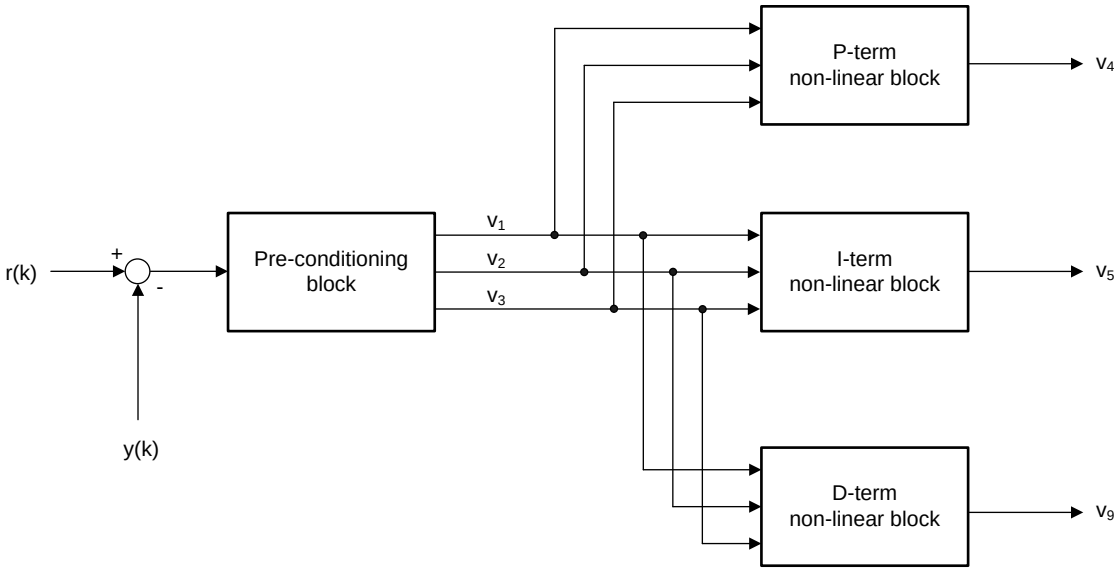

Figure 3-7. Non-Linear PID Input Architecture

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The linear part of the NLPID controller is shown in Figure 3-8.

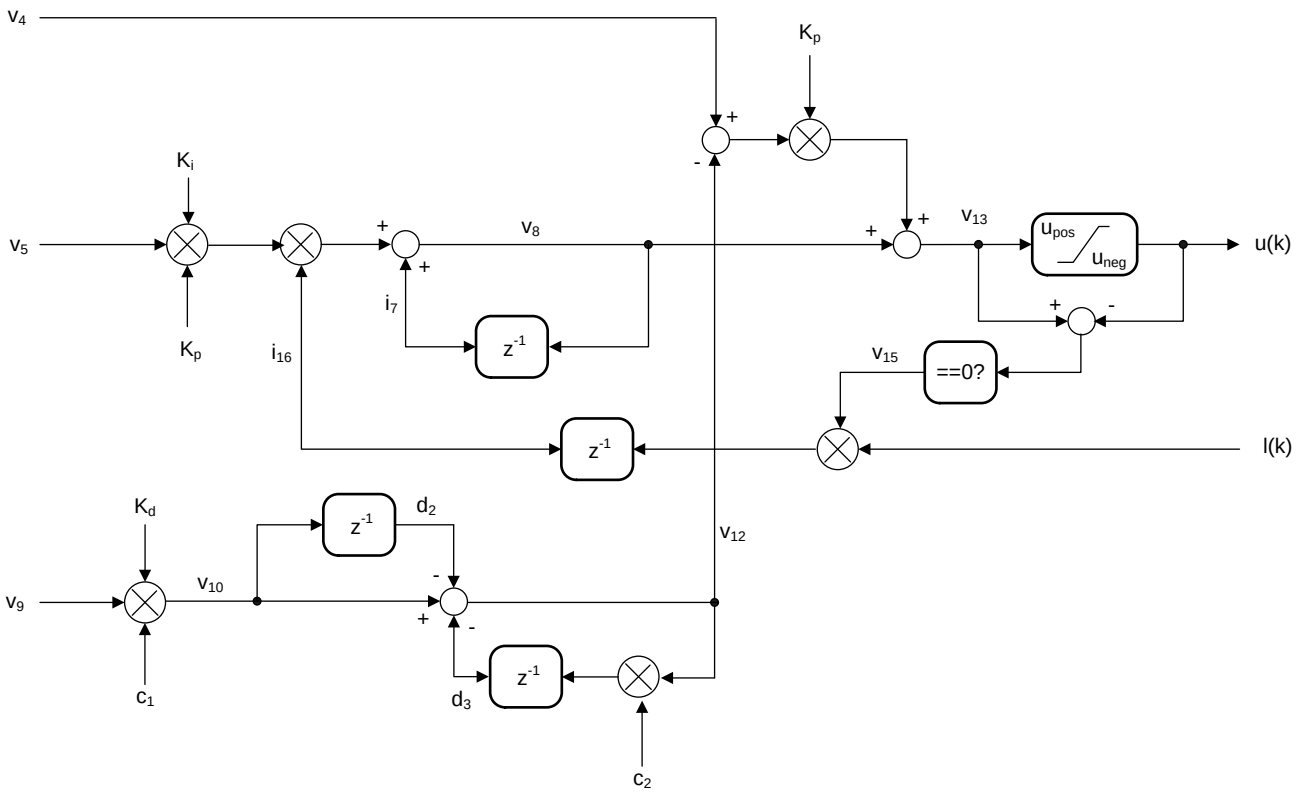

Figure 3-8. Non-Linear PID Output Architecture

The non-linear control law is based on a power function of the modulus of the servo error, with a linearized region about the zero error point. In Equation 8, x represents the input to the control law, y, the output, and α is a user selectable modulus exponent representing the degree of non-linearity.

$$y = |x|^{\alpha} \, sign(x) \tag{8}$$

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Figure 3-9 shows the x-y relationship for values of α between 0.2 and 2. Notice that the curves intersect at x = 0, and x = ±1.

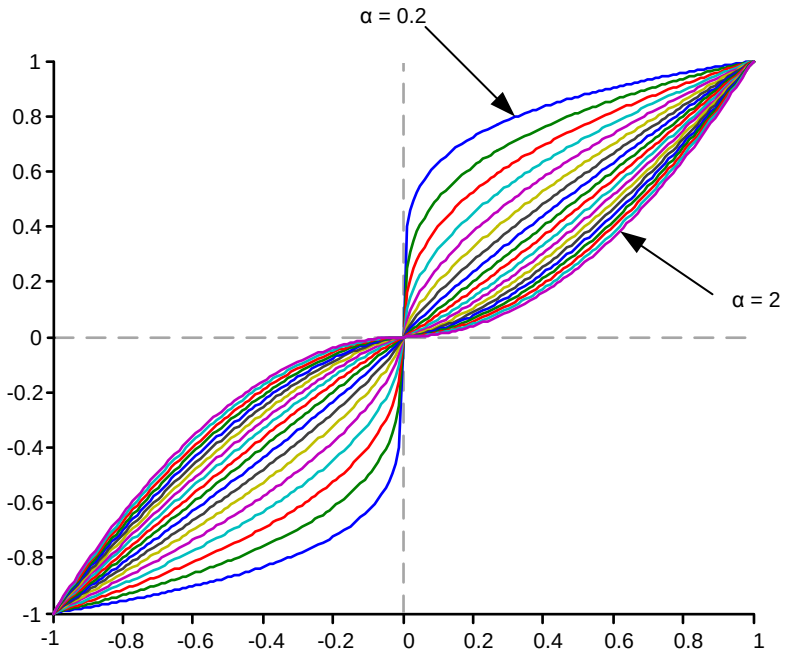

Figure 3-9. Non-Linear Control Law Input-Output Plot

The gain of the control law is the slope of the x-y curve. Observe that with α = 1 the control is linear with unity gain. With α > 1 the gain is zero when x = 0, and increases as x increases. In the controller, this value of α produces controller gain that increases with increasing control error. With α < 1, the gain at x = 0 is infinite, and falls as x increases. This α setting produces controller gain that decreases with increasing control error.

The presence of zero or infinite gain at the zero control error point leads to practical control difficulties. For example, with α < 1, it is common to encounter oscillation or “chattering” near the steady-state. These issues can be overcome by limiting the controller gain close to x = 0. This is done by modifying the control law as follows to introduce a user selectable region about x = 0 with linear gain is applied. The non-linear control law becomes

$$y = \begin{cases} |x|^{\alpha} \, sign(x) & : |x| \geq \delta \\ x \, \delta^{\alpha - 1} & : |x| \leq \delta \end{cases} \tag{9}$$

When the magnitude of servo error falls below δ, the linear gain is applied; otherwise, the gain is determined by the non-linear law. For computational efficiency, define the gain in the linear region as γ.

$$\gamma = \delta^{\alpha - 1} \tag{10}$$

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A typical plot of the linearized control law is shown in Figure 3-10. Observe that when x = δ the linear and non-linear curves intersect, so the controller makes a smooth transition between the linear and non-linear regions as the servo error passes through x = ±δ.

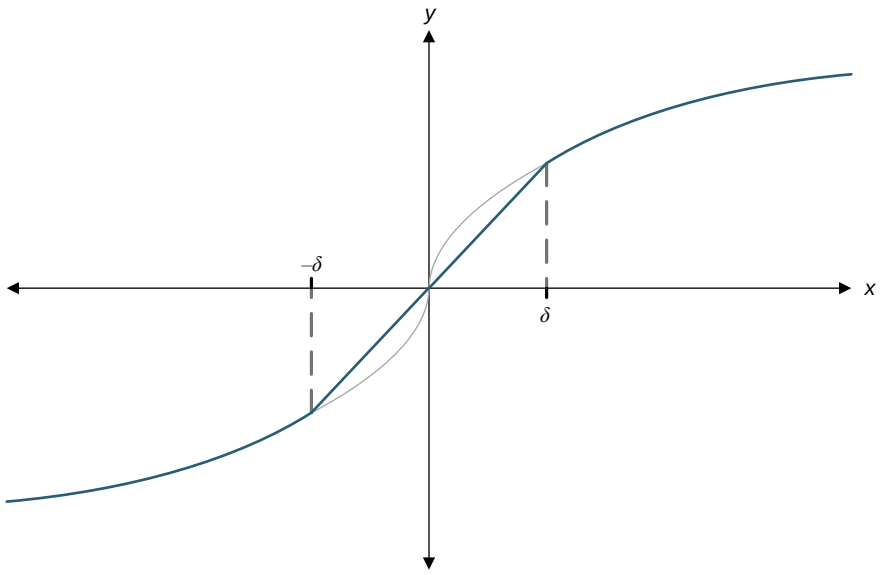

Figure 3-10. NLPID Linearized Region

In addition to the P, I, and D gains, the user must select two additional terms in each control path: α and δ. The library includes a separate function to compute and update γ for each path.

The NLPID controller has been seen to provide significantly improved control in many cases; however, it must be remembered that increased gain, even if only applied to part of the control range, can lead to significantly increased output from the controller. In most cases, this 'control effort' is limited by practical factors such as actuator saturation, PWM modulation range, and so on. The corollary is that not every application benefits equally from the use of non-linear control and some may see no benefit at all. In cases where satisfactory performance cannot be achieved through the use of linear PID control, the user is advised to start with all α = 1, and experiment by introducing non-linear terms gradually while monitoring both control performance and the magnitude of the control effort. In general, P and I paths benefit from increased gain at high servo error (α > 1), while the D path benefits from reduced gain at high servo error (α <1), but this is not universally true.

Further information on this control law can be found in: "From PID to Active Disturbance Rejection Control", Jingqing Han, IEEE Transactions on Industrial Electronics, Vol. 56, NO. 3, March 2009.

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3.3.2 Implementation

The NLPID controller uses a C structure to hold coefficients and data, defined in the header file "DCL_NLPID.h". Note that the NLPID functions make use of the "pow()" function in the standard C library. For this reason, the header file "math.h" must be included, which is not supported by the CLA compiler. To allow different DCL functions to be run on both the CPU and CLA in the same program, the NLPID functions are located in a separate header file. The NLPID structure is shown below.

```
typedef volatile struct {
    float Kp;           //!< Linear proportional gain
    float Ki;           //!< Linear integral gain
    float Kd;           //!< Linear derivative gain
    float alpha_p;      //!< P path non-linear exponent
    float alpha_i;      //!< I path non-linear exponent
    float alpha_d;      //!< D path non-linear exponent
    float delta_p;      //!< P path linearized range
    float delta_i;      //!< I path linearized range
    float delta_d;      //!< D path linearized range
    float gamma_p;      //!< P path gain limit
    float gamma_i;      //!< I path gain limit
    float gamma_d;      //!< D path gain limit
    float c1;           //!< D path filter coefficient 1
    float c2;           //!< D path filter coefficient 2
    float d2;           //!< D path filter intermediate storage 1
    float d3;           //!< D path filter intermediate storage 2
    float i7;           //!< I path intermediate storage
    float i16;          //!< Intermediate saturation storage
    float Umax;         //!< Upper saturation limit
    float Umin;         //!< Lower saturation limit
} NLPID;
```

The memory address offsets of the NLPID structure are shown in Table 3-5.

Table 3-5. List of NLPID Structure Elements and Address Offsets

Element	Offset (Hex)	Offset (Dec)	Description
Kp	0	0	Linear proportional gain
Ki	2	2	Linear integral gain
Kd	4	4	Linear derivative gain
alpha_p	6	6	P path non-linear exponent
alpha_i	8	8	I path non-linear exponent
alpha_d	A	10	D path non-linear exponent
delta_p	C	12	P path linearized range
delta_i	E	14	I path linearized range
delta_d	10	16	D path linearized range
gamma_p	12	18	P path gain limit
gamma_i	14	20	I path gain limit
gamma_d	16	22	D path gain limit
c1	18	24	D path filter coefficient 1
c2	1A	26	D path filter coefficient 2
d2	1C	28	D path filter intermediate storage 1
d3	1E	30	D path filter intermediate storage 2
i7	20	32	I path intermediate storage
i16	22	34	Intermediate saturation storage
Umax	24	36	Upper saturation limit
Umin	26	38	Lower saturation limit

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As with all DCL controllers, it is the responsibility of the user to initialize the NLPID structure before use. A set of default values is defined in the library header file and can be used with the variable declaration. An example of an initialized NLPID structure declaration is shown below.

```
NLPID myCtrl = NLPID_DEFAULTS;
```

3.3.3 NLPID Functions

Table 3-6. Summary of NLPID Functions

Title	Page
DCL_runNLPID_C1 —Run the Non-Linear PID Controller	36
DCL_setGamma —Compute the Non-Linear PID Gain Limits	36

DCL_runNLPID_C1 *Run the Non-Linear PID Controller*

Header File DCL_NLPID.h

Source File N/A

Declaration float DCL_runNLPID_C1(NLPID *p, float rk, float yk, float lk)

Description This function executes a non-linear PID controller on the C28x. The function is coded in inline C.

Parameters

p	The NLPID structure
rk	The controller set-point reference
yk	The measured feedback value
lk	External output clamp flag

Return The control effort

DCL_setGamma *Compute the Non-Linear PID Gain Limits*

Header File DCL_NLPID.h

Source File N/A

Declaration void DCL_setGamma(NLPID *p)

Description This function computes the three gain limits for the non-linear PID controller on the C28x. The function is coded in inline C.

Parameters

p	The NLPID structure

Return The control effort

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3.4 Direct Form 1 (Third Order) Compensators

3.4.1 Description

The Direct Form 1 (DF1) structure is a common type of discrete time control structure used to implement a control law specified either as a pole-zero set, or as a rational polynomial in z (transfer function). The DCL includes one third order DF1 example, denoted “DF13”.

In general, the Direct Form 1 structure is less numerically robust than the Direct Form 2 (see below), and for this reason users are encouraged to choose the latter type whenever possible. The DF13 structure is very common in digital power supplies and for that reason is included in the library. The same function supports a second order control law after the superfluous coefficients (a3 and b3) have been set to zero.

