

RL78 Family

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Digital Signal Controller Library - Filter

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Introduction

This document presents the specifications for a Digital Signal Controller Library (DSCL) function library for the Renesas RL78 which includes generic specifications, detailed specifications for filter algorithm kernels and guidelines for the DSCL Library API. In this document, the word *kernel* refers to a common DSCL function such as FIR filter. In the DSCL library, several different C-language function calls may be associated with a single DSP kernel. To avoid confusion, the word *kernel* refers to the DSP algorithm, including the collection of functions that implement the DSP algorithm in the DSCL Library. Specific DSCL Library function names are used to refer to individual functions. The specification of this application is similar to RX DSP library V1.0, thus newer versions of RX DSP Library may have different specifications.

Target Device

RL78 core S3 - Unspecified

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1. DSCL Library Kernels

Filter kernels defined in this document include:

1. Generic FIR
2. IIR Biquad
3. Single-pole IIR

1.1 List of Abbreviations and Acronyms

Abbreviation	Full Form
DSC	Digital Signal Controller
DSP	Digital Signal Processor
FIR	Finite Impulse Response
GPIO	General Purpose I/O
I/O	Input/Output
LSB	Least Significant Bit
MSB	Most Significant Bit

1.2 DSCL Library Build information

1.2.1 Tool Chain Information

The DSCL Library was built and tested using the following:

- CubeSuite+ Version 1.02.00; Build tool: CA78K0R (V1.40)
- IAR Embedded Workbench for Renesas RL78 Version 1.40.1; Build tool: IAR Compiler (V1.40.1.x)

2. DSCL Library API

In this document we outline aspects of the Renesas DSCL Library API design that are common to all functions within the DSCL Library.

2.1 Terminology

In this document we use the word “kernel” to refer to a DSP algorithm (or a variant of a DSP algorithm) implemented in the DSCL library. We use the word “function” to refer to a single, specific function call in the DSCL library API. Note that a kernel’s implementation may require multiple functions. For example, a filter kernel typically requires one or more functions for initialization and/or other housekeeping tasks, and a main function for the filter processing.

2.2 Data structures

The library will define the following categories of data structures:

- Vectors
- Algorithm kernel handles

2.2.1 Vectors

Vector data structures contain vector dimensions, and a pointer to the actual array of data:

```
typedef struct
{
    uint32_t n;
    void *data;
} vector_t;
```

Note: the user is responsible for allocating buffer memory for the vector data. In addition, because the “data” member of the vector structure is declared as (void *), there is no need for separate vector structures for the different data types supported by the library.

2.2.2 Algorithm kernel handles

For kernel functions that require state information, constant data, and/or various run-time parameters, all such data is aggregated in a “handle” data structure specific to the kernel function (or class of functions, e.g. transforms). For example, an FIR filter handle may be defined as follows:

```
typedef struct
{
    uint16_t taps;        // number of filter taps
    void *coefs;         // pointer to filter coefficients
    void *state;         // pointer to filter state data, including
                        // the filter's delay line and any other
                        // implementation-dependent state
    uint16_t options;    // option flags that may specify rounding,
                        // saturation, or other behaviors
} r_dscl_firfilter_t;
```

Note: the handle data structure contains only members that need to be visible to the user. Some kernels may need to maintain additional implementation-specific states.

All members of kernel “handle” data structures must be initialized by the user. This includes pointers to coefficient and/or state memory. Coefficient and/or state memory must be allocated by the user. Some DSP kernels have implementation-dependent memory requirements for the state and/or coefficients. In such cases, API functions are provided that return the amount of memory to be allocated, given the desired parameters for the kernel.

Also note that many functions will have to perform run-time checks on handle structure members such as ‘*options*,’ in order to branch to the appropriate implementation of the kernel for the given parameters. To ensure that the most common implementation selections accrue the smallest overhead from these run-time checks, a default value of NULL is defined wherever possible. The default value provides the most common desired behavior (often the fastest possible implementation of the kernel).

Kernel parameters supplied in a handle structure must not be changed by the user without re-initializing the kernel. For example, changing the rounding mode or number of taps of an FIR filter “on the fly” is prohibited. When changing such kernel parameters, users must ensure that sufficient memory is allocated for the kernel’s internal state, given the new parameters, and must re-initialize the kernel. Note that this restriction does not apply to changes to filter coefficient values. Filter coefficients can be always changed “on the fly.”

2.3 Function arguments

All functions accept arguments in the following order:

<handle>: a pointer to a kernel handle data structure containing kernel-specific state, coefficients, parameters, and options.

<input1>...<inputN>: one or more input arguments passed as pointers for most data types, except scalar data. Scalar data values may be passed directly.

