UM0585
User manual

STM32F10xxx
DSP library

Introduction

This user manual describes the STM32F10xxx DSP (digital signal processing) library, which is a suite of common digital signal processing functions:

- PID controller
- Fast Fourier transform
- FIR and IIR filters

The library contains C and assembly functions that have been ported and tested on the IAR EWARM 5.20, Keil RVMDK 3.23 and Raisonance RIDE7 (GNU compiler) toolchains.

Contents

1 DSP Library description 6

2 PID controller 7

2.1 Description 7

2.2 DSP library functions 7

2.2.1 `DoPID` function 7

2.2.2 `DoFullPID` function 8

2.2.3 `PID_stm32` function 8

3 Complex 16-bit radix-4 FFT 9

3.1 Description 9

3.2 DSP library functions 9

3.2.1 `cr4_fft_64_stm32` function 9

3.2.2 `cr4_fft_256_stm32` function 10

3.2.3 `cr4_fft_1024_stm32` function 10

3.3 FFT performance improvement 10

4 16-bit FIR filter 12

4.1 Description 12

4.2 DSP library function 12

4.2.1 `fir_16by16_stm32` function 13

5 16-bit IIR filters 14

5.1 Description 14

5.2 DSP library functions 15

5.2.1 `iiarma_stm32` function 15

5.2.2 `iir_biquad_stm32` function 16

6 STM32F10xxx DSP library benchmark 18

6.1 Function code footprint 18

6.2 Function execution time 18

6.2.1 PID controller 18

6.2.2 Fast Fourier transform (FFT) 19

6.2.3 FIR filter 19

6.2.4 IIR filters 19

7 Conclusion 21

8 Revision history 22

List of tables

Table 1. STM32F10xxx DSP library functions . . . 6
Table 2. `DoPID` function . . . 7
Table 3. `DoFullPID` function . . . 8
Table 4. `PID_stm32` function . . . 8
Table 5. `cr4_fft_64_stm32` function . . . 9
Table 6. `cr4_fft_256_stm32` function . . . 10
Table 7. `cr4_fft_1024_stm32` function . . . 10
Table 8. `fir_16by16_stm32` function . . . 13
Table 9. `iirarma_stm32` function . . . 15
Table 10. `iir_biquad_stm32` function . . . 16
Table 11. STM32F10xxx DSP library functions code footprint . . . 18
Table 12. PID controller, error computed outside the routine . . . 18
Table 13. PID controller, error computed within the routine . . . 19
Table 14. Complex radix 4, 16-bit FFT, coefficients in Flash memory . . . 19
Table 15. Complex radix 4, 16-bit FFT, coefficients in RAM. . . . 19
Table 16. 16-bit, 32-tap FIR filter . . . 19
Table 17. 16-bit canonic form, 4 biquad IIR filter . . . 19
Table 18. 16-bit direct-form I, 8^{th}-order IIR filter . . . 20
Table 19. Document revision history . . . 22

List of figures

Figure 1. Block diagram of PID controller 7
Figure 2. Block diagram of an FIR filter of length N 12
Figure 3. Block diagram of the direct form I of second-order IIR filter 14
Figure 4. Block diagram of the canonical form of a second-order IIR filter 15

1 DSP Library description

The STM32F10xxx DSPLib is a suite of common functions for signal processing. It includes the following functions:

Table 1. STM32F10xxx DSP library functions

Function name	Description
DoPID	PID controller in C, error computed outside the routine
DoFullPID	PID controller in C, error computed inside the routine
PID_stm32	PID controller in ASM, error computed outside the routine
cr4_fft_64_stm32	Complex radix-4 16-bit FFT optimized for 64 points
cr4_fft_256_stm32	Complex radix-4 16-bit FFT optimized for 256 points
cr4_fft_1024_stm32	Complex radix-4 16-bit FFT optimized for 1024 points
fir_16by16_stm32	16-bit FIR filter
iiarma_stm32	16-bit auto-regressive moving-average IIR (ARMA) filter
iir_biquad_stm32	16-bit biquad IIR filter