The general form of third order transfer function is shown in Equation 11.

$$F(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}} \tag{11}$$

Notice that the coefficients have been adjusted to normalize the highest power of z in the denominator. There is no notational standard for numbering of the controller coefficients. The notation used here has the advantage that the coefficient suffixes are the same as the delay line elements and this helps with clarity of the assembly code, however, other notation may be found in the literature. The corresponding difference equation is shown in Equation 12.

$$\begin{aligned} u(k) = {} & b_0 e(k) + b_1 e(k-1) + b_2 e(k-2) + b_3 e(k-3) \\ & - a_1 u(k-1) - a_2 u(k-2) - a_3 u(k-3) \end{aligned} \tag{12}$$

The DF13 controller uses two, three-element delay lines to store previous input and output data required to compute u(k). A diagrammatic representation is shown in Figure 3-11.

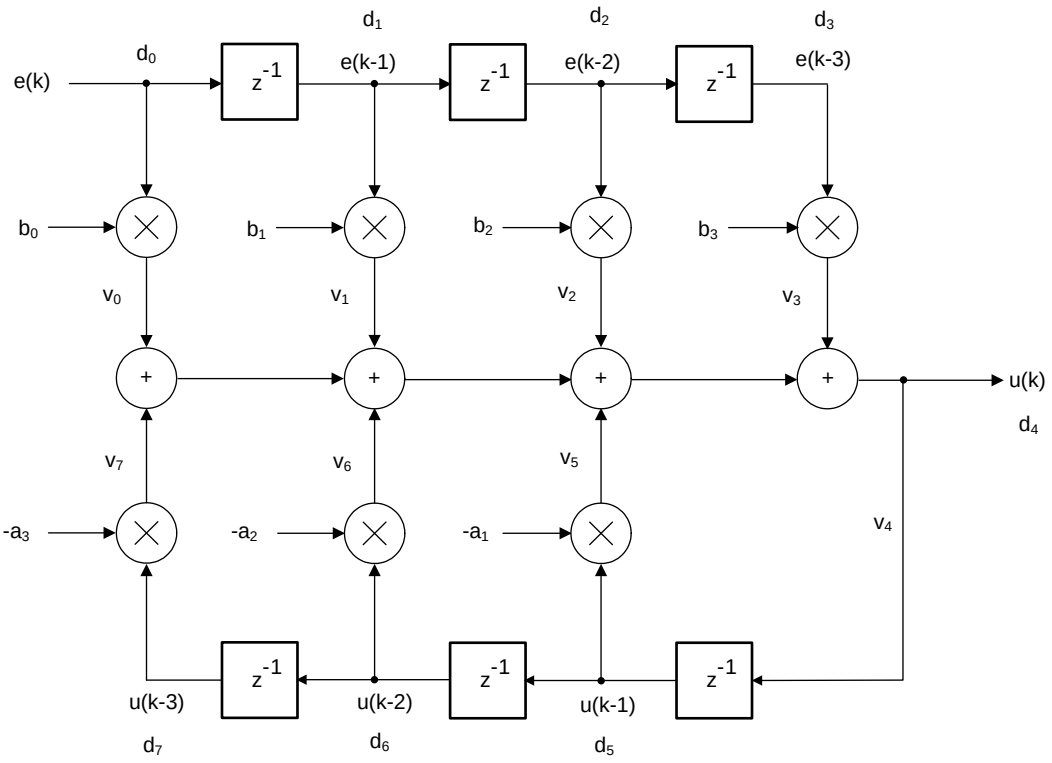

Figure 3-11. DCL_DF13_C1 Architecture

The DF13 control law consists of seven multiplication operations that yield seven partial products, and six addition or subtraction operations that combine the partial products to obtain the compensator output, u(k). When implemented in this way, the control law is referred to as the “full” DF13 form.

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The DF13 control law can be re-structured to reduce control latency by pre-computing six of the seven partial products that are already known in the previous sample interval. The control law is then broken into two parts: the “immediate” part and the “partial” part.

The advantage of doing this is to reduce the “sample-to output” delay, or the time between e(k) being sampled, and a corresponding u(k) becoming available. By partially pre-computing the control law, the computation delay can be reduced to one multiplication and one addition.

In the k^{th} interval, the immediate part is computed.

$$u(k) = b_0 e(k) + v(k-1) \tag{13}$$

Next, the v(k) partial result is pre-computed for use in the $(k+1)^{th}$ interval.

$$v(k) = b_1 e(k) + b_2 e(k-1) + b_3 e(k-2) - a_1 u(k) - a_2 u(k-1) - a_3 u(k-2) \tag{14}$$

Structurally, the pre-computed control law can be drawn as shown in Figure 3-12.

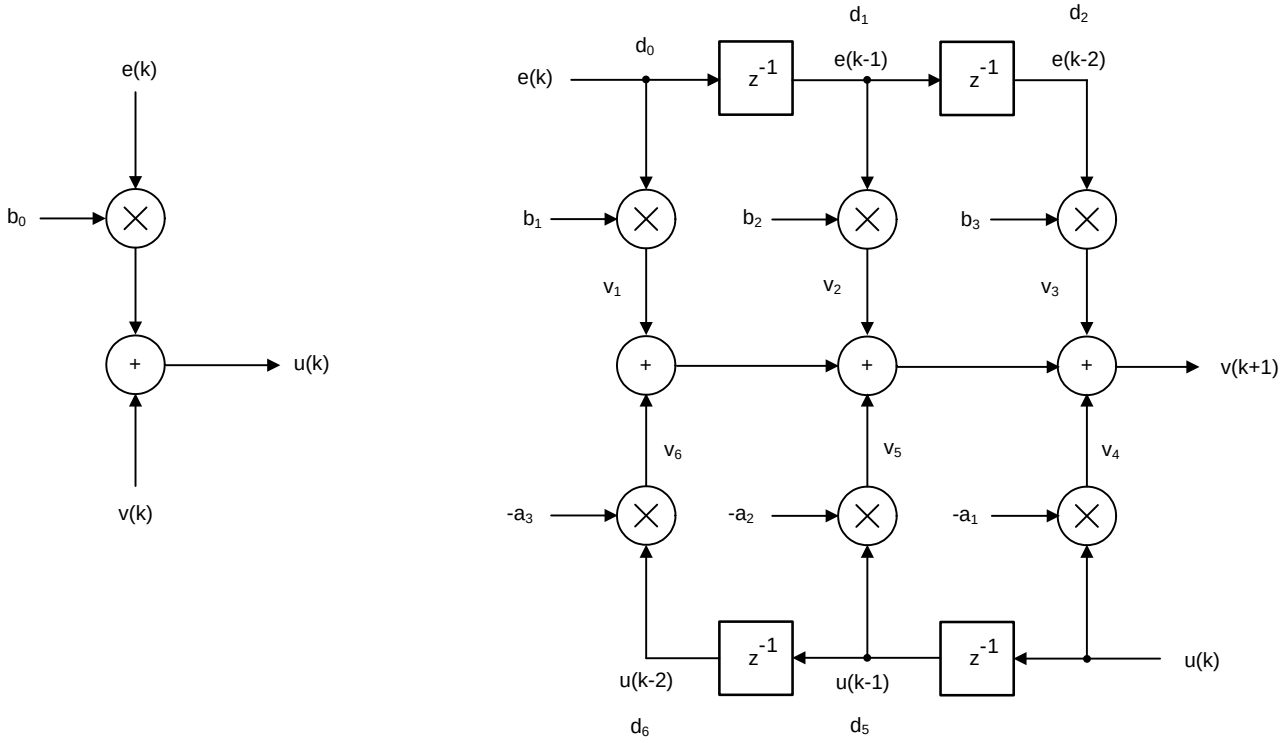

Figure 3-12. DCL_DF13_C2C3 Architecture

The pre-computed structure allows the controller output (u(k)) to be used as soon as it is computed. The remaining terms in the third order control law do not involve the newest input e(k) and, therefore, do not affect u(k). These terms can be computed after u(k) has been applied to the control loop and the input-output latency of the controller is therefore reduced.

A further benefit of the pre-computed structure is that it allows the control effort to be clamped after the immediate part. Computation of the pre-computed part can be made dependent on the outcome of the clamp such that if u(k) matches or exceeds the clamp limits there is no point in pre-computing the next partial control variable and the computation can be avoided. The DCL includes three clamp functions intended for this purpose (see Chapter 4).

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3.4.2 Implementation

All DF13 functions use a common C structure to hold coefficients and data, defined in the header file "DCL.h".

```
typedef volatile struct {
    float c[8];   // coefficients
    float d[8];   // data
    } DF13;
```

The memory address offsets of the structure elements are shown in Table 3-7.

Table 3-7. List of DF13 Structure Elements and Address Offsets

Element	Offset (Hex)	Offset (Dec)	Description
b0	0	0	Coefficient b0
b1	2	2	Coefficient b1
b2	4	4	Coefficient b2
b3	6	6	Coefficient b3
a0	8	8	Coefficient a0
a1	A	10	Coefficient a1
a2	C	12	Coefficient a2
a3	E	14	Coefficient a3
d0	10	16	Data e(k)
d1	12	18	Data e(k-1)
d2	14	20	Data e(k-2)
d3	16	22	Data e(k-3)
d4	18	24	Data u(k)
d5	1A	26	Data u(k-1)
d6	1C	28	Data u(k-2)
d7	1E	30	Data u(k-3)

The assignment of coefficients and data in the DF13 structure to those in the diagram is shown in Figure 3-13.

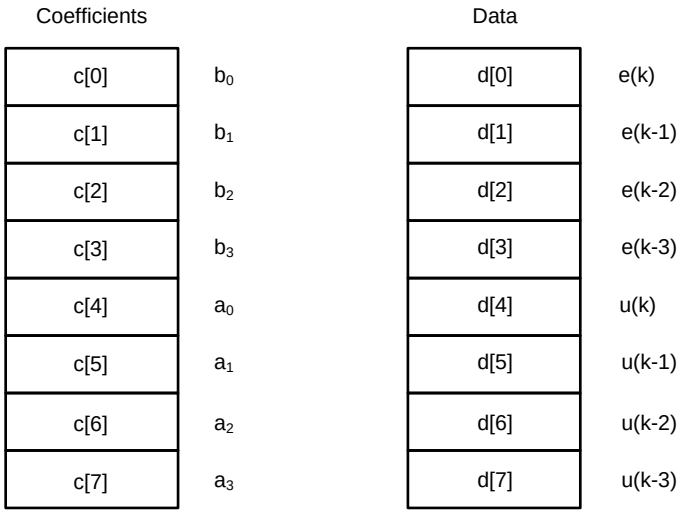

Figure 3-13. DF13 Data and Coefficient Layout

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It is the responsibility of the user to initialize both arrays prior to use. A set of default values is defined in the library header file and can be used with the variable declaration. An example of an initialized DF13 structure declaration is shown below:

```
DF13 myCtrl = DF13_DEFAULTS;
```

3.4.3 DF13 Functions

Table 3-8. Summary of DF13 Functions

Title	Page
DCL_runDF13_C1 —Run the DF13 Full Compensator	40
DCL_runDF13_C2 —Run the Immediate DF13 Compensator	41
DCL_runDF13_C3 —Run the Partial DF13 Compensator	41
DCL_runDF13_C4 —Run the DF13 Full Compensator	42
DCL_runDF13_C5 —Run the Immediate DF13 Compensator	42
DCL_runDF13_C6 —Run the Partial DF13 Compensator	43
DCL_runDF13_L1 —Run the DF13 Full Compensator on the CLA	43
DCL_runDF13_L2 —Run the Immediate DF13 Compensator on the CLA	44
DCL_runDF13_L3 —Run the Partial DF13 Compensator on the CLA	44

DCL_runDF13_C1 *Run the DF13 Full Compensator*

Header File DCL.h

Source File DCL_DF13_C1

Declaration float DCL_runDF13_C1(DF13 *p, float ek)

Description This function computes a full third order control law using the Direct Form 1 structure. The function is coded in C28x assembly.

Parameters

p	The DF13 structure
ek	The servo error

Return The control effort

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DCL_runDF13_C2 *Run the Immediate DF13 Compensator*

Header File DCL.h

Source File DCL_DF13_C2C3.asm

Declaration float DCL_runDF13_C2(DF13 *p, float ek, float vk)

Description This function computes the immediate part of the pre-computed DF13 controller. The function is coded in C28x assembly.

Parameters

p	The DF13 structure
ek	The servo error
vk	The pre-computed partial control effort

Return The control effort

DCL_runDF13_C3 *Run the Partial DF13 Compensator*

Header File DCL.h

Source File DCL_DF13_C2C3.asm

Declaration float DCL_runDF13_C3(DF13 *p, float ek, float uk)

Description This function computes the partial result of the pre-computed DF13 controller. The function is coded in C28x assembly.

Parameters

p	The DF13 structure
ek	The servo error
vk	The pre-computed partial control effort

Return The control effort

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DCL_runDF13_C4 *Run the DF13 Full Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF13_C4(DF13 *p, float ek, float uk)

Description This function computes a full third order control law using the Direct Form 1 structure, and is identical in structure and operation to the C1 form. The function is coded in inline C.

Parameters

p	The DF13 structure
ek	The servo error

Return The control effort

DCL_runDF13_C5 *Run the Immediate DF13 Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF13_54(DF13 *p, float ek, float uk)

Description This function computes the immediate part of the pre-computed DF13 controller. The function is identical in structure and operation to the C2 form. The function is coded in inline C.

Parameters

p	The DF13 structure
ek	The servo error
vk	The pre-computed partial control effort

Return The control effort

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DCL_runDF13_C6 *Run the Partial DF13 Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF13_C6(DF13 *p, float ek, float uk)

Description This function computes the partial result of the pre-computed DF13 controller. The function is identical in structure and operation to the C3 form. The function is coded in inline C.

Parameters

p	The DF13 structure
ek	The servo error
vk	The control effort in the previous sample interval

Return The control effort

DCL_runDF13_L1 *Run the DF13 Full Compensator on the CLA*

Header File DCL.h

Source File DCL_DF13_L1.asm

Declaration float DCL_runDF13_L1(DF13 *p, float ek)

Description This function computes a full third order control law using the Direct Form 1 structure, and is identical in structure and operation to the C1 form. The function is coded in CLA assembly language.

Parameters

p	The DF13 structure
ek	The servo error

Return The control effort

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DCL_runDF13_L2 *Run the Immediate DF13 Compensator on the CLA*

Header File DCL.h

Source File DCL_DF13_L2L3.asm

Declaration float DCL_runDF13_L2(DF13 *p, float ek, float vk)

Description This function computes the immediate part of the pre-computed DF13 controller. The function is identical in structure and operation to the C2 form. The function is coded in CLA assembly language.

Parameters

p	The DF13 structure
ek	The servo error
vk	The pre-computed partial control effort

Return The control effort

DCL_runDF13_L3 *Run the Partial DF13 Compensator on the CLA*

Header File DCL.h

Source File DCL_DF13_L2L3.asm

Declaration float DCL_runDF13_L3(DF13 *p, float ek, float vk)

Description This function computes the partial result of the pre-computed DF13 controller. The function is identical in structure and operation to the C3 form. The function is coded in CLA assembly language.

Parameters

p	The DF13 structure
ek	The servo error
vk	The control effort in the previous sample interval

Return The control effort

3.5 Direct Form 2 (Second Order) Compensators

3.5.1 Description

The C2000 Digital Controller Library contains a second order implementation of the Direct Form 2 controller structure, denoted “DF22”. This structure is sometimes referred to as a “bi-quad” filter and is commonly used in a cascaded chain to build up digital filters of high order.

The transfer function of a second order discrete time compensator is shown in Equation 15.

$$F(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \tag{15}$$

The corresponding difference equation is shown in Equation 16.

$$u(k) = b_0 e(k) + b_1 e(k-1) + b_2 e(k-2) - a_1 u(k-1) - a_2 u(k-2) \tag{16}$$

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Figure 3-14 shows a diagrammatic representation of the full Direct Form 2 realization.