<output1>...<outputN>: one or more output pointers

<additional options>: any kernel parameters or options that are not included in the kernel handle data structure.

Note: a function call may not include all of the above elements. For example a FIR filter initialization function does not have inputs or outputs.

Most functions return a 16-bit integer result. The integer result may contain an error code or other information required for application housekeeping tasks. For example, the return value may indicate the amount of memory that the user must allocate for a kernel's internal state, or may indicate the occurrence of kernel-specific special conditions. Exceptions to this rule occur where functions compute a single real-valued scalar result, and no error conditions can occur. In such cases, the result may be returned by the function instead of a status code.

Functions whose return value indicates the amount of memory that the user must allocate for some task may also return a negative value to indicate an error condition (see section 2.4 Error handling). Since C99, the *malloc()* function expects *size_t*, which is an unsigned data type. The actual bit-width of *size_t* is platform dependent. Therefore, care must be taken to ensure that a valid (non-error) result has been returned by the DSCL Library function before passing the result to *malloc()*.

In summary, most function calls have the following format:

```
int16_t <status/size> = function(<handle>, <input1>, ..., <inputN>, <output1>, ..., <outputN>, <additional options>);
```

Where most functions will include only a subset of the above argument classes.

2.4 Error handling

All functions perform checks on input arguments and kernel parameters to the greatest extent possible. Most functions return a 16-bit integer status code. Functions that return the size of a kernel's internal state (for memory allocation purposes) are a noteworthy exception. For example, the *R_DSCL_FIR_stateSize_i16i16* functions fall in this latter category.

All functions return a negative integer value to indicate an error condition. Specific error conditions are assigned unique negative integer values specified on a per-function basis. Functions may return zero for success, or may return a positive integer value to indicate non-error result or special condition. For example, the *R_DSCL_FIR_stateSize_i16i16* functions return the memory size requirement for the FIR filter's state. Other functions may return positive integer values indicating special non-error conditions such as the occurrence of overflow.

Functions that return a memory size result for memory allocation purposes may return zero if no memory is required for the given kernel parameters.

Note the distinction between error and status conditions: error conditions (declared with *R_DSCL_ERR_<description>*) always have a negative integer value and indicate conditions that prevent operation of a kernel, e.g. a NULL input pointer. In contrast, status conditions (declared with *R_DSCL_STATUS_<description>*) have positive integer values (or zero for *R_DSCL_STATUS_OK*) and indicate conditions that may impact the kernel's output, but do not prevent the arithmetic operations of the kernel from proceeding. For example, arithmetic overflow is indicated with a status condition. Thus, status conditions can be ignored in some applications, while error conditions always require attention. The assignment of negative values to error codes and positive (or zero) values to status codes allows the user's code to easily distinguish between these two types of conditions.

Error and status codes will be defined by an *enum* declaration in the header file *r_dscl_types.h*.

The following common formats will be used for error codes of all functions:

R_DSCL_STATUS_OK: No issues encountered. This code has a value of zero.

R_DSCL_ERR_<pointer>_NULL: A null pointer was encountered by the function. <pointer> names the offending pointer, e.g. *R_DSCL_ERR_INPUT_NULL* means that the pointer to an input argument is null. If *input* is a vector or matrix, this code would also be used if the data pointer within the vector/matrix struct is null.

R_DSCL_ERR_INVALID_<x>: an option or parameter passed to the function (via a handle or directly) is not supported by the implementation. <x> identifies the offending function argument, kernel parameter, or struct member. For example, if a filter's handle structure has an 'options' member that specified rounding modes, and this member has an unsupported value, then the R_DSCL_ERR_INVALID_OPTIONS code would be used.

In addition, some function-specific error and status codes are defined. The error and status codes defined in Phase 1 of the DSCL library specification include:

R_DSCL_STATUS_OK = Status Ok, no issues encountered.

R_DSCL_ERR_HANDLE_NULL = If the pointer to the handle is NULL.

R_DSCL_ERR_INPUT_NULL = If the pointer to the input vector or the data therein is NULL.

R_DSCL_ERR_OUTPUT_NULL = If the pointer to the output vector or the data therein is NULL.

R_DSCL_ERR_STATE_NULL = If the pointer to the FIR or IIR filter internal state is NULL.

R_DSCL_ERR_COEFF_NULL = If the pointer to the coefficient array is NULL.

R_DSCL_ERR_INVALID_TAPS = The number of filter taps is zero or is not supported by the implementation.

R_DSCL_ERR_INVALID_STAGES = The number of filter stages is zero or is not supported by the implementation.

R_DSCL_ERR_INVALID_OPTIONS = *options* value in *handle* specified a mode not currently supported.