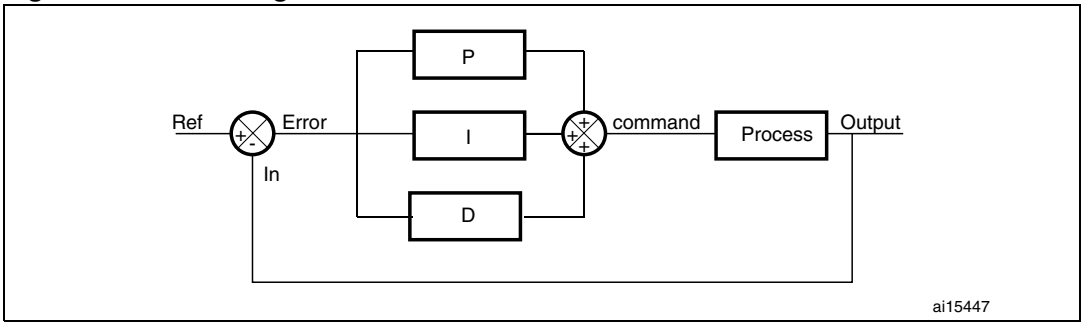
2 PID controller

2.1 Description

The proportional-integral-derivative or PID controller is commonly used in the industry. It is a feedback loop controller that manages the process command with a view to reducing the error between the desired setpoint and the measured process variable.

The following block diagram shows the parallel structure of a PID controller. This is the structure implemented in this DSP library.

Figure 1. Block diagram of PID controller



2.2 DSP library functions

The DSP library provides three PID functions:

- **`DoPID`**: a PID core loop coded in C (the error is computed outside the function)
- **`DoFullPID`**: a full PID controller coded in C (with error computing)
- **`PID_stm32`**: an optimized PID core loop written in assembly

2.2.1 `DoPID` function

Table 2 describes the `DoPID` function.

Table 2. `DoPID` function

Function name	**`DoPID`**
Prototype	`u16 DoPID(u16 Error, u16 *Coeff)`
Behavior description	PID in C, error computed outside the function.
Input parameter	– Error: difference between reference and measured values – Coeff: pointer to the coefficients table
Output parameter	None
Return parameter	PID output command

Example

```
/* Fill the coefficients table */
Coeff[0] = Kp;/*proportional coefficient*/
Coeff[1] = Ki;/*integral coefficient*/
```

```
Coeff[2] = Kd;/*derivative coefficient*/
/* Compute the error */
Error = Target_Signal - Measured_Signal;
/* PID control process */
Command = DoPID(Error, Coeff);
```

2.2.2 DoFullPID function

Table 3 describes the DoFullPID function.

Table 3. DoFullPID function

Function name	DoFullPID
Prototype	u16 DoFullPID(u16 In, u16 Ref, u16 *Coeff)
Behavior description	PID in C, error computed inside the function.
Input parameter	– In: Input (measured value) – Ref: reference (target value) – Coeff: pointer to the coefficients table
Output parameter	Computed error
Return parameter	PID output command

Example

```
/* Fill the coefficients table */
Coeff[0] = Kp;/*proportional coefficient*/
Coeff[1] = Ki;/*integral coefficient*/
Coeff[2] = Kd;/*derivative coefficient*/

/* PID control process, the error is computed inside the function */
Command = DoFullPID(Measured_Signal, Target_Signal, Coeff);
```

2.2.3 PID_stm32 function

Table 4 describes the PID_stm32 function.

Table 4. PID_stm32 function

Function name	PID_stm32
Prototype	u16 PID_stm32(u16 Error, u16 *Coeff);
Behavior description	Assembly optimized PID controller with error computed outside the function.
Input parameter	– Error: difference between reference and measured values – Coeff: pointer to the coefficients table
Output parameter	None
Return parameter	PID output command

The PID_stm32 function is used in the same way as the DoPID function. The error must be computed, then the PID_stm32 function is called to improve the PID control process and to return the appropriate command according to the coefficients table.