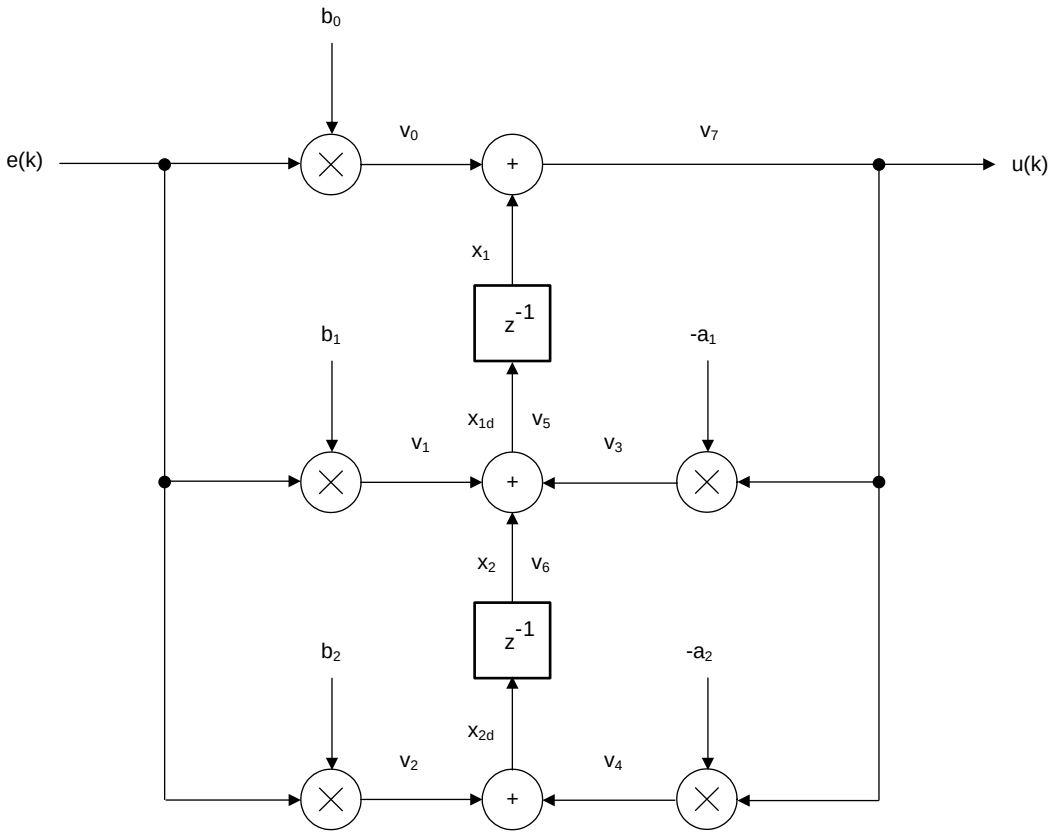

Figure 3-14. DCL_DF22_C1 Architecture

As with the DF13 compensator, sample-to-output delay can be reduced through the use of pre-computation. The immediate and pre-computed control laws are as follows. In the k^{th} interval, the immediate part is computed.

$$u(k) = b_0 e(k) + v(k) \quad (17)$$

Next, the v(k) partial result is pre-computed for use in the $(k+1)^{th}$ interval.

$$v(k+1) = b_1 e(k) + b_2 e(k-1) - a_1 u(k) - a_2 u(k-1) \quad (18)$$

The pre-computed form of DF22 is shown in Figure 3-15 and Figure 3-16.

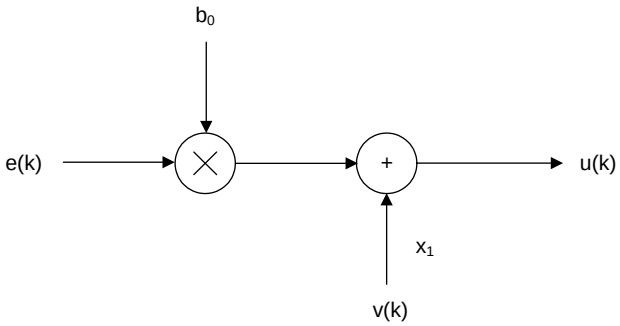

Figure 3-15. DCL_DF22_C2 Architecture

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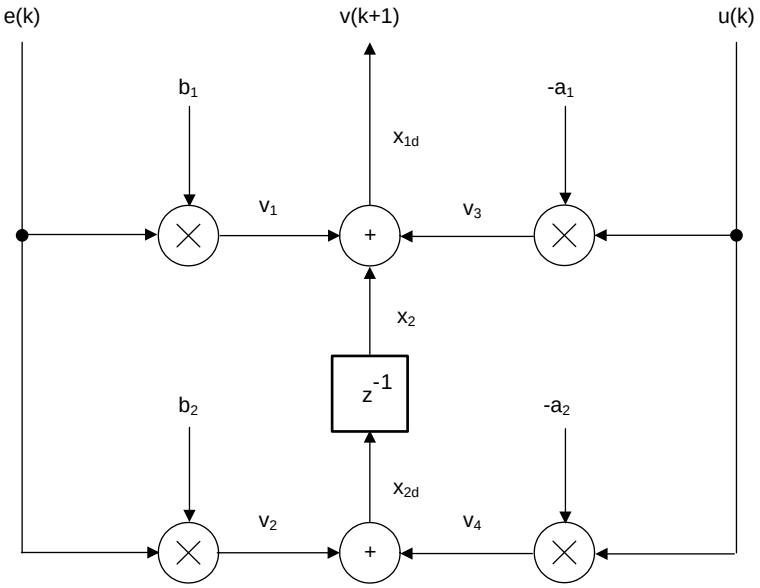

Figure 3-16. DCL_DF22_C3 Architecture

3.5.2 Implementation

All DF22 functions use a common C structure to hold coefficients and data, defined in the header file "DCL.h".

```
typedef volatile struct {
    float b0;       //!< b0
    float b1;       //!< b1
    float b2;       //!< b2
    float a1;       //!< a1
    float a2;       //!< a2
    float x1;       //!< x1
    float x2;       //!< x2
} DF22;
```

The memory address offsets of the structure elements are shown in Table 3-9.

Table 3-9. List of DF22 Structure Elements and Address Offsets

Element	Offset (Hex)	Offset (Dec)	Description
b0	0	0	Coefficient b0
b1	2	2	Coefficient b1
b2	4	4	Coefficient b2
a1	6	6	Coefficient a1
a2	8	8	Coefficient a2
x1	A	10	State x1
x2	C	12	State x2

It is the responsibility of the user to initialize both arrays prior to use. A set of default values is defined in the library header file and can be used with the variable declaration. An example of an initialized DF22 structure declaration is shown below:

```
DF22 myCtrl = DF22_DEFAULTS;
```


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3.5.3 DF22 Functions

Table 3-10. Summary of DF22 Functions

Title	Page
DCL_runDF22_C1 —Run the DF22 Full Compensator	47
DCL_runDF22_C2 —Run the Immediate DF22 Compensator	47
DCL_runDF22_C3 —Run the Partial DF22 Compensator	48
DCL_runDF22_C4 —Run the DF22 Full Compensator	48
DCL_runDF22_C5 —Run the Immediate DF22 Compensator	48
DCL_runDF22_C6 —Run the Partial DF22 Compensator	49
DCL_runDF22_L1 —Run the DF22 Full Compensator on the CLA	49
DCL_runDF22_L2 —Run the Immediate DF22 Compensator on the CLA	49
DCL_runDF22_L3 —Run the Partial DF22 Compensator on the CLA	50

DCL_runDF22_C1 *Run the DF22 Full Compensator*

Header File DCL.h

Source File DCL_DF22_C1

Declaration float DCL_runDF22_C1(DF22 *p, float ek)

Description This function computes a full second order control law using the Direct Form 2 structure. The function is coded in C28x assembly.

Parameters

p	The DF22 structure
ek	The servo error

Return The control effort

DCL_runDF22_C2 *Run the Immediate DF22 Compensator*

Header File DCL.h

Source File DCL_DF22_C2C3.asm

Declaration float DCL_runDF22_C2(DF22 *p, float ek)

Description This function computes the immediate part of the pre-computed DF22 controller. The function is coded in C28x assembly.

Parameters

p	The DF22 structure
ek	The servo error

Return The control effort

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DCL_runDF22_C3 *Run the Partial DF22 Compensator*

Header File DCL.h

Source File DCL_DF22_C2C3.asm

Declaration void DCL_runDF22_C3(DF22 *p, float ek, float uk)

Description This function computes the partial result of the pre-computed DF22 controller. The function is coded in C28x assembly.

Parameters

p	The DF22 structure
ek	The servo error
uk	The control effort in the previous sample interval

Return The control effort

DCL_runDF22_C4 *Run the DF22 Full Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF22_C4(DF22 *p, float ek)

Description This function computes a full second order control law using the Direct Form 2 structure, and is identical in structure and operation to the C1 form. The function is coded in inline C.

Parameters

p	The DF22 structure
ek	The servo error

Return The control effort

DCL_runDF22_C5 *Run the Immediate DF22 Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF22_C5(DF22 *p, float ek)

Description This function computes the immediate part of the pre-computed DF22 controller. The function is identical in structure and operation to the C2 form. The function is coded in inline C.

Parameters

p	The DF22 structure
ek	The servo error

Return The control effort

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DCL_runDF22_C6 *Run the Partial DF22 Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF22_C6(DF22 *p, float ek)

Description This function computes the partial result of the pre-computed DF22 controller. The function is identical in structure and operation to the C3 form. The function is coded in inline C.

Parameters

p	The DF22 structure
ek	The servo error
uk	The control effort in the previous sample interval

Return The control effort

DCL_runDF22_L1 *Run the DF22 Full Compensator on the CLA*

Header File DCL.h

Source File DCL_DF22_L1.asm

Declaration float DCL_runDF22_L1(DF22 *p, float ek)

Description This function computes a full third order control law using the Direct Form 2 structure, and is identical in structure and operation to the C1 form. The function is coded in CLA assembly language.

Parameters

p	The DF22 structure
ek	The servo error

Return The control effort

DCL_runDF22_L2 *Run the Immediate DF22 Compensator on the CLA*

Header File DCL.h

Source File DCL_DF22_L2L3.asm

Declaration float DCL_runDF22_L2(DF22 *p, float ek)

Description This function computes the immediate part of the pre-computed DF22 controller. The function is identical in structure and operation to the C2 form. The function is coded in CLA assembly language.

Parameters

p	The DF22 structure
ek	The servo error

Return The control effort

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DCL_runDF22_L3 *Run the Partial DF22 Compensator on the CLA*

Header File DCL.h

Source File DCL_DF22_L2L3.asm

Declaration float DCL_runDF22_L3(DF22 *p, float ek)

Description This function computes the partial result of the pre-computed DF22 controller. The function is identical in structure and operation to the C3 form. The function is coded in CLA assembly language.

Parameters

p	The DF22 structure
ek	The servo error
uk	The control effort in the previous sample interval

Return The control effort

3.6 Direct Form 2 (Third Order) Compensators

3.6.1 Description

The third order Direct Form 2 compensator (DF23) is similar in all respects to the DF22 compensator. Separate full and pre-computed forms are supplied in C and assembly for computation on the C28x, and in assembly for computation on the CLA.

The control law is the same as the DF13 compensator.

$$u(k) = b_0e(k) + b_1e(k-1) + b_2e(k-2) + b_3e(k-3) - a_1u(k-1) - a_2u(k-2) - a_3u(k-3) \quad (19)$$

Figure 3-17 shows a diagrammatic representation of the full third order Direct Form 2 compensator.

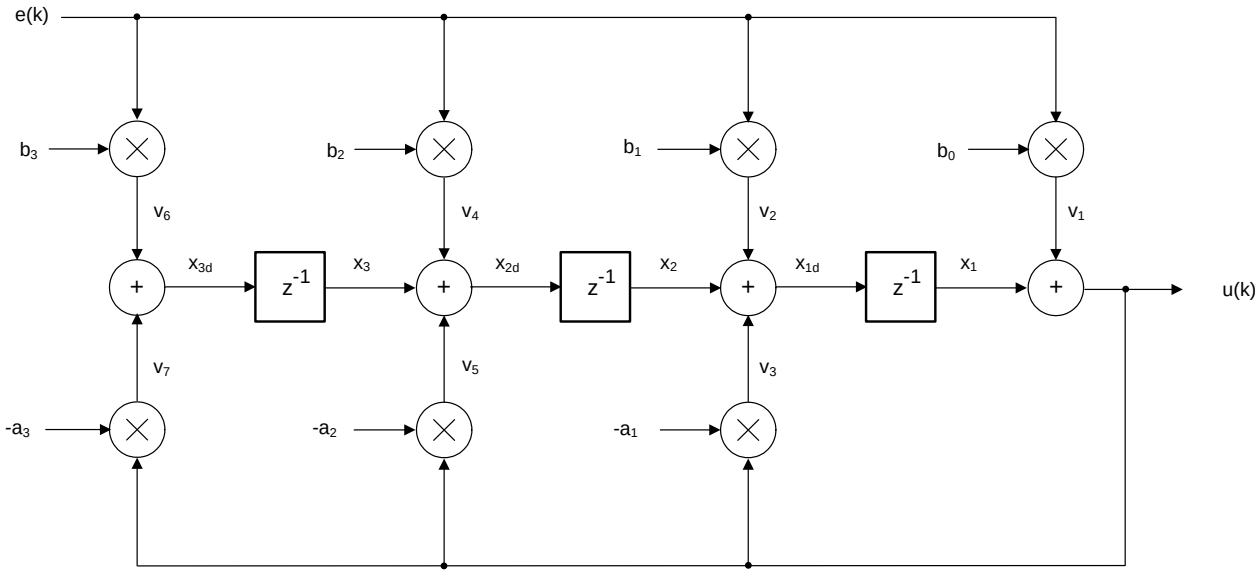

Figure 3-17. DCL_DF23_C1 Architecture

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Sample-to-output delay can be reduced through the use of pre-computation, in a similar way to the DF22 compensator. In the k^{th} interval, the immediate part is computed.

$$u(k) = b_0 e(k) + v(k) \tag{20}$$

Next, the v(k) partial result is pre-computed for use in the $(k+1)^{th}$ interval.

$$v(k+1) = b_1 e(k) + b_2 e(k-1) + b_3 e(k-2) - a_1 u(k) - a_2 u(k-1) - a_3 u(k-2) \tag{21}$$

Figure 3-18 and Figure 3-19 show the pre-computed form of DF23.

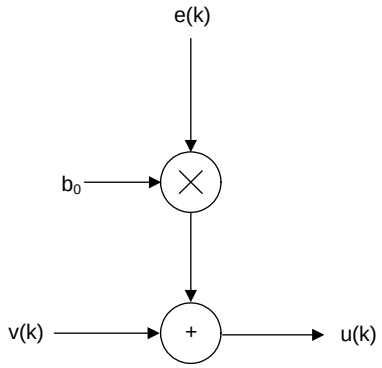

Figure 3-18. DCL_DF23_C2 Architecture

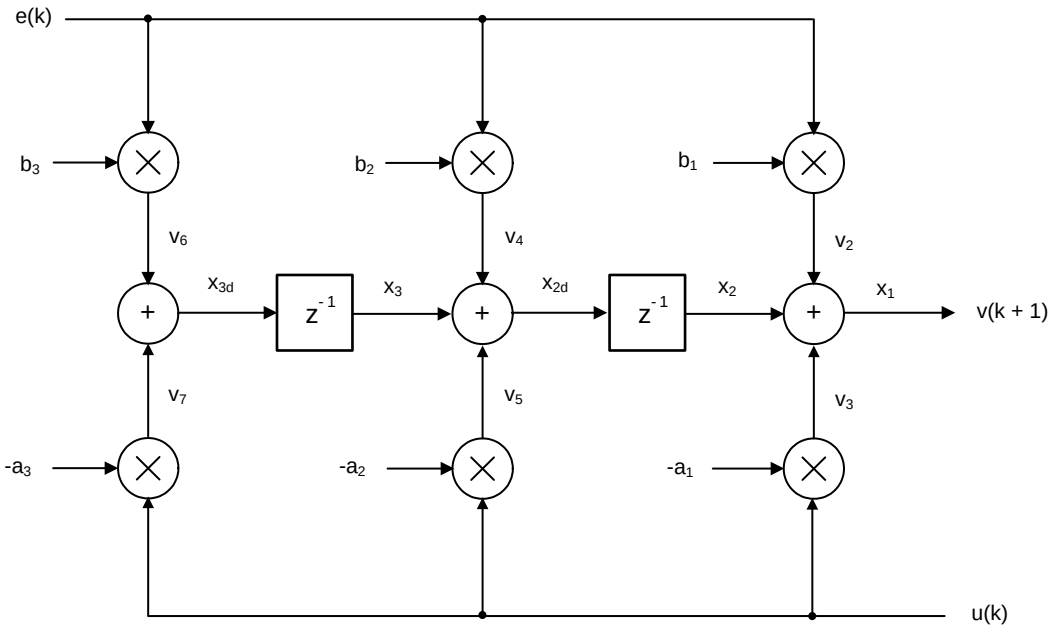

Figure 3-19. DCL_DF23_C3 Architecture

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3.6.2 Implementation

All DF23 functions use a common C structure to hold coefficients and data, defined in the header file "DCL.h".

```
typedef volatile struct {
    float b0;       //!< b0
    float b1;       //!< b1
    float b2;       //!< b2
    float b3;       //!< b3
    float a1;       //!< a1
    float a2;       //!< a2
    float a3;       //!< a3
    float x1;       //!< x1
    float x2;       //!< x2
    float x3;       //!< x3
} DF23
```

The memory address offsets of the structure elements are shown in Table 3-11.