2.5 Rounding Support

Some kernels in the DSCL Library provide support for multiple rounding mode. These modes apply to the fixed-point data types.

Rounding modes are supported via an *options* element in the kernel's handle structure. The following bit-fields in *options* are reserved for rounding and saturation modes:

- Bits 0-2: rounding mode
 - R_DSCL_ROUNDING_DEFAULT = 0
 - R_DSCL_ROUNDING_TRUNC = 1
 - R_DSCL_ROUNDING_NEAREST = 2
 - reserved = 3-7
- **Note:** R_DSCL_ROUNDING_DEFAULT is the default behaviors of the kernels. For all the filter types in the library, the default behavior is the truncation.

3. Filter Function API

This section covers the filter functions implemented in the RL78 DSCL Library.

3.1 FIR Data Structure Definition

The FIR kernel uses a handle to the filter of type `r_dscl_firfilter_t`. This handle is passed as part of the call to the filter. The data structure for the handle type is as follows:

```
typedef struct
{
    uint16_t    taps; // number of filter taps
    void *      coefs; // pointer to filter coefficients
    void *      state; // pointer to filter state data, including the filter's
delay line
                // and any other implementation-dependent state
    uint16_t    options; // options that specify rounding, saturation, or other
behaviors
} r_dscl_firfilter_t;
```

Each member of the data structure is explained below:

taps = Number of filter taps

coefs = Pointer to the coefficient vector (must be the same data type as the input vector). The content of this array is maintained by the user.

state = Pointer to the internal state of the filter, including the delay line and any other implementation-dependent state. The memory for the internal state is allocated by the user and the content of the internal state is maintained by the kernel.

options = A bit-mapped parameter controlling options. See “Rounding Support” in software overview section, for the definition of available modes.

3.2 FIR Initialize API

This is a function used to initialize the filter state (including zeroing the delay line and other parameters), given the options specified in the handle. It must be called once prior to invoking the run-time calling function.

Format

```
int16_t R_DSCL_FIR_Init_i16i16 (r_dscl_firfilter_t * handle)
```

Parameters

handle Pointer to an instance of the `r_dscl_firfilter_t` data structure.

handle → *state* Pointer to the starting address of delay line, which shall be on the same array as the input data.

Return Values

R_DSCL_STATUS_OK = Status OK, no issues encountered.

R_DSCL_ERR_HANDLE_NULL = Pointers to the handle is NULL.

R_DSCL_ERR_STATE_NULL = Pointer to delay-line, is NULL.

R_DSCL_ERR_INVALID_TAPS = Number of taps is 0.

R_DSCL_ERR_INVALID_OPTIONS = options value in handle specified a mode not currently supported.

Others = Reserved.

NOTE: This function initializes only the contents of the FIR state pointed to by the state element of the handle structure. It does not initialize the filter coefficients or any other contents of the handle structure, which must be initialized separately.

Example

Since this function is not used by itself, see FIR filter example for the use of this in Context.

Restrictions

Handle must have already been instantiated. See FIR example for more details.

3.3 FIR Filter API

The block finite impulse response (FIR) filter kernel operates on a user selectable number of input samples and produces the same number of output samples each time it is invoked.

Format

```
int16_t R_DSCL_FIR_i16i16 (const r_dscl_firfilter_t * handle, const vector_t *
input, vector_t * output)
```

Parameters

<i>handle</i>	Pointer to an instance of the <code>r_dscl_firfilter_t</code> data structure.
<i>input</i>	Pointer to an instance of <code>vector_t</code> data structure for the input data. Neither the instance nor the actual input data will be altered by the function.
<i>input→n</i>	Number of input samples to be processed by the function. This value must be set before the function call.
<i>input→data</i>	Pointer to starting address of the input data. This pointer must be set before the function call.
<i>output</i>	Pointer to an instance of <code>vector_t</code> data structure for the output data. Both the instance and the actual output data will be altered by the function.
<i>output→n</i>	Number of output samples produced by the function. This value will be filled by the function.
<i>output→data</i>	Pointer to the output data buffer. This pointer must be set before the function call. The output data buffer will be filled by the function.

Return Values

R_DSCL_STATUS_OK = Status OK, no issues encountered.

R_DSCL_ERR_HANDLE_NULL = If the pointer to the handle is NULL.

R_DSCL_ERR_INPUT_NULL = If the pointer to the input vector or the data therein is NULL.

R_DSCL_ERR_OUTPUT_NULL = If the pointer to the output vector or the data therein is NULL.

R_DSCL_ERR_STATE_NULL = If the pointer to the filter internal state is NULL.

R_DSCL_ERR_COEFF_NULL = If the pointer to the coefficient array is NULL.