3 Complex 16-bit radix-4 FFT

3.1 Description

The discrete Fourier transform (DFT) converts N complex values from the time domain to the frequency domain.

The fast Fourier transform (FFT) is an optimized algorithm designed to compute the DFT efficiently.

The STM32F10xxx DSP library provides a complex radix-4 , with decimation-in-time, linear-order FFT.

Let x[N] be the time signal samples. To use the FFT functions of the DSP library, the following conditions must be satisfied:

- N is a power of 4
- All the signal samples must be 32-bit data containg the 16-bit real part followed by the 16-bit imaginary part (in the little Endian order: imaginary_real).

3.2 DSP library functions

The DSP provides three complex 16-bit radix-4 FFT functions:

1. **`cr4_fft_64_stm32`**: an optimized FFT function to compute 64-point DFT
2. **`cr4_fft_256_stm32`**: an optimized FFT function to compute 256-point DFT
3. **`cr4_fft_1024_stm32`**: an optimized FFT function to compute 1024-point DFT

3.2.1 `cr4_fft_64_stm32` function

Table 5 describes the `cr4_fft_stm32` function.

Table 5. `cr4_fft_64_stm32` function

Function name	**`cr4_fft_64_stm32`**
Prototype	`void cr4_fft_64_stm32(void *pssOUT, void *pssIN, u16 Nbin);`
Behavior description	complex 16-bit, 64-point radix-4 FFT
Input parameter	– `pssOUT`: pointer to the output array data – `pssIN`: pointer to the input array data – `Nbin`: the number of points, must be 64.
Output parameter	None
Return parameter	None

3.2.2 `cr4_fft_256_stm32` function

Table 6 describes the `cr4_fft_256_stm32` function.

Table 6. `cr4_fft_256_stm32` function

Function name	cr4_fft_256_stm32
Prototype	`void cr4_fft_256_stm32(void *pssOUT, void *pssIN, u16 Nbin);`
Behavior description	complex 16-bit, 256-point radix-4 FFT
Input parameter	– `pssOUT`: pointer to the output array data – `pssIN`: pointer to the input array data – `Nbin`: the number of points, must be 256.
Output parameter	None
Return parameter	None

3.2.3 `cr4_fft_1024_stm32` function

Table 7 describes the `cr4_fft_1024_stm32` function.

Table 7. `cr4_fft_1024_stm32` function

Function name	cr4_fft_1024_stm32
Prototype	`void cr4_fft_1024_stm32(void *pssOUT, void *pssIN, u16 Nbin);`
Behavior description	complex 16-bit, 1024-point radix-4 FFT
Input parameter	– `pssOUT`: pointer to the output array data – `pssIN`: pointer to the input array data – `Nbin`: the number of points, must be 1024.
Output parameter	None
Return parameter	None

Example

```
#define N 64 /*Number of points*/
u32 x[N],y[N]; /* input and output arrays */
u16 real[N], imag[N]; /* real and imaginary arrays */
/* Fill the input array */
for(i=0; i<N; i++)
  x[i] = (((u16)(real[i])) | ((u32)(imag[i]<<16)));
cr4_fft_64_stm32(y, x, N); /*computes the FFT of the x[N] samples*/
```

3.3 FFT performance improvement

The FFT coefficients table is stored in the Flash memory since it is declared as code in the assembly file. The performance of the FFT function can be improved by placing the FFT coefficients in RAM. This is done as described below:

1. Comment all the FFT coefficients in the FFT function assembly file.

```
/* TableFFT_V7
         ;N=16
        DC16 0x4000,0x0000, 0x4000,0x0000, 0x4000,0x0000
        DC16 0xdd5d,0x3b21, 0x22a3,0x187e, 0x0000,0x2d41
        DC16 0xa57e,0x2d41, 0x0000,0x2d41, 0xc000,0x4000
        DC16 0xdd5d,0xe782, 0xdd5d,0x3b21, 0xa57e,0x2d41
        ; N=64
        DC16 0x4000,0x0000, 0x4000,0x0000, 0x4000,0x0000
        DC16 0x2aaa,0x1294, 0x396b,0x0646, 0x3249,0x0c7c
       ...
*/
```

2. Then, in the main, include the *table_fft.h* file, which is a part of the DSP library.
3. Finally, go to the FFT function assembly code, and inverse the comment in the following lines:

```
ADRL    R0, TableFFT_V7   /* Coeff in Flash */
//LDR.W R0, =TableFFT       /* Coeff in RAM */
```

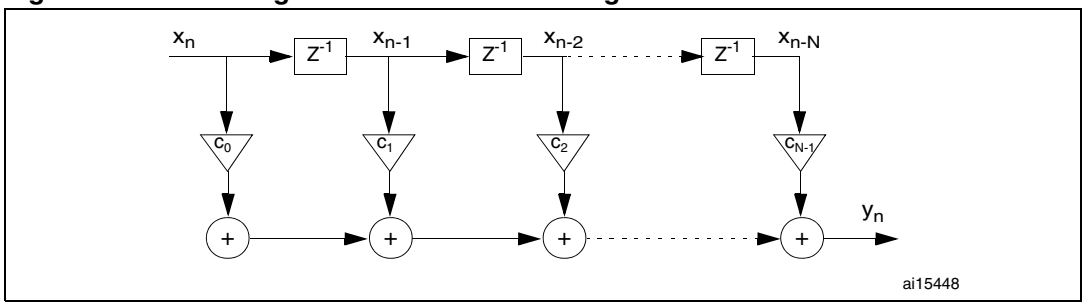
4 16-bit FIR filter

4.1 Description

The finite impulse filter (FIR) is a digital filter that is linearly dependent on a fixed finite number of input samples.

The FIR filter can be defined by the number of coefficients to be processed (also called taps), which gives the number of MAC (multiply-accumulate) operations to be done.

Figure 2. Block diagram of an FIR filter of length N



The FIR filter of the DSP library is a direct-form real FIR filter that uses an array of M 16-bit coefficients to filter N 16-bit samples.

Let us put:

- a, the output vector of length N
- c, the coefficients vector of length M
- x, the input vector

So, x must have a length of M + N – 1.

4.2 DSP library function

The FIR function of the DSP library is an optimized assembly function that takes into account the load-store architecture of the Cortex™-M3. Therefore, and as an optimization constraint, the number of taps and the number of output samples must be a multiple of 4.

4.2.1 `fir_16by16_stm32` function

Table 8 describes the `fir_16by16_stm32` function.

Table 8. `fir_16by16_stm32` function

Function name	`fir_16by16_stm32`
Prototype	`void fir_16by16_stm32(int *a,short *x,struct COEFS *p,unsigned int N)`
Behavior description	Block Fir 16-bit filter.
Input parameter	– a: output array – x: input array – p: pointer to the coefficient structure of the COEFS type – N: number of output samples
Output parameter	None
Return parameter	None

The filter coefficients and their number must be filled into a structure of the COEFS type.

The coefficients structure is defined as follows:

```
typedef struct {
  short *h;
  unsigned int nh;
}COEFS;
```

Example

```
#define M 32 /*number of coefficients*/
#define N 32 /*number of output samples*/

COEFS fir_coefs;/*coefficients structure*/

int a[N];/*filter output vector*/
short x[M+N-1] = {x0,x1...,xM+N-1};/*filter input vector*/
short h[M]={h0,h1...,hM-1};/*filter coefficients vector*/

fir_coefs.nh = M; /*Number of Coefficients for FIR*/
fir_coefs.h = h; /*Pointer on FIR coefficient vector*/

fir_16by16_stm32(a,x,&fir_coefs,N);/*performs the FIR filtering*/
```

5 16-bit IIR filters

5.1 Description

The infinite impulse response (IIR) filter is a digital filter that depends linearly on a finite number of input samples and a finite number of previous filter outputs.