Table 3-11. List of DF23 Structure Elements and Address Offsets

Element	Offset (Hex)	Offset (Dec)	Description
b0	0	0	Coefficient b0
b1	2	2	Coefficient b1
b2	4	4	Coefficient b2
b3	6	6	Coefficient b3
a1	8	8	Coefficient a1
a2	A	10	Coefficient a2
a3	C	12	Coefficient a3
x1	E	14	State x1
x2	10	16	State x2
x3	12	18	State x3

The assignment of coefficients and data in the DF23 structure to those in the diagram shown in Figure 3-20.

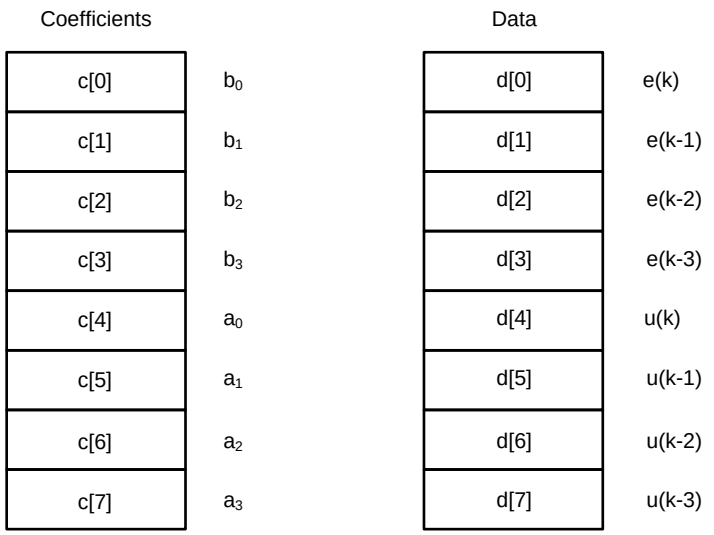

Figure 3-20. DF23 Data and Coefficient Layout

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It is the responsibility of the user to initialize both arrays prior to use. A set of default values is defined in the library header file and can be used with the variable declaration. An example of an initialized DF23 structure declaration is shown below:

```
DF23 myCtrl = DF23_DEFAULTS;
```

3.6.3 DF23 Functions

Table 3-12. Summary of DF23 Functions

Title	Page
DCL_runDF23_C1 —Run the DF23 Full Compensator	53
DCL_runDF23_C2 —Run the Immediate DF23 Compensator	53
DCL_runDF23_C3 —Run the Partial DF23 Compensator	54
DCL_runDF23_C4 —Run the DF23 Full Compensator	54
DCL_runDF23_C5 —Run the Immediate DF23 Compensator	54
DCL_runDF23_C6 —Run the Partial DF23 Compensator	55
DCL_runDF23_L1 —Run the DF23 Full Compensator on the CLA	55
DCL_runDF23_L2 —Run the Immediate DF23 Compensator on the CLA	55
DCL_runDF23_L3 —Run the Partial DF23 Compensator on the CLA	56

DCL_runDF23_C1 *Run the DF23 Full Compensator*

Header File DCL.h

Source File DCL_DF23_C1

Declaration float DCL_runDF23_C1(DF23 *p, float ek)

Description This function computes a full third order control law using the Direct Form 2 structure. The function is coded in C28x assembly.

Parameters

p	The DF23 structure
ek	The servo error

Return The control effort

DCL_runDF23_C2 *Run the Immediate DF23 Compensator*

Header File DCL.h

Source File DCL_DF23_C2C3.asm

Declaration float DCL_runDF23_C2(DF23 *p, float ek)

Description This function computes the immediate part of the pre-computed DF23 controller. The function is coded in C28x assembly.

Parameters

p	The DF23 structure
ek	The servo error

Return The control effort

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DCL_runDF23_C3 *Run the Partial DF23 Compensator*

Header File DCL.h

Source File DCL_DF23_C2C3.asm

Declaration void DCL_runDF23_C3(DF23 *p, float ek, float uk)

Description This function computes the partial result of the pre-computed DF23 controller. The function is coded in C28x assembly.

Parameters

p	The DF23 structure
ek	The servo error
uk	The control effort in the previous sample interval

Return The control effort

DCL_runDF23_C4 *Run the DF23 Full Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF23_C4(DF23 *p, float ek)

Description This function computes a full third order control law using the Direct Form 1 structure, and is identical in structure and operation to the C1 form. The function is coded in inline C.

Parameters

p	The DF23 structure
ek	The servo error

Return The control effort

DCL_runDF23_C5 *Run the Immediate DF23 Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF23_C5(DF23 *p, float ek)

Description This function computes the immediate part of the pre-computed DF23 controller. The function is identical in structure and operation to the C2 form. The function is coded in inline C.

Parameters

p	The DF23 structure
ek	The servo error

Return The control effort

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DCL_runDF23_C6 *Run the Partial DF23 Compensator*

Header File DCL.h

Source File N/A

Declaration float DCL_runDF23_C6(DF23 *p, float ek, float uk)

Description This function computes the partial result of the pre-computed DF23 controller. The function is identical in structure and operation to the C3 form. The function is coded in inline C.

Parameters

p	The DF23 structure
ek	The servo error
uk	The control effort in the previous sample interval

Return The control effort

DCL_runDF23_L1 *Run the DF23 Full Compensator on the CLA*

Header File DCL.h

Source File DCL_DF23_L1.asm

Declaration float DCL_runDF23_L1(DF22 *p, float ek)

Description This function computes a full third order control law using the Direct Form 2 structure, and is identical in structure and operation to the C1 form. The function is coded in CLA assembly language.

Parameters

p	The DF23 structure
ek	The servo error

Return The control effort

DCL_runDF23_L2 *Run the Immediate DF23 Compensator on the CLA*

Header File DCL.h

Source File DCL_DF23_L2L3.asm

Declaration float DCL_runDF23_L2(DF23 *p, float ek)

Description This function computes the immediate part of the pre-computed DF23 controller. The function is identical in structure and operation to the C2 form. The function is coded in CLA assembly language.

Parameters

p	The DF23 structure
ek	The servo error

Return The control effort

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DCL_runDF23_L3 *Run the Partial DF23 Compensator on the CLA*

Header File DCL.h

Source File DCL_DF23_L2L3.asm

Declaration float DCL_runDF23_L3(DF23 *p, float ek, float uk)

Description This function computes the partial result of the pre-computed DF23 controller. The function is identical in structure and operation to the C3 form. The function is coded in CLA assembly language.

Parameters

p	The DF23 structure
ek	The servo error
uk	The control effort in the previous sample interval

Return The control effort

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Utilities

This chapter describes the supporting functions included in the Digital Control Library.

The Digital Controller Library includes a small number of utilities intended to support use of the library. These include:

- Clamp functions for the CPU and CLA
- A floating-point data-logger
- A Transient Capture Module
- Functions for measurement of control performance

Topic **Page**

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4.2 Data Logger **59**
4.3 Transient Capture Module **65**
4.4 Performance Measurement **73**

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4.1 Control Clamps

4.1.1 Description

The library contains three functions for clamping a control variable to specified upper and lower limits. These would typically be used to bound the output of a controller function to pre-defined limits to avoid actuator saturation or overload. Saturation in a control loop must be handled with care since control of the system is effectively lost. Furthermore, controllers that implement integration of historical servo data can exhibit a phenomenon known as “wind-up”, in which the controller output increases in magnitude while the loop is saturated. This condition leads to delay in recovering from the saturation because the accumulated controller output must be “wound down” before it comes within range of the actuator and the controller resumes proper operation. For more information on wind-up, refer to the linear PID controller description in Section 3.1.

The clamp functions bound the input data variable to pre-determined limits and return a logical value 1 if either bound is matched or exceeded. If the input data lies definitely within limits (for example, neither bound is matched or exceeded) the functions return logical 0. The return value can be used by the PID regulators in the library to implement anti-windup reset, and may be used to clamp the output of the pre-computed forms of DF1 and DF2 compensators. An example of the latter can be found in the DF22 example project supplied with the library (see Chapter 5).

A difference exists between the C28x clamp function and that of the CLA. On the CPU the returned value is an unsigned integer of either 0 or 1, while the corresponding CLA function returns a floating point value of 0.0f or 1.0f. This is because the handling of fixed-point data on the CLA is less efficiently supported than on the main CPU.

4.1.2 Clamp Functions

Table 4-1. Summary of Clamp Functions

Title	Page
DCL_runClamp_C1 —Floating-Point Data Clamp	58
DCL_runClamp_C2 —Floating-Point Data Clamp	59
DCL_runClamp_L1 —Floating-Point Data Clamp	59

DCL_runClamp_C1 *Floating-Point Data Clamp*

Header File DCL.h

Source File DCL_clamp_C1.asm

Declaration uint16_t DCL_runClamp_C1(float *data, float Umax, float Umin)

Description This function clamps a floating-point data value to defined limits and returns a non-zero integer if either limit is matched or exceeded. The function is coded in assembly.

Parameters

data	The TCM structure
Umin	The upper data limit
Umax	The lower data limit

Return 0 if the data lies definitely within limits, 1 if the data matches or exceeds the limits.

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DCL_runClamp_C2 *Floating-Point Data Clamp*

Header File DCL.h

Source File N/A

Declaration uint16_t DCL_runClamp_C2(float *data, float Umax, float Umin)

Description This function clamps a floating-point data value to defined limits and returns a non-zero integer if either limit is matched or exceeded. The function is coded in inline C.

Parameters

data	The TCM structure
Umin	The upper data limit
Umax	The lower data limit

Return 0 if the data lies definitely within limits, 1 if the data matches or exceeds the limits.

DCL_runClamp_L1 *Floating-Point Data Clamp*

Header File DCL.h

Source File DCL_clamp_L1.asm

Declaration float DCL_runClamp_L1(float *data, float Umax, float Umin)

Description This function clamps a floating-point data value to defined limits and returns a non-zero floating-point result if either limit is matched or exceeded. The function is coded in CLA assembly.

Parameters

data	The TCM structure
Umin	The upper data limit
Umax	The lower data limit

Return 0 if the data lies definitely within limits, 1 if the data matches or exceeds the limits.

4.2 Data Logger

4.2.1 Description

The Digital Control Library includes a general-purpose floating-point data logger utility, which is useful when testing and debugging control applications. The intended use of the data logger utility is to capture a stream of data values in a block of memory for subsequent analysis. The data logger is supplied in the form of a C header file and one assembly file, and it may be used on any C2000 device irrespective of whether the DCL is used. The utility may not be used on the CLA.

The data logger operates with arrays of 32-bit floating-point data. The location, size and indexing of each array are defined by three pointers capturing the start address, end address, and data index address. All three pointers are held in a common C structure with the data type “FDLOG”, defined as follows.

```
typedef volatile struct {
    float *fptr;
    float *lptr;
    float *dptr;
} FDLOG;
```


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Conceptually, the relationship between the array pointers and the elements of a data array of length “N” is shown in Figure 4-1.

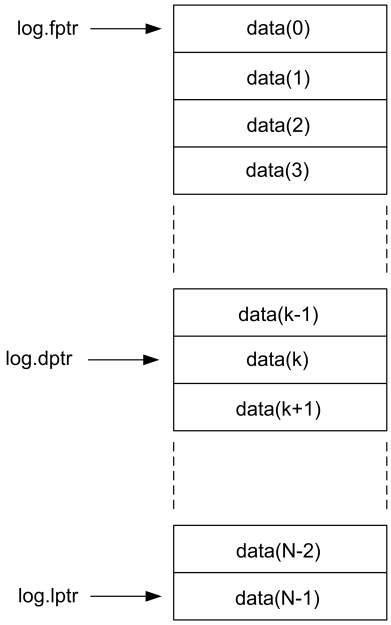

Figure 4-1. Data Log Pointer Allocation

The data index pointer (dptr) always points to the next address to be written or read, and advances through the memory block as each new data value is written into the log. On reaching the end of the log, the pointer is reset to the first address in the log. The data logger header file contains a set of in-line C functions to access and manipulate data logs.

To use the data logger, you must include the header file “DCL_fdlog.h” in your project. Typically, a user would create an instance of an FDLOG structure as follows:

```
FDLOG myBuf = FDLOG_DEFAULTS;
```

The log pointers can then be initialized in the user’s code such that they reference a memory block in a specific address range. Thereafter, the code can clear or load the buffer a specific data value, and then begin writing data into it using the DCL_writeLog() function. The DF22 code example project shows how this is done.

Version 2.0 of the DCL adds two functions that perform fast read and write to a data log. These are assembly coded functions in the source file “DCL_frwlog.asm”. The execution cycles for these and the corresponding C coded DCL functions are shown in Table 4-2.

Table 4-2. Data Log Read/Write Benchmarks

DCL_writeLog	48
DCL_readLog	39
DCL_fwriteLog	22
DCL_freadLog	22

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4.2.2 DCL Functions

Table 4-3. Summary of DCL Functions

Title	Page
DCL_deleteLog —Delete a Data Log	61
DCL_resetLog —Reset a Data Log	61
DCL_initLog —Initialize a Data Log Structure	62
DCL_writeLog —Write Data into a Log	62
DCL_fillLog —Fill a Data Log with Specified Data	62
DCL_clearLog —Fill a Data Log Contents with Zero	63
DCL_readLog —Fill a Data Log Contents with Zero	63
DCL_freadLog —Performs Fast Read from a Data Log	64
DCL_writeLog —Performs Fast Write into a Data Log	64

DCL_deleteLog *Delete a Data Log*

Header File DCL_fdlog.h

Source File N/A

Declaration void DCL_deleteLog(FDLOG *p)

Description This function resets all structure pointers to null value.

Parameters

p	The FDLOG structure

Return None

DCL_resetLog *Reset a Data Log*

Header File DCL_fdlog.h

Source File N/A

Declaration void DCL_resetLog(FDLOG *p)

Description This function resets the data index pointer to start of the data log.

Parameters

p	The FDLOG structure

Return None

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DCL_initLog *Initialize a Data Log Structure*

Header File DCL_fdlog.h

Source File N/A

Declaration void DCL_initLog(FDLOG *p, float *addr, uint16_t size)

Description This function assigns the buffer pointers to a memory block or array and sets the data index pointer to the first address.

Parameters

p	The FDLOG structure
addr	The start address of the memory block
size	The length of the memory block in 32-bit words

Return None

DCL_writeLog *Write Data into a Log*

Header File DCL_fdlog.h

Source File N/A

Declaration float DCL_writeLog(FDLOG *p, float data)

Description This function writes a data point into the buffer and advances the indexing pointer, wrapping if necessary. The function returns the data value being over-written, which allows simple implementation of a fixed-length delay line.

Parameters

p	The FDLOG structure
data	The input data value addr

Return The over-written data value

DCL_fillLog *Fill a Data Log with Specified Data*

Header File DCL_fdlog.h

Source File N/A

Declaration void DCL_fillLog(FDLOG *p, float data)

Description This function fills the data log with a given data value and resets the data index pointer to the start of the log.

Parameters

p	The FDLOG structure
data	The input data value addr

Return None

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DCL_clearLog *Fill a Data Log Contents with Zero*

Header File DCL_fdlog.h

Source File N/A

Declaration void DCL_clearLog(FDLOG *p)

Description This function clears the buffer contents by writing 0 to all elements and resets the data index pointer to the start of the log.

Parameters

p	The FDLOG structure

Return None

DCL_readLog *Fill a Data Log Contents with Zero*

Header File DCL_fdlog.h

Source File N/A

Declaration float DCL_readLog(FDLOG *p)

Description This function reads a data point from the buffer and then advanced the index pointer, wrapping if necessary.