R_DSCL_ERR_INVALID_TAPS = The number of filter taps is zero.

R_DSCL_ERR_INVALID_OPTIONS = options value in handle specified a mode not currently supported.

Others = Reserved.

Description

The Block FIR filter kernels implement a finite impulse response filter on each input sample. The following equation shows the general structure of a T-tap FIR filter where h represents the coefficients, x represents the input data, and y represents the output data.

$$y(n) = \sum_{i=0}^{T-1} h(i) * x(n - i)$$

Each output sample is the result of performing FIR filter of n taps. This is shown graphically in **Figure 1**.

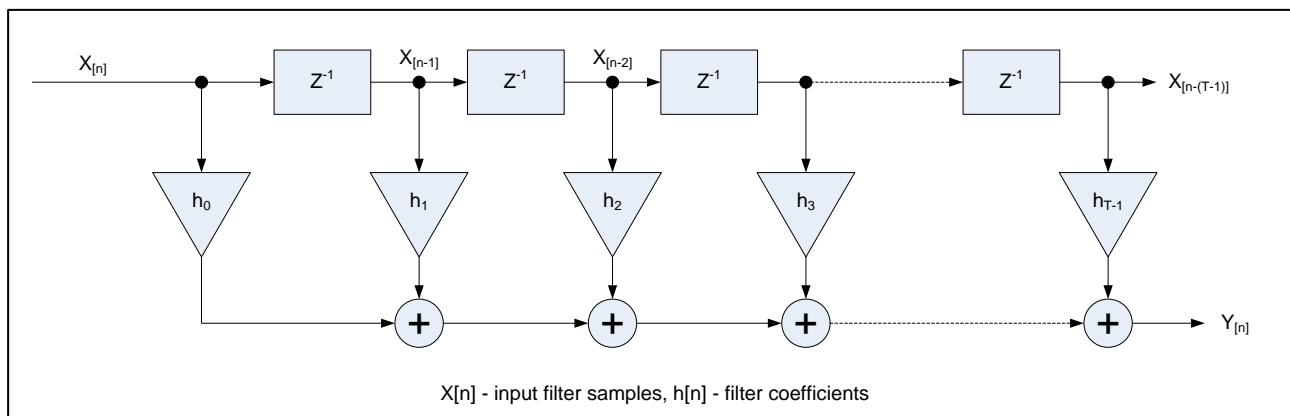


Figure 1: FIR Filter

Fixed-point Behavior

Since the function is implemented by fixed point, the behavior of fixed point must be taken care. Following issues must be considered:

- Scaling
- Overflow

Scaling: The scaling factor “*FIR_SCALE_A*” for the output data is defined in “*r_dscl_filter_asm.inc*”. Results are right-shifted by scale prior to writing the output to memory.

The scale must be equal to the number of fraction bits of coefficient. For example:

If the filter coefficients are in Q4.12 format and the filter’s input is in Q2.14 format, then the accumulated result for each output sample is in Q6.26 format. The scale value of 12 should be set, such that it will perform the required conversion by discarding 12 LSBs of the accumulated result, leaving 14 fractional bits in the final output word.

The default value of this scaling factor is 15. If the value is changed, the library needs to be compiled again.

Overflow: The function is optimized for speed at the cost of precision and overflow protection. It’s implemented by using a sequence of multiply-accumulate operations. The accumulator is just 32 bit, overflows may happen. After accumulations, the final result is converted to 16 bit, precision is also lost. To avoid overflows completely, the input data must be scaled down by $\log_2(\text{taps})$ bits (Maximum is 15 bits).

Example

The following is an example showing initialization and run-time usage for the FIR Filter.

```
#define NUM_TAPS          (64)
#define NUM_SAMPLES      (200)

r_dscl_firfilter_t  myFilterHandle;    // instantiate a handle for this filter
vector_t           myInput;           // See introduction section describing
the API document
vector_t           myOutput;          // for a definition of the "vector_t"
data type.

// Coefficients should be stored in time-reversed order
int16_t            myCoeffs[NUM_TAPS] = {...};

// The input data buffer should contain previous (T-1) input samples (i.e.
delay line)
// contiguous with the present (N) input samples
int16_t            inputData[NUM_TAPS - 1 + NUM_SAMPLES];
int16_t            outputData[NUM_SAMPLES];
int16_t            myFIRFlags;

/*----- Set up the FIR filter -----*/
myFilterHandle.taps = NUM_TAPS;
myFilterHandle.options = 0; // default

/* No need to call StateSize API for FIR */
myFilterHandle.state = (void *)&inputData[0]; // starting address of
delayline

/*----- Initialize the coefficients and internal state -----*/
myFilterHandle.coefs = (void *)myCoeffs;
myFIRFlags = R_DSCL_FIR_Init_i16i16(&myFilterHandle);

/*----- Set up the input/output -----*/
myInput.n = NUM_SAMPLES;
myInput.data = (void *)&inputData[NUM_TAPS - 1]; // starting address of
current input block
myOutput.data = (void *)outputData;
/*----- Wait for input data -----*/
/*----- Main library function call -----*/
myFIRFlags = R_DSCL_FIR_i16i16 (&myFilterHandle, &myInput, &myOutput);

/*----- Output data are now ready -----
* Note: At this point myOutput.n holds the number of output samples generated
by
* the library, where the data are written to the array pointed to by
myOutput.data.
*-----*/
```