The IIR filter is represented by *Equation 1* below.

Equation 1

$$y[n] = \sum_{i=0}^{M} b_i x[n-i] - \sum_{i=1}^{N} a_i y[n-i]$$

Equation 1 is known as an auto-regressive moving average form (ARMA). The first sum of *Equation 1* represents the moving average part, which is similar to an FIR block, and the second sum represents the auto-regressive part, which is the feedback from previous outputs.

This IIR filter structure is called direct form I.

Figure 3 shows the structure of the direct form I of a second-order IIR filter. Direct form I uses four delays to realize a second-order IIR filter.

To reduce the number of delays, the canonical form may be used. *Figure 4* represents the block diagram of the canonical form of a second-order IIR filter. The number of delays is reduced from 4 to only 2.

Figure 3. Block diagram of the direct form I of second-order IIR filter

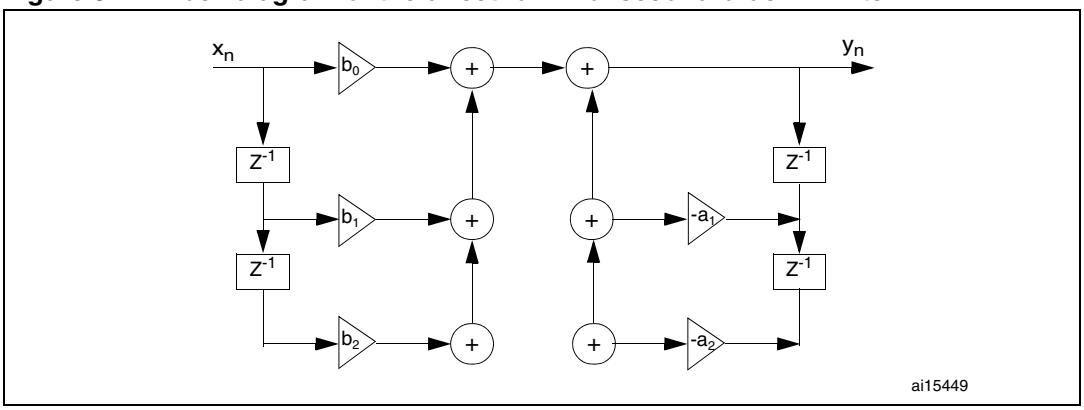
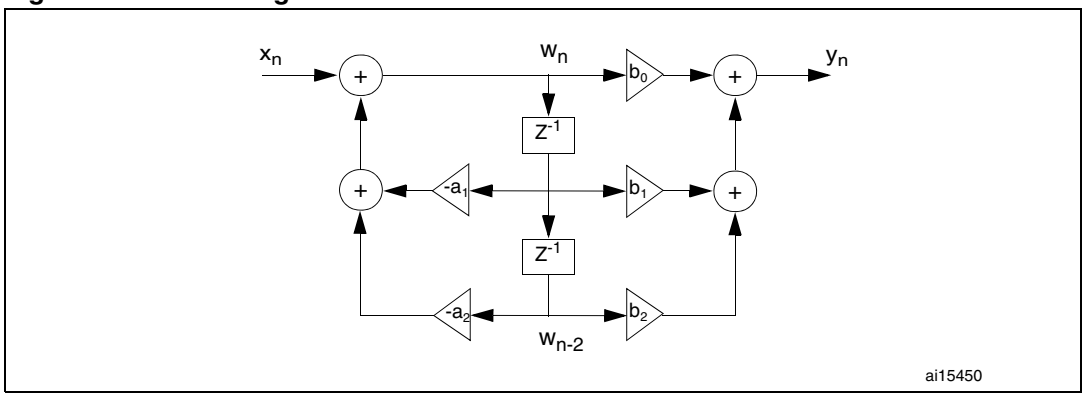


Figure 4. Block diagram of the canonical form of a second-order IIR filter



The DSP library implements the two forms (direct form I and the canonical form) of the IIR filter:

- Direct form I is used to design an IIR filter of order 4 (ARMA IIR)
- The canonical form is used to design an IIR filter of order 8, by using 4 second-order IIR filter sections (biquads) arranged in series (biquad IIR filter).