Parameters

p	The FDLOG structure

Return The indexed data value

DCL_copyLog *Copies one Data Log into Another*

Header File DCL_fdlog.h

Source File N/A

Declaration void DCL_copyLog(FDLOG *p, FDLOG *q)

Description This function copies the contents of one log into another and resets both buffer index pointers. The function assumes both logs have the same length.

Parameters

p	The FDLOG structure
q	The source FDLOG structure

Return None

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DCL_freadLog *Performs Fast Read from a Data Log*

Header File DCL_fdlog.h

Source File DCL_frwlog.asm

Declaration float DCL_freadLog(FDLOG *p)

Description This function reads a data point from the log and then advances the indexing pointer, wrapping if necessary. This function is coded in assembly.

Parameters

p	The FDLOG structure

Return The indexed data value

DCL_writeLog *Performs Fast Write into a Data Log*

Header File DCL_fdlog.h

Source File DCL_frwlog.asm

Declaration float DCL_fwriteLog(FDLOG *p, float data)

Description This function writes a data point into the buffer and advances the indexing pointer, wrapping if necessary. Returns the over-written data value for delay line or FIFO implementation. This function is coded in assembly.

Parameters

p	The FDLOG structure
data	The input data value

Return The over-written data value

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4.3 Transient Capture Module

The Transient Capture Module (TCM) is a triggered data logger that captures a burst of incoming data. A typical use is the capture of a transient response following a step input to a control system. The trigger conditions are a pair of user defined limits on the incoming data. The capture process is triggered by the first data point that exceeds either limit.

A feature of the TCM is that it captures a programmable length lead frame, allowing the user to inspect conditions immediately prior to the trigger condition. This is accomplished with three FDLOG structures, which are elements in the TCM data structure, together with the limit pair. Once initialized, the status of the TCM is captured in one of four enumerated operating modes:

- TCM_idle
- TCM_armed
- TCM_capture
- TCM_complete

The TCM data is contained in a C structure as shown below:

```
typedef volatile struct {
    FDLOG moniFrame;    //!< Monitor data frame
    FDLOG leadFrame;    //!< Lead data frame
    FDLOG captFrame;    //!< Capture data frame
    float trigMax;      //!< Upper trigger threshold
    float trigMin;      //!< Lower trigger threshold
    uint16_t mode;      //!< Operating mode
    uint16_t lead;      //!< Lead frame size in 32-bit words = trigger crossing index
} TCM;
```

The current mode is available in the “mode” element in the TCM structure. To use the TCM, the user must do the following.

1. Include the header file “TCM.h” in the project
2. Allocate a RAM memory block to hold the full capture buffer.
3. Create an instance of the TCM structure and initialize it using DCL_initTCM().
4. Arm the TCM using DCL_armTCM()
5. Log data into the TCM using DCL_runTCM()
6. Monitor the “mode” element in the TCM structure to determine when the capture is complete.

A code example illustrating the use of the TCM is supplied with the library and is described in Chapter 5.

In the following diagrams, lead, capture, and monitor frames are indexed using the FDLOG structures x, y, and z, respectively (note that these are not the names used in the TCM structure). FDLOG pointers are color coded blue, green, and red, respectively. To help visualize the sequence of events, the diagram shows the data that will eventually be logged into the TCM in light gray, and in blue the current frame contents in each mode.

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4.3.1 TCM_idle Mode

In “TCM_idle” mode the TCM buffers are as shown in Figure 4-2. All buffer contents are zero, all frame data pointers are at the start of their respective frames and no data is being logged. This is the condition after the DCL_initTCM() function has been called.

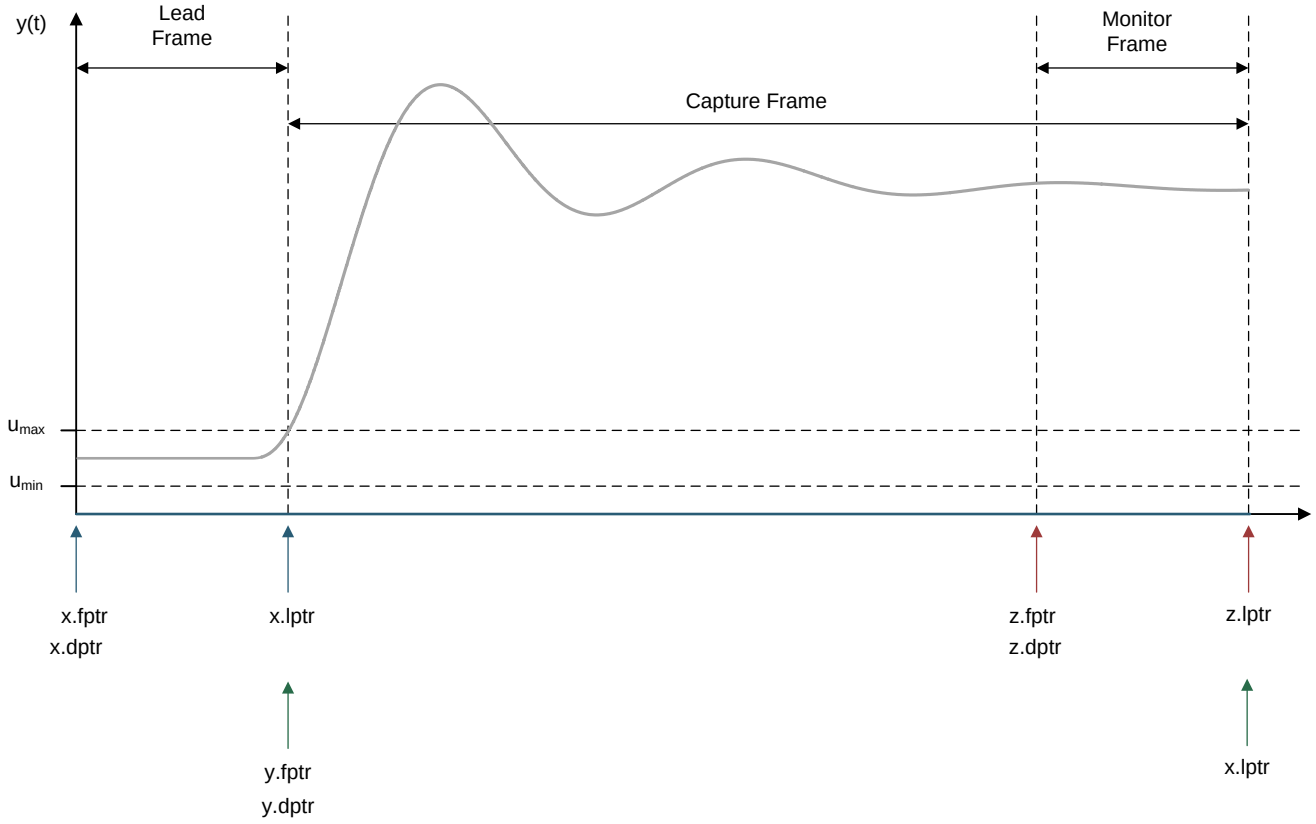

Figure 4-2. TCM Operation in TCM_idle Mode

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4.3.2 TCM_armed Mode

The TCM is armed by a call to DCL_armTCM(). In this mode, incoming data is continually logged in the monitor frame. The monitor frame acts as a circular buffer, the index pointer wrapping to the start of the monitor frame when it reaches the end

Each data point is compared with the upper and lower trigger thresholds to determine whether to initiate a capture sequence. As long as the incoming data remains within the specified limits, the TCM remains in TCM_armed mode.

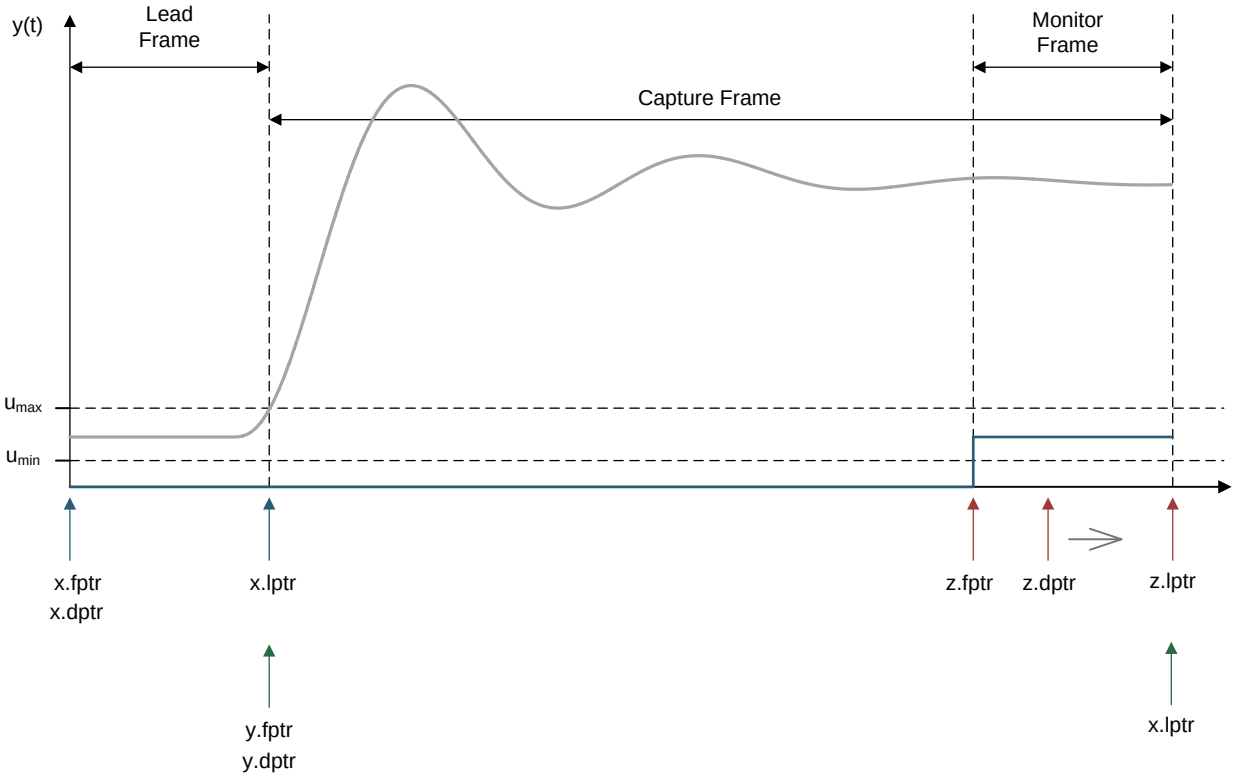

Figure 4-3. TCM Operation in TCM_armed Mode

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4.3.3 TCM_capture Mode

The first data point that exceeds either trigger threshold initiates a capture sequence. The TCM automatically enters “TCM_capture” mode and incoming data is logged into the capture frame. Meanwhile, the monitor frame stops collecting data and starts to “un-wind” its contents into the lead frame. Notice that the monitor frame contains the lead data sequence, but the starting point is not aligned with the frame.

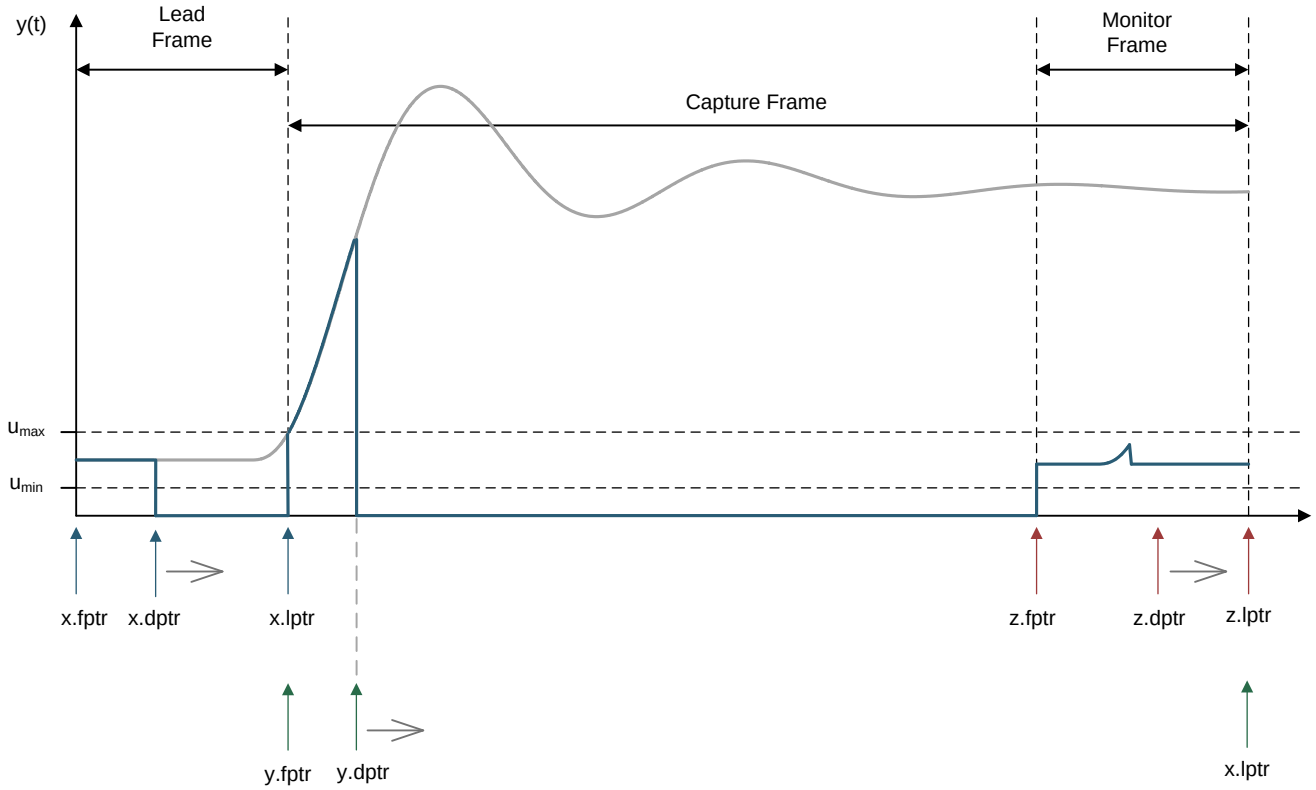

Figure 4-4. TCM Operation in Capture Mode (monitor frame un-winding)

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Once the lead frame is full, the monitor frame stops copying out its data. Incoming data continues being logged into the capture frame until it is full. The monitor frame contents have now been completely loaded into the lead frame and will be over-written.

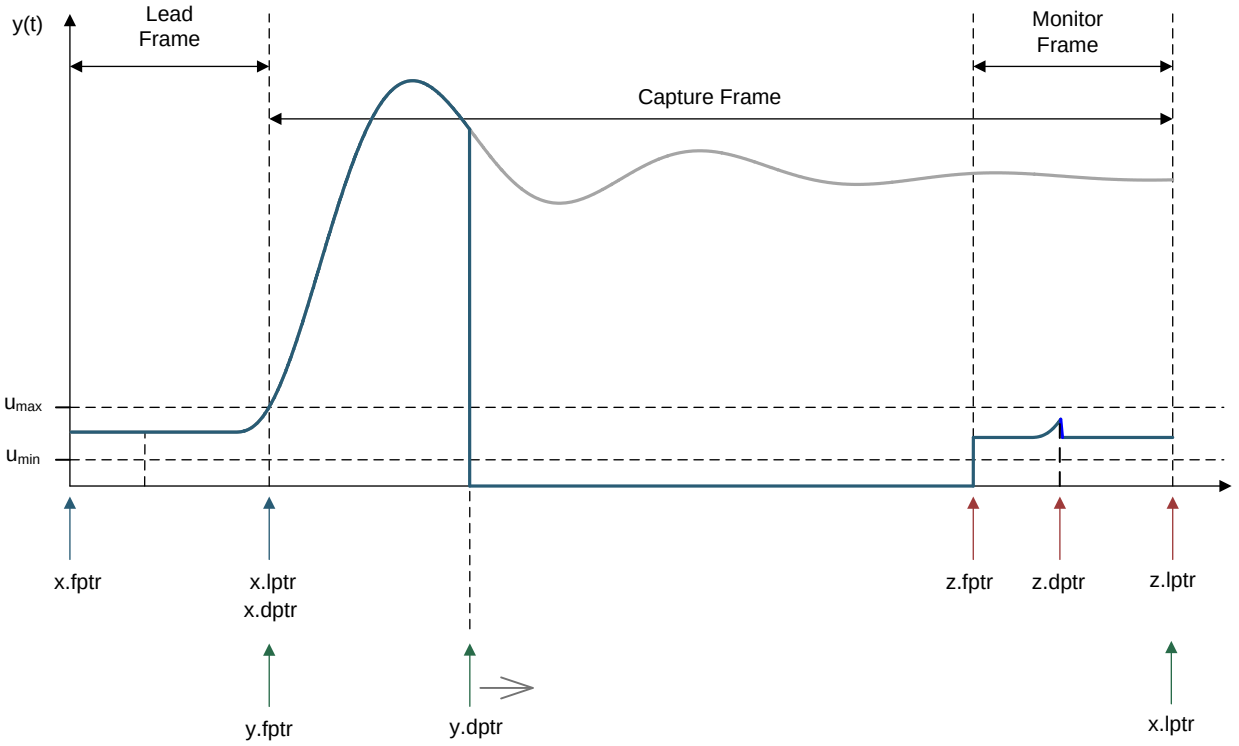

Figure 4-5. TCM Operation in TCM_capture Mode (lead frame complete)

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4.3.4 TCM_complete Mode

Once the capture frame is full, data logging stops and the TCM enters “TCM_complete” mode. The capture frame pointers are adjusted to span the entire TCM buffer, as shown below.