Processing Flow

The example above just gives an example to do all the filter sample once, in this case, the input buffer and output buffer should be sufficient to hold all the data, if not, we need to filter the input sample into several times. The processing flow is shown in **Figure 2**, including the setting of scaling factor.

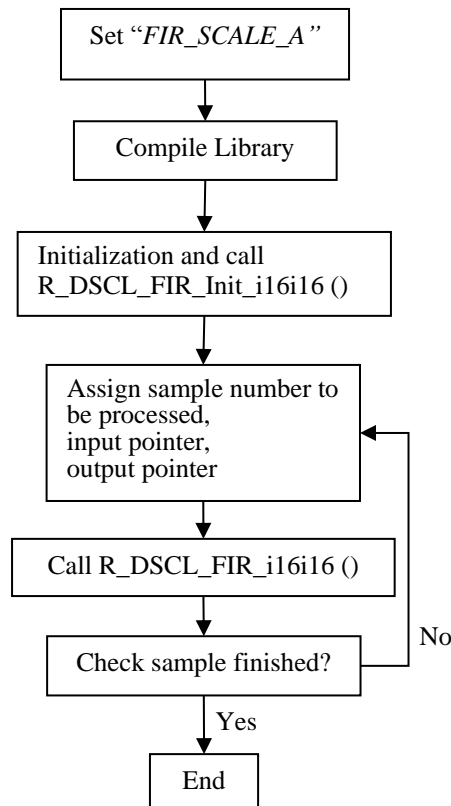


Figure 2: Processing flow

Restrictions

The number of taps in the coefficient vector must match that specified in the filter handle.

3.4 IIR Biquad Data Structure Definition

The following is the definition of the filter handle `r_dscl_iirbiquad_t`.

```
typedef struct
{
    uint16_t    stages;        // number of biquad stages
    void *      coefs;         // pointer to filter coefficients
    void *      state;         // pointer to filter's internal state (delay line)
    uint16_t    options;       // options that specify rounding, saturation, or other behaviors
} r_dscl_iirbiquad_t;
```

Each member of the data structure is explained below:

stages = Number of biquad stages

coefs = Pointer to the coefficient vector (must be the same data type as the input vector). The content of this array is maintained by the user.

state = Pointer to the internal state of the filter, including the delay line and any other implementation-dependent state. The memory for the internal state is allocated by the user and the content of the internal state is maintained by the kernel.

options = A bit-mapped parameter controlling options. See “Rounding Support” section, for the definition of available modes.

3.5 IIR Biquad State Size API

This is a “maintenance” function for the IIR filters. This function returns the size (in bytes) that must be allocated by the user to maintain the internal state (including the delay line) of the filter.

Format

```
int16_t R_DSCL_IIRBiquad_StateSize_i16i16 (const r_dscl_iirbiquad_t * handle)
```

Parameters

handle Pointer to an instance of the `r_dscl_iirbiquad_t` data structure.

Return Values

Buffer Size in Bytes (type `int16_t`) required by the filter.

Note: The size returned should allow the implementer to use this buffer to maintain any private information associated with the filter including items such as pointers, a record of input and output data types, etc. Also the size returned by this function does not include the filter handle, nor does it include the coefficient array.

Description

The function can be used as part of the filter initialization to decide the buffer size a user must allocate. Alternatively, the user can use this function to determine the required memory size during development, and allocate a static array of that size for the internal state (for example, in the faster on-chip RAM).

Note: Since C99, the `malloc()` function expects `size_t`, which is an unsigned data type. The actual bit-width of `size_t` is platform dependent. If `malloc(R_DSCL_IIRBiquad_StateSize_i16i16())` is used to allocate the memory for the internal state, and `R_DSCL_IIRBiquad_StateSize_i16i16()` returns a negative value, unexpected behavior could happen.

Example

Since this function is not used by itself, see IIR filter example for the use of this in Context.

Restrictions

IIRHandle must have already been instantiated. See IIR example for more details.