5.2 DSP library functions

The DSP library provides two IIR filters:

1. `iiarma_stm32`: an ARMA IIR filter, designed with 4 auto-regressive and 5 moving-average filter coefficients, so, in *Equation 1*, M = 4 and N = 4. The function code is written in assembly.
2. `iir_biquad_stm32`: a biquad IIR filter, designed by connecting 4 biquads in series. The function code is written in C.

5.2.1 `iiarma_stm32` function

Table 9 describes the `iirarma_stm32` function.

Table 9. `iirarma_stm32` function

Function name	`iirarma_stm32`
Prototype	`void iirarma_stm32(short *y, short *x, short *h2, short *h1, int ny)`
Behavior description	16-bit, auto-regressive moving-average IIR (ARMA) filter.
Input parameter	– y: output array of length ny+4 – x: input array of length ny+4 – h2: filter coefficient vector, moving-average part. – h1: filter coefficient vector, auto-regressive part. – ny: number of output samples
Output parameter	None
Return parameter	None

To use the `iirarma_stm32` function, the following conditions must be satisfied:

- The moving-average coefficient vector, h2, must have a length of 5 shorts:
  - `short h2[5];`
- The auto-regressive coefficient vector, h1, must have a length of 5 shorts. The h1[0] value is not used, so 4 coefficients remain:
  - `short h1[5];`
- The number of output samples, ny, must be a multiple of 4 greater than or equal to 8.
- Input and output vectors must have a length of (ny+4) shorts.
- The first four elements of the output vector must have the previous outputs.

Example

```
#define NY 32/*number of outputs, must be a multiple of 4 and >= 8*/
/* Coefficients for the ARMA IIR filter */
short h2[5] = { 0x09c2,  0x270a,  0x3a8f,  0x270a,  0x09c2 };
short h1[5] = { 0x7fff,  0xd24a,  0x72ca,  0xcf4e,  0x1ad4 };
/* Input and output vectors */
short x[NY+4],y[NY+4];

/* Fill the input vector x */
...
/* Fill the 4 previous outputs */
y[0] = y0;
y[1] = y1;
y[2] = y2;
y[3] = y3;
/* Improve the filtering of NY samples */
iirarma_stm32(y, x, h2, h1, NY);
```

5.2.2 `iir_biquad_stm32` function

Table 10 describes the `iir_biquad_stm32` function.

Table 10. `iir_biquad_stm32` function

Function name	iir_biquad_stm32
Prototype	`void iir_biquad_stm32(u16 *y, u16 *x, s16 *IIRCoeff, u16 ny)`
Behavior description	8th-order 4 biquad IIR filter
Input parameter	– y: output array – x: input array – IIRCoeff: IIR filter coefficients – ny: number of output samples
Output parameter	None
Return parameter	None

Example

```
#define NY 32/*number of outputs*/
/* Coefficients for the biquad IIR filter: 4 sections, with 5
coefficients in each section */
s16 Coeff[20] = {...};
/* Input and output vectors */
short x[NY],y[NY];
/* Fill the input vector x */
...
/* Improve the filtering of NY samples */
iir_biquad_stm32(y, x, Coeff, NY);
```

6 STM32F10xxx DSP library benchmark

This section provides the STM32F10xxx DSP library benchmark results, which are computed using the IAR EWARM 5.20 toolchain, with high-speed optimization.