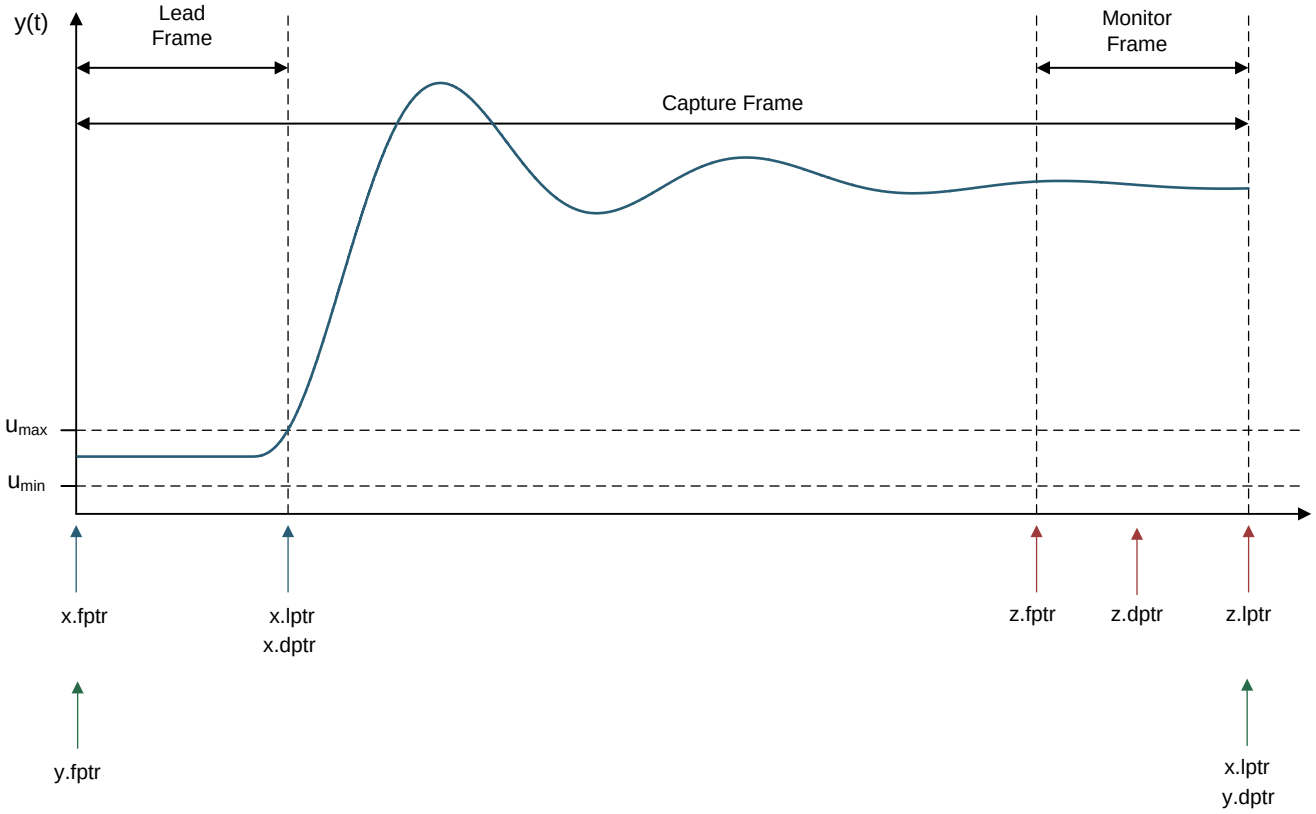

Figure 4-6. CM Capture Complete

The buffer contents may now be read out using DCL_readLog() or DCL_freadLog().

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4.3.5 TCM Functions

Table 4-4. Summary of TCM Functions

Title	Page
DCL_initTCM —Initialize the TCM	71
DCL_armTCM —Arm the TCM	72
DCL_runTCM —Run the TCM	72

DCL_initTCM *Initialize the TCM*

Header File DCL_TCM.h

Source File N/A

Declaration void DCL_initTCM(TCM *q, float *addr, uint16_t size, uint16_t lead, float tmin, float tmax)

Description This function resets the TCM module. All buffer contents are loaded with zero, and the operating mode is set to “TCM_idle”.

Parameters

p	The TCM structure
addr	The start address of the memory block
size	The size of the memory block in 32-bit words
lead	The length of the lead frame in samples
tmin	The upper trigger threshold
tmax	The lower trigger threshold

Return None

DCL_resetTCM *Reset the TCM*

Header File DCL_TCM.h

Source File N/A

Declaration void DCL_resetTCM(TCM *q)

Description This function resets the TCM. The contents of the capture frame are loaded with zero. All data log pointers are re-initialized, and the operating mode is set to “TCM_idle”.

Parameters

q	The TCM structure

Return The over-written data value

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DCL_armTCM *Arm the TCM*

Header File DCL_TCM.h

Source File N/A

Declaration uint16_t DCL_armTCM(TCM *q)

Description If the current TCM mode is “TCM_idle”, this function changes it to “TCM_armed”, otherwise it is unchanged.

Parameters

q	The TCM structure

Return The current operating mode

DCL_runTCM *Run the TCM*

Header File DCL_TCM.h

Source File N/A

Declaration uint16_t DCL_runTCM(TCM *q, float data)

Description Runs the TCM module.

Parameters

q	The TCM structure

Return The current operating mode

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4.4 Performance Measurement

4.4.1 Description

The Digital Control Library includes functions for the computation of control performance. All functions are based on discrete integration over a fixed interval of a variable representing servo error. The result is a non-negative scalar representing the quality of control: the smaller the result, the better the control. Figure 4-7 shows conceptually the transient servo error during a typical transient response.

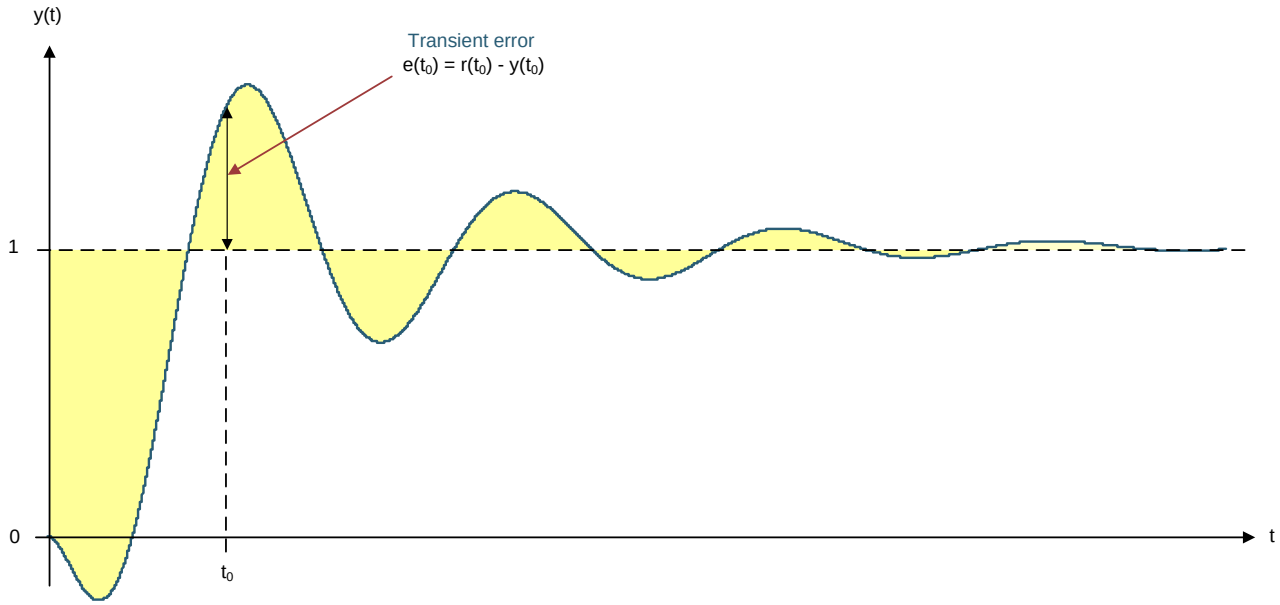

Figure 4-7. Transient Servo Error

There are three performance measures available in the library.

- The IES performance index is based on the square of the servo error. For an interval of N samples, with loop reference r and feedback y, the IES index (PIES) is computed as shown in Equation 22.

$$P_{IES} = \sum_{k=1}^{N} (r(k) - y(k))^2 \quad (22)$$

- The IAE performance index is based on the absolute value of the servo error. For an interval of N samples, with loop reference r and feedback y, the IAE index (PIAE) is computed as shown in Equation 23.

$$P_{IAE} = \sum_{k=1}^{N} |r(k) - y(k)| \quad (23)$$

- The ITAE performance index is based on the time weighted absolute value of the servo error. For an interval of N samples, with loop reference r and feedback y, the ITAE index (PITAE) is computed as shown in Equation 24.

$$P_{ITAE} = \sum_{k=1}^{N} k|r(k) - y(k)| \quad (24)$$

Each index is available in two forms: one coded in assembly, the other in inline C. The computation time will depend on the length of the error log, but the assembly functions will always be significantly faster.

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Table 4-5 shows cycle count benchmarks for each function, for a buffer of N data points. Cycle counts include function calling overhead from C.

Table 4-5. Performance Index Function Benchmarks

Function	Cycles
IES_C1	24 + 6N
IES_C2	73 + 30N
IAE_C1	24 + 6N
IAE_C2	72 + 24N
ITAE_C1	26 + 7N
ITAE_C2	77 + 31N

4.4.2 IES Functions

Table 4-6. Summary of IES Functions

Title **Page**

DCL_runIES_C1 —Compute the IES Performance Index 74
DCL_runIES_C2 —Compute the IES Performance Index 75
DCL_runIAE_C1 —Compute the IAE Performance Index 75
DCL_runIAE_C2 —Compute the IAE Performance Index 75
DCL_runITAE_C1 —Compute the ITAE Performance Index 76
DCL_runITAE_C2 —Compute the ITAE Performance Index 76

DCL_runIES_C1 *Compute the IES Performance Index*

Header File DCL_TCM.h

Source File DCL_index.asm

Declaration float DCL_runIES_C1(FDLOG *eLog)

Description This function computes an IES performance index using the servo error data in a given memory block. The function is coded in assembly.

Parameters

eLog	The servo error data log

Return The IES index

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DCL_runIES_C2 *Compute the IES Performance Index*

Header File DCL_TCM.h

Source File N/A

Declaration float DCL_runIES_C2(FDLOG *eLog)

Description This function is equivalent to DCL_runIES_C1, but is coded in inline C.

Parameters

eLog	The servo error data log

Return The IES index

DCL_runIAE_C1 *Compute the IAE Performance Index*

Header File DCL_TCM.h

Source File DCL_index.asm

Declaration float DCL_runIAE_C1(FDLOG *eLog)

Description This function computes an IES performance index using the servo error data in a given memory block. The function is coded in assembly.

Parameters

eLog	The servo error data log

Return The IES index

DCL_runIAE_C2 *Compute the IAE Performance Index*

Header File DCL_TCM.h

Source File N/A

Declaration float DCL_runIAE_C2(FDLOG *eLog)

Description This function is equivalent to DCL_runIAE_C1, but is coded in inline C.

Parameters

eLog	The servo error data log

Return The IES index

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DCL_runITAE_C1 *Compute the ITAE Performance Index*

Header File DCL_TCM.h

Source File N/A

Declaration float DCL_runIAE_C2(FDLOG *eLog)

Description This function is equivalent to DCL_runIAE_C1, but is coded in inline C.

Parameters

eLog	The servo error data log

Return The ITAE index

DCL_runITAE_C2 *Compute the ITAE Performance Index*

Header File DCL_TCM.h

Source File N/A

Declaration float DCL_runITAE_C2(FDLOG *eLog, float prd)

Description This function is equivalent to DCL_runITAE_C1, but is coded in inline C.

Parameters

eLog	The servo error data log
prd	The sample period in seconds

Return The ITAE index

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Examples

This chapter describes the example projects shipped with the Digital Controller Library.

The Digital Controller Library package includes a set of code examples intended to illustrate how to integrate the library functions into a user program. All examples are supplied as CCS projects prepared for use with the F28069, and will run on any target board fitted with that device. Code changes to support a different C2000 device are minimal and do not affect the DCL. There are six example projects:

- DF22 compensator running on C28x
- DF23 compensator running on CLA
- NLPID controller running on C28x
- PI controller running on CLA
- PID controller running on C28x
- TCM running on C28x

The examples are located in the C2000ware installation directory, at the sub-directory "\libraries\control\DCL\c28\examples". Each example has a "CCS" sub-directory containing a ".projectspec" file, which should be imported as a project into your CCS workspace.

The following sections describe the example code and outline the steps to run them. The examples were prepared using CCS version 6 and a F28069 target board. It is assumed the reader is familiar with CCS v6 and how to build and run code. For information on these topics, the reader is referred to the F28069 training workshop (see Section 6.2).

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5.1 Example 1: DF22 Compensator Running on C28x

5.1.1 Example Overview

This example demonstrates the DF22 compensator running on the C28x core. The code creates two separate instances of the DF22 compensator: one to be implemented using the full DCL_DF22_C1 function, the other using the pre-computed DCL_DF22_C2 and DCL_DF22_C3 functions. The pre-computed compensator makes use of a clamp function to limit the compensator output.

The program contains one ISR that is triggered by a CPU timer at 1kHz. The ISR reads a single input from a data buffer and runs both DF22 compensators. The compensator outputs are compared, and then both outputs and their difference logged into three separate data buffers. When the last point of the input buffer has been read and processed, the ISR passes through the line containing a “NOP” instruction near the bottom of the program. The user can place a break-point here to examine the results of the compensator test.

The program makes use of four data buffers at the following addresses:

- 0xC000 – contains input data representing servo loop error
- 0xE000 – contains output data from the full DF22 compensator
- 0x10000 – contains output data from the pre-computed DF22 compensator
- 0x12000 – contains the difference between the two compensator outputs

Each data buffer contains 1601 single precision floating-point data points.

5.1.2 Code Description

The following lines in the Example_F28069_DF22.c program files are important:

- Lines 9-29: create four data buffers and assign them to memory blocks defined in the linker file “F28069_DCL.cmd”
- Lines 43-44: create instances of the two DF22 compensators
- Lines 66-72: initialize the data log structures and data buffers
- Lines 75-86: initialize the coefficients of the two compensators
- Lines 89-90: set the clamp limits for the pre-computed compensator
- Line 115: tests whether the last element in the input data buffer has been reached
- Line 118: reads the input data point
- Line 121: runs the full DF22 compensator
- Line 124: runs the immediate part of the pre-computed compensator
- Line 125 clamps the output of the pre-computed compensator
- Lines 126-129: run the partial part of the pre-computed compensator

5.1.3 Running the Example

To run this example, first build and load the program onto the C28x, then load the data file “DF22_edata.dat” into data memory at address 0xc000. This file contains a pre-recorded data sequence representing simulated servo loop error at the controller input.

Place a break-point at the line indicated in the control ISR and run the program. When the program reaches the break-point, inspect the memory buffers by opening a CCS graph window.