3.6 IIR Biquad Initialize API

This is a function used to initialize the filter state (including zeroing the delay line and other parameters), given the options specified in the handle. It must be called once prior to invoking the run-time calling function.

Format

```
int16_t R_DSCL_IIRBiquad_Init_i16i16 (r_dscl_iirbiquad_t * handle)
```

Parameters

handle Pointer to an instance of the `r_dscl_iirbiquad_t` data structure.

Return Values

`R_DSCL_STATUS_OK` = Status OK, no issues encountered.

`R_DSCL_ERR_HANDLE_NULL` = Pointers to the handle is NULL.

`R_DSCL_ERR_STATE_NULL` = Pointer to delay-line, is NULL.

`R_DSCL_ERR_INVALID_STAGES` = Number of biquad stages is 0.

`R_DSCL_ERR_INVALID_OPTIONS` = options value in handle specified a mode not currently supported.

Others = Reserved.

NOTE: This function initializes only the contents of the IIR state pointed to by the state element of the handle structure. It does not initialize the filter coefficients or any other contents of the handle structure, which must be initialized separately.

Description

This is a function used to initialize the filter state (including zeroing the delay line and possibly other implementation-dependent parameters). It must be called once prior to invoking the run-time calling function.

Example

Since this function is not used by itself, see IIR filter example for the use of this in Context.

Restrictions

IIRHandle must have already been instantiated. See IIR example for more details.

3.7 IIR Biquad Filter API

This kernel implements the IIR (Infinite Impulse Response) filter in the form of cascaded biquads. A biquad is a section of the 2nd-order IIR filter. For higher order IIR filters, cascaded biquads often generate smaller numerical errors than a direct-form implementation.

A biquad can have many forms, such as direct-forms I and II, transposed direct-forms I and II. Each has its advantages and disadvantages. The IIR biquad API is designed by using direct-forms I.

This kernel operates on a user selectable number of input samples and produces the same number of output samples each time it is invoked. The number of cascaded biquads is also selectable by the user.

FORMAT

```
int16_t R_DSCL_IIRBiquad_i16i16 (const r_dscl_iirbiquad_t * handle, const
vector_t * input, vector_t * output)
```

Parameters

<i>handle</i>	Pointer to an instance of the <code>r_dscl_iirbiquad_t</code> data structure.
<i>input</i>	Pointer to an instance of <code>vector_t</code> data structure for the input data. Neither the instance nor the actual input data will be altered by the function.
<i>input→n</i>	Number of input samples to be processed by the function. This value must be set before the function call.
<i>input→data</i>	Pointer to the input data buffer. This pointer must be set before the function call.
<i>output</i>	Pointer to an instance of <code>vector_t</code> data structure for the output data. Both the instance and the actual output data will be altered by the function.
<i>output→n</i>	Number of output samples produced by the function. This value will be filled by the function.
<i>output→data</i>	Pointer to the output data buffer. This pointer must be set before the function call. The output data buffer will be filled by the function.

Return Values

`R_DSCL_STATUS_OK` = Status OK, no issues encountered.

`R_DSCL_ERR_HANDLE_NULL` = If the pointer to the handle is NULL.

`R_DSCL_ERR_INPUT_NULL` = If the pointer to the input vector or the data therein is NULL.

`R_DSCL_ERR_OUTPUT_NULL` = If the pointer to the output vector or the data therein is NULL.

`R_DSCL_ERR_STATE_NULL` = If the pointer to the filter internal state is NULL.

`R_DSCL_ERR_COEFF_NULL` = If the pointer to the coefficient array is NULL.

`R_DSCL_ERR_INVALID_STAGES` = Number of biquad stages is 0.

`R_DSCL_ERR_INVALID_OPTIONS` = options value in handle specified a mode not currently supported.

Others = Reserved.

Description

The IIR biquad filter is in the form of cascaded biquads. Each biquad is a section of the 2nd-order IIR filter with the following equation between its input and output:

$$y(n) = b_0 * x(n) + b_1 * x(n - 1) + b_2 * x(n - 2) - a_1 * y(n - 1) - a_2 * y(n - 2)$$

where $y(n)$ is the output sample, $x(n)$ is the input sample, $y(n-1)$ and $x(n-1)$ are output and input samples delayed by one sampling period, respectively, $y(n-2)$ and $x(n-2)$ are output and input samples delayed by two sampling periods, respectively, b_0 , b_1 , and b_2 are feed forward coefficients, and a_1 and a_2 are feedback coefficients.

The overall transfer function is as below:

$$H(z) = \prod_0^{N-1} \frac{b_0 + b_1z^{-1} + b_2z^{-2}}{1 + a_1z^{-1} + a_2z^{-2}}$$

where N is the number of cascaded biquad stages. Note that each stage has a different set of coefficients b0, b1, b2, a1, and a2.