6.1 Function code footprint

Table 11. STM32F10xxx DSP library functions code footprint

Function name	Code size (bytes)
DoPID	52
DoFullPID	58
PID_stm32	72
cr4_fft_64_stm32	718(1)
cr4_fft_256_stm32	1486(1)
cr4_fft_1024_stm32	4560(1)
fir_16by16_stm32	162
iiarma_stm32	156
iir_biquad_stm32	294

1. FFT code size was computed with FFT coefficients table stored in Flash memory. If the FFT coefficients are stored in SRAM, the code size of the three FFT functions is equal to 480 bytes.

6.2 Function execution time

6.2.1 PID controller

Table 12. PID controller, error computed outside the routine

PID	24 MHz 0 wait state		48 MHz 1 wait state		72 MHz 2 wait states	
	cycle count	time	cycle count	time	cycle count	time
ASM function	45	1.87 µs	51	1.06 µs	59	0.819 µs
C function	47	1.96 µs	50	1.04 µs	54	0.75 µs

Analysis of the PID timing shows that assembly code is not as fast as C code. The compiler is more efficient in accessing variables than manual optimization (offset computation and data placement in literal pool).

Table 13. PID controller, error computed within the routine

PID	24 MHz 0 wait state		48 MHz 1 wait state		72 MHz 2 wait states	
	cycle count	time	cycle count	time	cycle count	time
C function	48	2 µs	52	1.08 µs	57	0.79 µs

6.2.2 Fast Fourier transform (FFT)

Table 14. Complex radix 4, 16-bit FFT, coefficients in Flash memory

FFT (ASM funct.)	24 MHz 0 wait state		48 MHz 1 wait state		72 MHz 2 wait states	
	cycle count	time	cycle count	time	cycle count	time
64 points	3847	0.16 ms	4 472	0.093 ms	5 661	0.078 ms
256 points	21 039	0.876 ms	24 964	0.52 ms	31 527	0.437 ms
1024 points	100 180	4.174 ms	114 350	2.382 ms	153 930	2.138 ms

Table 15. Complex radix 4, 16-bit FFT, coefficients in RAM

FFT (ASM funct.)	24 MHz 0 wait state		48 MHz 1 wait state		72 MHz 2 wait states	
	cycle count	time	cycle count	time	cycle count	time
64 points	3 847	0.16 ms	4 025	0.084 ms	4 764	0.066 ms
256 points	21 039	0.876 ms	22 176	0.462 ms	26 065	0.362 ms
1024 points	100 180	4.174 ms	102 057	2.126 ms	127 318	1.768 ms

6.2.3 FIR filter

Table 16. 16-bit, 32-tap FIR filter

FIR (ASM filter)	24 MHz 0 wait state		48 MHz 1 wait state		72 MHz 2 wait states	
	cycle count	time	cycle count	time	cycle count	time
32 samples	3516	146.5 µs	3525	73.4 µs	3727	51.76 µs

6.2.4 IIR filters

Table 17. 16-bit canonic form, 4 biquad IIR filter

IIR (C filter)	24 MHz 0 wait state		48 MHz 1 wait state		72 MHz 2 wait states	
	cycle count	time	cycle count	time	cycle count	time
32 samples	3478	144.9 µs	3636	75.75 µs	3929	54.57 µs

Table 18. 16-bit direct-form I, 8th-order IIR filter

IIR (ASM filter)	24 MHz 0 wait state		48 MHz 1 wait state		72 MHz 2 wait states	
	cycle count	time	cycle count	time	cycle count	time
32 samples	1696	70 µs	1761	36.69 µs	1986	27.58 µs

7 Conclusion

This user manual describes the STM32F10xxx DSP library, which contains:

- a PID controller
- complex 16-bit radix-4 FFT optimized functions for 64, 256 and 1024 points
- a 16-bit FIR filter
- a 16-bit direct-form I IIR filter
- a 16-bit canonical-form IIR filter designed by biquads

8 Revision history

Table 19. Document revision history

Date	Revision	Changes
13-Oct-2008	1	Initial release.

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