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Figure 5-1 shows how to configure the graph to view the pre-computed compensator output (u2k).

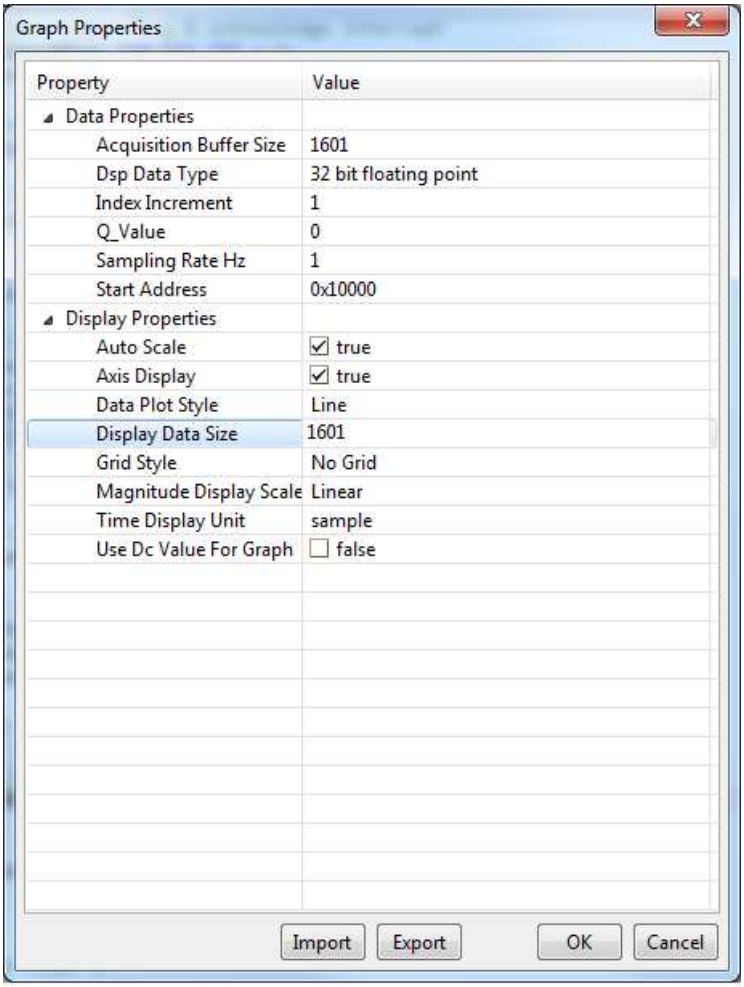

Figure 5-1. Graph Setup Window

Figure 5-2 shows what the ek buffer should look like.

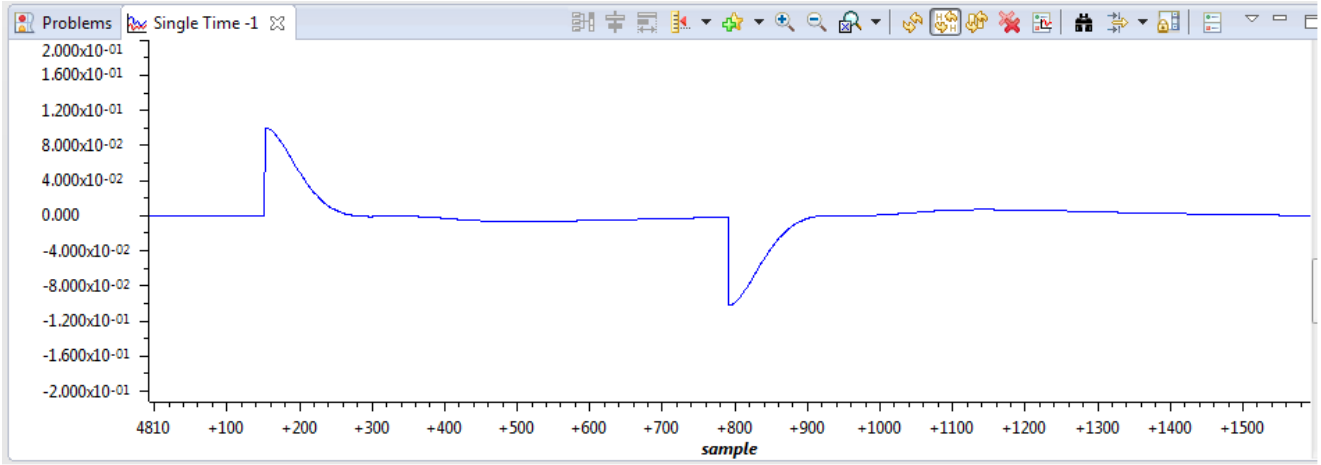

Figure 5-2. ek Buffer

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Figure 5-3 shows what the plot of the u1k and u2k buffers should look like.

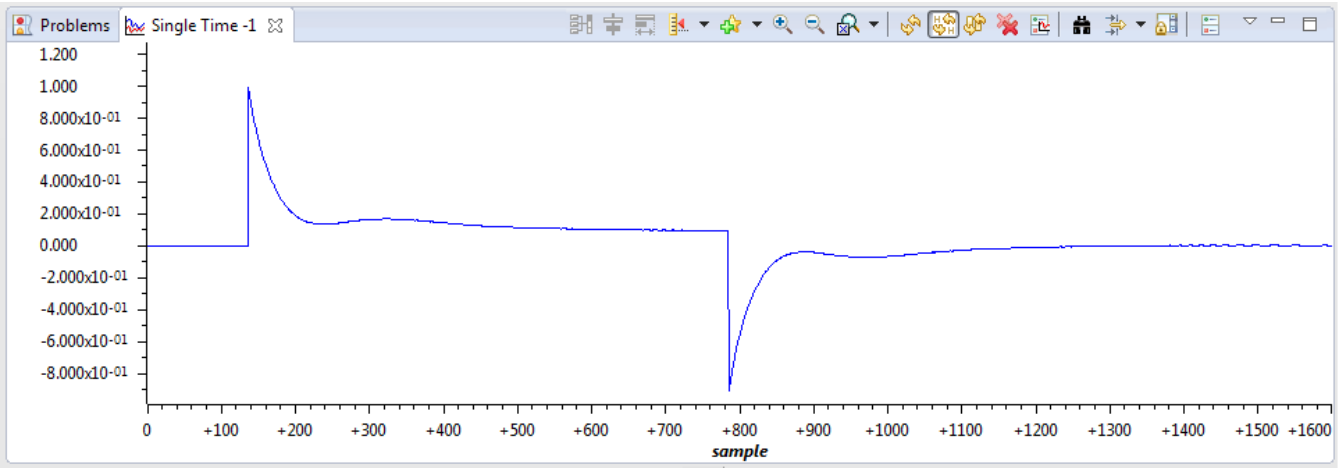

Figure 5-3. Plot of u1k and u2k Buffers

5.2 Example 2: DF23 Compensator Running on CLA

5.2.1 Example Overview

This example demonstrates one method of running a DF23 compensator on the CLA. In this example, incoming data is read in an ISR on the C28x CPU and passed to the CLA using a variable (ek), which is located in CPU-to-CLA message RAM. The ISR then triggers task 3 on the CLA and waits for it to complete.

The CLA task calls two different DF23 compensators and stores their results in two variables (u1k and u2k), which are located in CLA-to-CPU message RAM. These results are read by the CPU ISR, which computes the difference between them. The ISR then stores both results and their difference to three data buffers. When the final input value has been processed in this way, the ISR passes through a “NOP” instruction allowing the user to place a break-point and inspect the results.

5.2.2 Code Description

The following lines in the file “Example_F28069_DF23.c” are important:

- Lines 11-31: create four buffers that will be used to hold control data
- Lines 37-42: create variables that will pass control data between C28x and CLA
- Lines 68-74: assign data logs to the buffers and initialize them
- Line 141: reads the next data point from the input data file
- Line 145: triggers the CLA task that will call the DF23 compensator
- Line 149: compute the difference between the two compensator results
- Lines 152-154: write the compensator results into the data buffers

The following lines in the file “F28069_DF23_CLA.cla” are important:

- Line 31: calls the full DF23 compensator and stores the result in “u1k”
- Line 34: calls the immediate DF23 compensator and stores the result in “u2k”
- Line 35: clamps the immediate result and sets the clamp flag “vk”
- Lines 36-39: pre-compute the next partial DF23 result, providing the immediate part is in range
- Lines 72-92: initialize the two DF23 compensator structures
- Lines 95-96: initialize the clamp limits for the pre-computed DF23 compensator

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5.2.3 Running the Example

To run this example, first build the project, then load the project onto the C28x and load symbols onto the CLA. Load the pre-recorded data file “DF23_edata.dat” into C28x memory at address 0xC000. Place a break-point at the “NOP” instruction in line 159 of the file Example_F28069_DF23.c, and run the program.

After the break-point is reached, open a graph window to inspect the contents of the u1k memory buffer at address 0xE000.

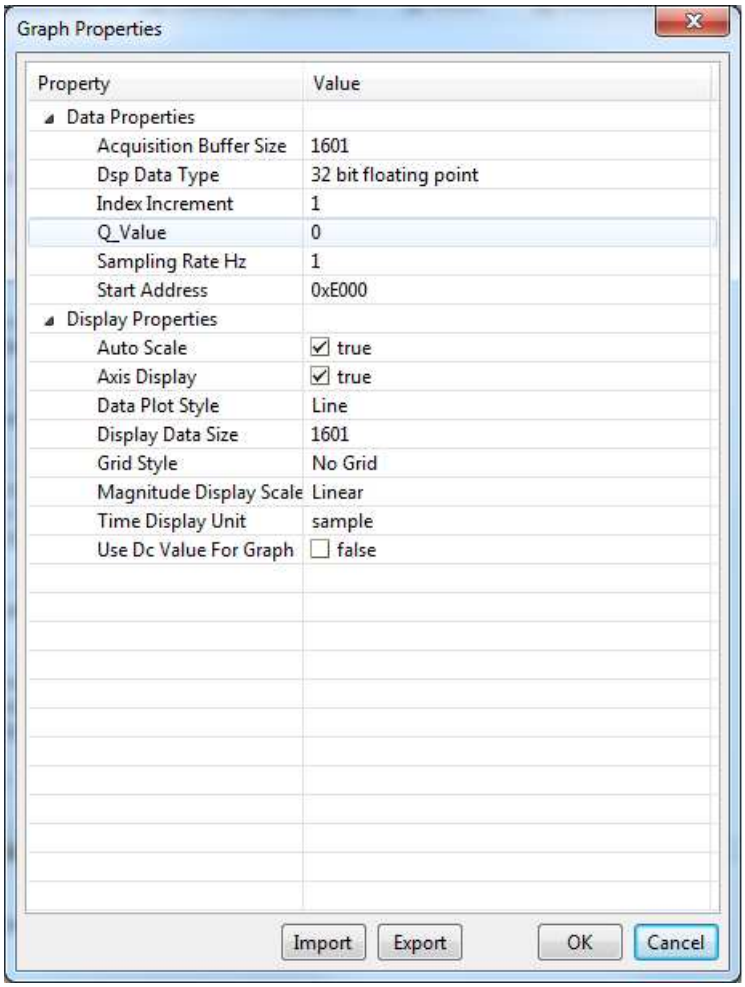

Figure 5-4. u1k Memory Buffer at Address 0xE000

The graph contents should look like this.

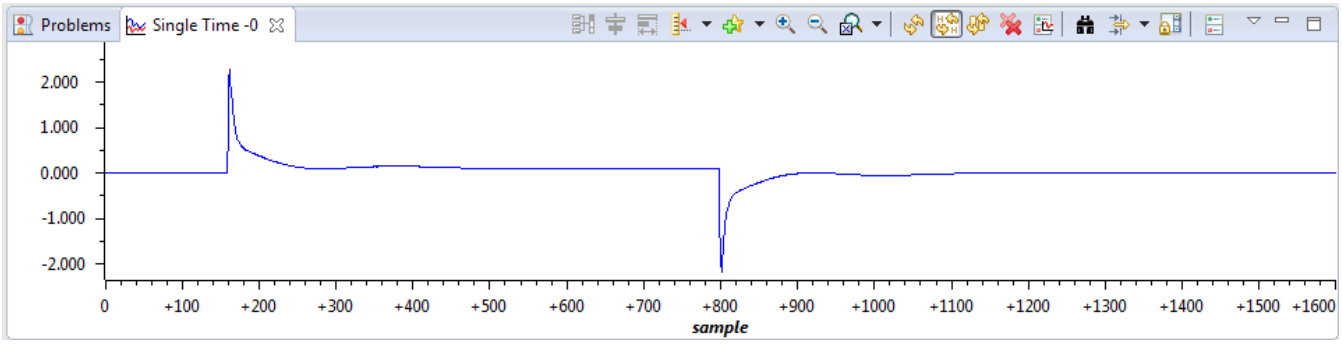

Figure 5-5. Plot of u1k Memory Buffer

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These results were produced by the full DF23 compensator. To view the pre-computed compensator, change the “Start Address” field in Graph Properties to 0x10000. The buffer at address 0x12000 contains the difference in compensator results, all of which should be zero or very small.

5.3 Example 3: NLPID Controller Running on C28x

5.3.1 Example Overview

This example demonstrates the use of the non-linear PID controller on the C28x core. The code is similar to the linear PID example below. Note that in addition to the DCL header file, the program also includes “DCL_NLPID.h” that contains the controller functions.

The ADC is triggered by a PWM zero match event, and samples two channels. An ISR is triggered by an ADC end-of-conversion event and reads the ADC results. Channel A0 represents the control loop feedback, and channel B0 represents an external saturation input that is used for integrator anti-windup. The DCL_runClamp_C2 function is used to convert the ADC result into an integer with the logical value 1 or zero.

The ISR calls the DCL_NLPID_C1 controller, and stores the control effort in the “uk” variable. This is converted into an unsigned 16-bit integer and used to modulate the PWM duty cycle. In this way, the program implements a non-linear closed loop controller that regulates the floating-point reference, “rk”.

5.3.2 Code Description

The following lines in the file Example_F28069_NLPID.c are important:

- Line 20: creates an instance of the NLPID controller
- Lines 93-113: initialize the elements of the NLPID structure
- Line 114: computes the linearized gains and updates the NLPID structure
- Lines 115-116: initialize the control reference and saturation flag
- Lines 132-136: update linearized gains if the NL parameters are changed
- Line 152: reads the control feedback and converts to signed floating-point format
- Line 156: converts the saturation input to 0.0f or 1.0f for anti-windup reset
- Line 159: calls the non-linear PID controller function
- Line 162: converts the controller output to unsigned 16-bit integer
- Line 163: updates the PWM duty cycle

5.3.3 Running the Example

To run this example, simply build, load, and run the program on the C28x core. Place a break-point at the last instruction in the ISR (line 164) and run the program. The following variables can be monitored in a watch window:

- rk – input reference
- yk – feedback
- lk – external saturation flag
- uk – controller output
- nlpid1 – the NLPID controller structure

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(x)= Variables | Registers | Expressions

Expression	Type	Value	Address
(x)= rk	float	0.25	0x0000B904@Data
(x)= yk	float	-0.422569603	0x0000B902@Data
(x)= lk	float	1.0	0x0000B90C@Data
(x)= uk	float	-0.270000011	0x0000B90E@Data
nlpid1	struct <unnamed>	{...}	0x0000B910@Data
(x)= Kp	float	3.5	0x0000B910@Data
(x)= Ki	float	0.00400000019	0x0000B912@Data
(x)= Kd	float	0.349999994	0x0000B914@Data
(x)= alpha_p	float	0.800000012	0x0000B916@Data
(x)= alpha_i	float	0.949999988	0x0000B918@Data
(x)= alpha_d	float	1.0	0x0000B91A@Data
(x)= delta_p	float	0.150000006	0x0000B91C@Data
(x)= delta_i	float	0.150000006	0x0000B91E@Data
(x)= delta_d	float	0.150000006	0x0000B920@Data
(x)= gamma_p	float	1.46144247	0x0000B922@Data
(x)= gamma_i	float	1.09950054	0x0000B924@Data
(x)= gamma_d	float	1.0	0x0000B926@Data
(x)= c1	float	151.709396	0x0000B928@Data
(x)= c2	float	0.517093956	0x0000B92A@Data
(x)= d2	float	35.7122955	0x0000B92C@Data
(x)= d3	float	-21.9822521	0x0000B92E@Data
(x)= i7	float	0.0	0x0000B930@Data
(x)= i16	float	0.0	0x0000B932@Data
(x)= Umax	float	0.310000002	0x0000B934@Data
(x)= Umin	float	-0.270000011	0x0000B936@Data
Add new expression			

Figure 5-6. Expression Window

The user can run repeatedly to the break-point, modifying controller parameters and examining the change of controller variables. If any of the “alpha” or “delta” parameters are changed, the variable “calFlag” should be set to 1 to enable the “gamma” gains to be computed and updated in the background loop.