Figure 3 shows the diagram of IIR biquad Direct Form I.

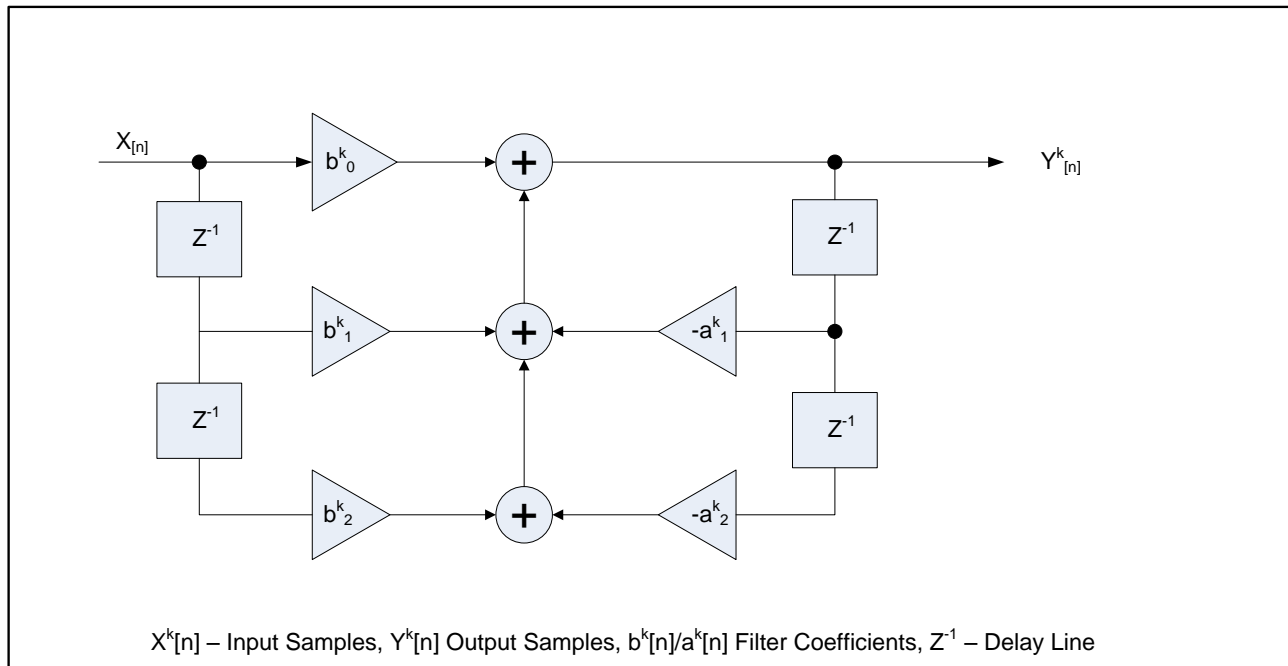


Figure 3: IIR Bi-Quad, Direct Form I

Fixed-point Behavior

Since the function is implemented by fixed point, the behavior of fixed point must be taken care. Following issues must be considered:

- Scaling
- Overflow

Scaling: The scaling factor “IIR_BQ_SCALE_A” for the output data is defined in “r_dscl_filter_asm.inc”. Results are right-shifted by scale prior to writing the output to memory.

The scale must be equal to the number of fraction bits of coefficient. For example:

If the filter coefficients are in Q4.12 format and the filter’s input is in Q2.14 format, then the accumulated result for each output sample is in Q6.26 format. The scale value of 12 should be set, such that it will perform the required conversion by discarding 12 LSBs of the accumulated result, leaving 14 fractional bits in the final output word.

The default value of this scaling factor is 14. This means the coefficients can represent the value in the range of [-2, 2). If all the coefficients values are in the range of [-1, 1), the scaling factor can be changed to 15. To do this, the library needs to be compiled again.

Overflow: The function is optimized for speed at the cost of precision and overflow protection. It’s implemented by using a sequence of multiply-accumulate operations. The accumulator is just 32 bit, overflows may happen. After accumulations, the final result is converted to 16 bit, precision is also lost. To avoid overflows completely, the input data must be scaled down by 3 bits (Maximum is 15 bits).