5.4 Example 4: PI Controller Running on CLA

5.4.1 Example Overview

This example demonstrates one method of running a PI controller on the CLA. The CPU program contains an ISR that is triggered by an ADC end-of-conversion in the same way as example 3. Feedback data is read from the ADC in an ISR on the C28x CPU and passed to the CLA using a variable (yk) that is located in CPU-to-CLA message RAM, together with the servo reference (rk). The ISR converts the ADC result into signed floating-point format, then triggers task 3 on the CLA and waits for it to complete.

CLA task 3 calls the function DCL_runPI_L1() that computes the PI controller in an assembly function. The result is stored in the variable uk, which is located in CLA-to-CPU message RAM.

The PI controller result is read by the ISR, converted into a scaled un-signed 16-bit integer, and written to the PWM duty cycle register.

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5.4.2 Code Description

The following lines in the file “Example_F28069_PI.c” are important:

- Lines 19-24: create instances of the control variables and assign them to the appropriate message RAM blocks
- Lines 26-27: create an instance of the PI controller structure and place it in CPU-to-CLA message RAM. This allows controller parameters to be modified from code running on the C28x CPU.
- Lines 44-49: initialize the PI controller parameters
- Line 168: reads the feedback data from the ADC and converts it into floating-point format
- Line 172: starts CLA task 3 and waits for it to complete
- Lines 175-176: convert the controller result to 16-but unsigned integer and write it to the PWM duty cycle register

The following line in the file “F2806x_PI_CLA.cla” is important:

- Line 24: calls the PI controller function DCL_runPI_L1()

Note that in this example, initialization of the PI controller is performed on the C28x CPU, so there is no need to allocate a separate CLA task for that purpose.

5.4.3 Running the Example

Build and load the project onto the C28x, then load the symbols onto the CLA. Place a break-point at the last instruction in the ISR (line 178), and run the program. Open an Expressions Window in CCS, and inspect the control variables and PI controller structure.

(x)= Variables | 1010 0101 Registers | Expressions

Expression	Type	Value	Address
(x)= rk	float	0.25	0x00001500@Data
(x)= yk	float	-0.421104044	0x00001502@Data
(x)= uk	float	3.82667089	0x00001480@Data
pi1	struct <unnamed>	{...}	0x00008C00@Data
(x)= Kp	float	5.5	0x00008C00@Data
(x)= Ki	float	0.0149999997	0x00008C02@Data
(x)= i10	float	0.135599017	0x00008C04@Data
(x)= Umax	float	10.1999998	0x00008C06@Data
(x)= Umin	float	-10.1999998	0x00008C08@Data
(x)= i6	float	1.0	0x00008C0A@Data
Add new expression			

Figure 5-7. Expression Window

At this point, controller gains can be manually changed and the code run repeatedly to observe the effect on the control variables.

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5.5 Example 5: PID Controller Running on C28x

5.5.1 Example Overview

This simple example demonstrates a common digital control scenario: a single linear PID controller running on the C28x core that reads an ADC channel and manipulates PWM duty cycle.

The example project contains an ISR that is triggered by an ADC end-of-conversion event. The ADC is triggered by a PWM zero match event, and samples two channels that are read by the ISR. Channel A0 represents the control loop feedback, and channel B0 represents an external saturation input that is used for integrator anti-windup. The DCL_runClamp_C1 function is used to convert the ADC result into an integer with the logical value 1 or zero.

The ISR calls the DCL_PID_C4 parallel form PID controller to compute control effort held in the “uk” variable. This is converted into an unsigned 16-bit integer and used to modulate the PWM duty cycle. In this way, the program implements a simple closed loop PWM controller that regulates the floating-point reference, “rk”.

5.5.2 Code Description

The following lines in the example file Example_F28069_PID.c are important:

- Lines 94-105: initializes the elements of the PID structure
- Line 107: sets the reference input to the control loop
- Line 108: initializes the external saturation flag
- Line 137: reads the feedback and converts to the range ±1.0f
- Line 138: reads the external saturation variable lk
- Line 141: converts lk to 1.0f or 0.0f
- Line 144: runs the PID controller
- Line 147: convert the controller output to unsigned integer in the range 0 to PRD
- Line 148: write result to PWM duty cycle register

5.5.3 Running the Example

To run this example, simply build, load, and run the program on the C28x core. Place a break-point at the last instruction in the ISR and run the program (line 150). The following variables can be monitored in a watch window:

- rk – input reference
- yk – feedback
- lk – external saturation flag
- uk – controller output
- pid1 – the PID controller structure

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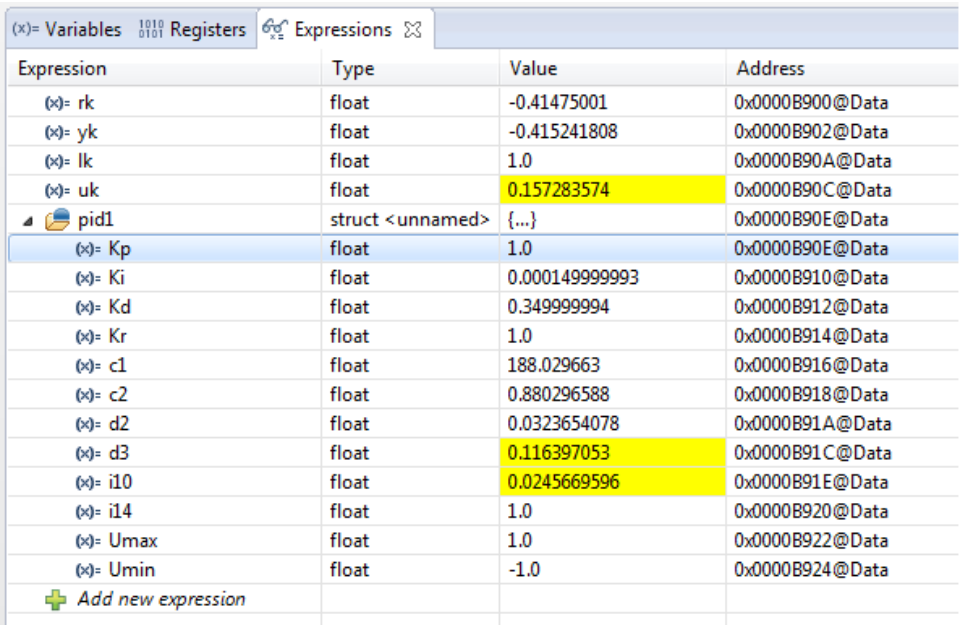

Expression	Type	Value	Address
(x)= rk	float	-0.41475001	0x0000B900@Data
(x)= yk	float	-0.415241808	0x0000B902@Data
(x)= lk	float	1.0	0x0000B90A@Data
(x)= uk	float	0.157283574	0x0000B90C@Data
pid1	struct <unnamed>	{...}	0x0000B90E@Data
(x)= Kp	float	1.0	0x0000B90E@Data
(x)= Ki	float	0.000149999993	0x0000B910@Data
(x)= Kd	float	0.349999994	0x0000B912@Data
(x)= Kr	float	1.0	0x0000B914@Data
(x)= c1	float	188.029663	0x0000B916@Data
(x)= c2	float	0.880296588	0x0000B918@Data
(x)= d2	float	0.0323654078	0x0000B91A@Data
(x)= d3	float	0.116397053	0x0000B91C@Data
(x)= i10	float	0.0245669596	0x0000B91E@Data
(x)= i14	float	1.0	0x0000B920@Data
(x)= Umax	float	1.0	0x0000B922@Data
(x)= Umin	float	-1.0	0x0000B924@Data
Add new expression			

Figure 5-8. Expression Window

The user can run repeatedly to the break-point modifying controller parameters and examining the change of controller variables.

5.6 Example 6: TCM Running on C28x

5.6.1 Example Overview

This example illustrates the use of the TCM to capture a portion of a pre-recorded sample transient response. The code demonstrates how to configure and use the TCM, together with computation and storage of servo error, use of the fast read and write data log functions, and use of the performance index functions.

The code contains a single ISR triggered at 1kHz by a CPU timer. The ISR uses the fast read function DCL_fread() to read values from two buffers representing servo reference (rBuf), and feedback (yBuf), and then runs the TCM on the feedback sample to detect and capture the transient response in a third buffer (dBuf). The code subtracts yk from rk to find the instantaneous servo error, and logs the result into a fourth buffer (eBuf). When the final point in the input data sequence has been read and acted upon, the dBuf buffer should contain a portion of the feedback sequence around the transient edge, while the eBuf buffer contains the servo error. The variables P1, P2, and P3 contain the ITAE, IAE, and IES performance indices respectively. These are computed over the entire input sequence.

5.6.2 Code Description

The following lines in the file Example_F28069_TCM.c are important:

- Lines 14-32: create instances of four data buffers and assign them to specific regions defined in the linker command file F28069_DCL.cmd.
- Lines 39-41: create instances of the control variables
- Line 42: creates an instance of the TCM module and initializes it to default values
- Lines 43-45: creates variables to hold the performance indices
- Lines 67-71: assign the data buffers to FDLOG structures and clear the servo error buffer
- Lines 101-102: read the servo reference and feedback data
- Line 105: runs the TCM

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- Lines 108-109: compute the servo error and log is to the eBuf data buffer
- Line 112: detects if the final point in the input buffer has been processed
- Lines 118-120: compute the three performance indices

5.6.3 Running the Example

To run this program, build and load the project onto the target device. Then, load the two supplied data files “TCM_input.dat” and “TCM_response.dat” into data memory addresses 0xc000 and 0xe000 respectively. Place a break-point on the “NOP” instruction at the bottom of the ISR, and run the program.

When the break-point is reached, open a graph window to view the contents of the 1601-point yBuf memory at address 0xe000.

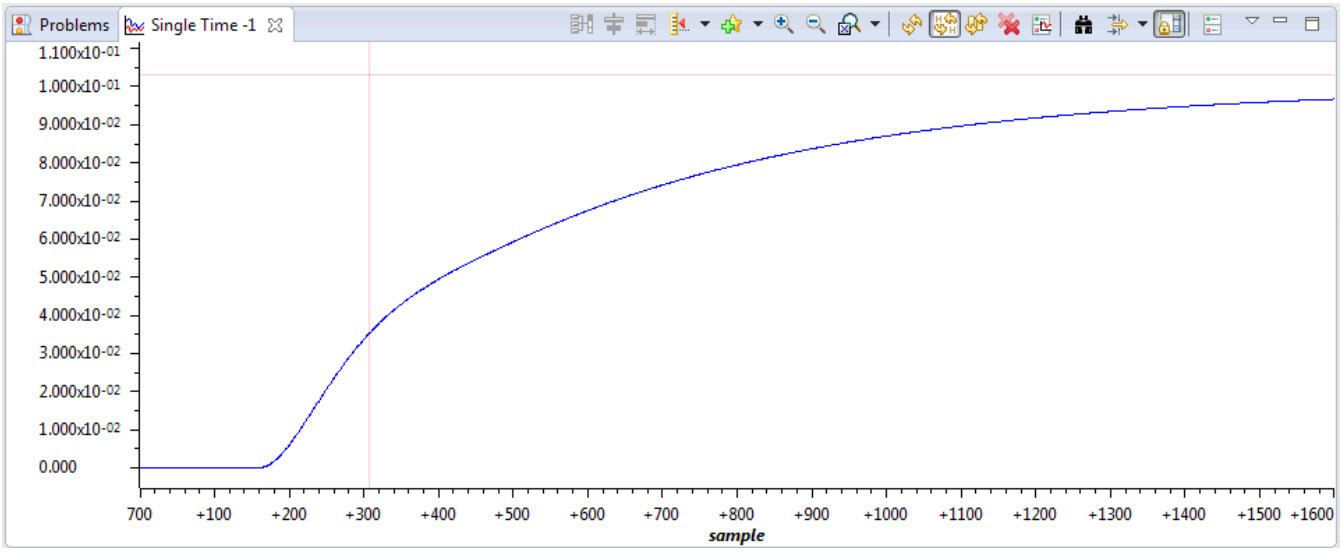

Figure 5-9. Contents of the 1601-Point yBuf Memory

Open a second graph to display the 350-point contents of the dBuf buffer at address 0x12000.

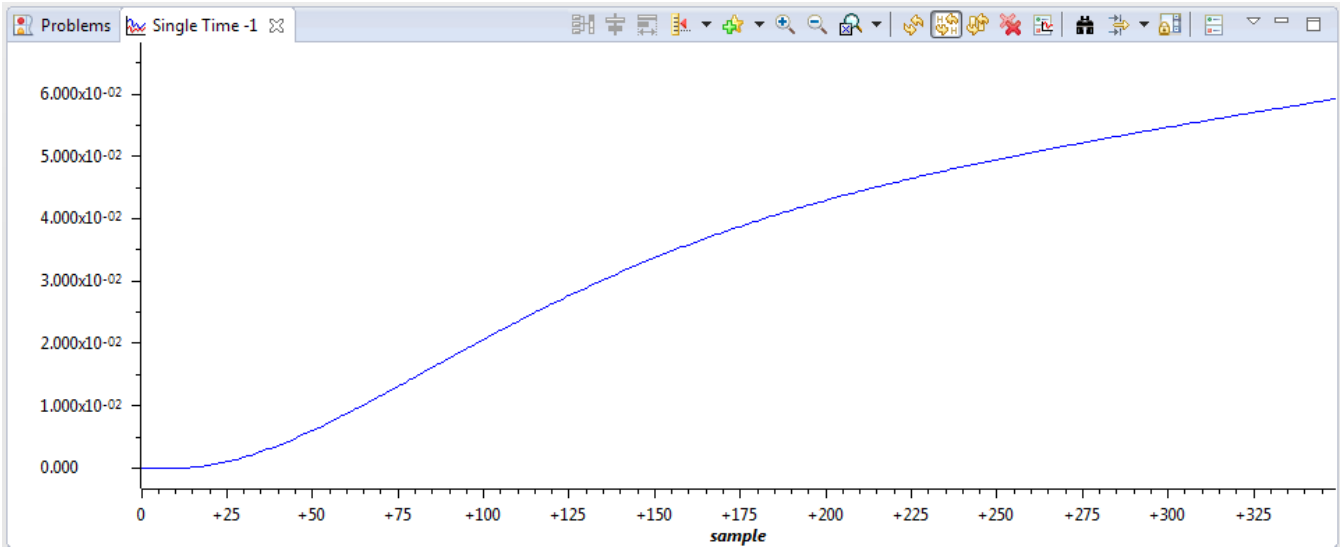

Figure 5-10. 350-Point Contents of the dBuf Buffer

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The TCM buffer contains part of the feedback data near the transient. Notice that the first part of the TCM buffer (approximately 25 samples) contains data that has not exceeded either trigger threshold. This is the lead frame.

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Support

This chapter contains a list of useful technical resources relevant to the DCL.

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6.1 References

Documentation for C2000 MCU devices can be found on their respective product pages at www.ti.com/c2000.

The following is a list of relevant publications:

- Feedback & Control Systems J.J.DiStefano, A.R.Stubberud and I.J.Williams, Schaum, 2011
- Digital Control of Dynamic Systems G.F.Franklin, J.D.Powell & M.L.Workman, Addison-Wesley, 1998
- Control Theory Fundamentals R.Poley, CreateSpace, 2015
- Running an Application from Internal Flash Memory on the TMS320F28xxx DSP
- TMS320C28x Assembly Language Tools User's Guide
- TMS320C28x Optimizing C/C++ Compiler v16.12.0.STS User's Guide

6.2 Training

- Training materials for the C2000 devices from Texas Instruments can be found at processors.wiki.ti.com/index.php/Category:C2000_Training
- Recordings of a 1-day hands-on workshop using the F28069 device can be found at training.ti.com/c2000-mcu-1-day-workshop-8-part-series
- Information on a series of technical seminars in control theory can be found at www.controltheoryseminars.com.

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