Example

The following is an example showing how to use IIR biquad function.

```
#define NUM_TAPS_PER_BIQUAD      (5)
#define NUM_BIQUAD_STAGES      (3)
r_dscl_iirbiquad_t      myFilterHandle; // instantiate a handle for my use
vector_t              myInput;        // See introduction section API section
vector_t              myOutput;       // for a definition of the "vector_t"
data type
int16_t               myCoeffs[NUM_TAPS_PER_BIQUAD * NUM_BIQUAD_STAGES]
                      = {b0, b1, b2, a1, a2,...};
int16_t               myDLine[NUM_TAPS_PER_BIQUAD * NUM_BIQUAD_STAGES];
int16_t               inputData[NUM_SAMPLES];
int16_t               outputData[NUM_SAMPLES];
int16_t               myIIRFlags;
int16_t               dynMemSize, staMemSize;

/*----- Set up the IIR filter biquads -----*/
myFilterHandle.stages = NUM_BIQUAD_STAGES;

/* Setup data format and options */
myFilterHandle.options = 0; // default

/* !!! It is important to setup the stages and the form before */
/* !!! calling function R_DSCL_IIRBiquad_StateSize_il6il6 () */
staMemSize = NUM_TAPS_PER_BIQUAD * NUM_BIQUAD_STAGES * sizeof(int16_t);
dynMemSize = R_DSCL_IIRBiquad_StateSize_il6il6(&myFilterHandle);
if (staMemSize >= dynMemSize)
{
    myFilterHandle.state = (void *)myDLine; // probably more common
}
else
{
    myFilterHandle.state = malloc((size_t) dynMemSize); //malloc expects size_t
}
/* Initialize the coefficients and internal state */
myFilterHandle.coefs = (void *)myCoeffs;
myIIRFlags = R_DSCL_IIRBiquad_Init_il6il6(&myFilterHandle);
/*----- Set up the input/output -----*/
myInput.n = NUM_SAMPLES;
myInput.data = (void *)inputData;
myOutput.data = (void *)outputData;
/*----- Wait for input data -----*/
/*----- Main library function call -----*/
myIIRFlags = R_DSCL_IIRBiquad_il6il6(&myFilterHandle, &myInput, &myOutput);
/*----- Output data are now ready -----*/
/* Note: At this point myOutput.n holds the number of output samples generated
by
* the library, where the data are written to the array pointed to by
myOutput.data.
*-----*/
```

Processing Flow

The example above just gives an example to do all the filter sample once, in this case, the input buffer and output buffer should sufficient to hold all the data, if not, we need to filter the input sample into several times. The processing flow is shown in **Figure 4**, including the setting of scaling factor.

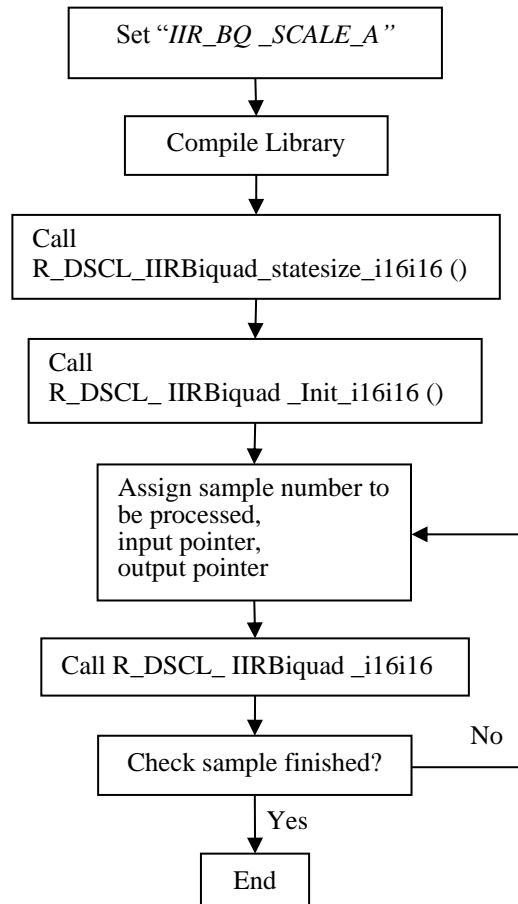


Figure 4: Processing flow

Restrictions

The length of the delay line depends on the number of cascaded stages. Therefore this parameter must be set before the function call to `R_DSCL_IIRBiquad_StateSize_i16i16 ()`.

3.8 Single Pole IIR Data Structure Definition

The following is the definition of the filter handle `r_dscl_iirsinglepole_t`, which is used for all variants of the single-pole filter kernel.

```
typedef struct
{
    void *      coefs;          // pointer to filter coefficient
    void *      state;         // pointer to filter's internal state (delay
line)
    uint16_t    options;       // options that specify rounding, saturation,
or other behaviors
} r_dscl_iirsinglepole_t;
```

Each member of the data structure is explained below:

coefs = Pointer to the coefficient of the feedback tap (must be the same data type as the input). The coefficient is maintained by the user.

state = Pointer to the state of the feedback tap. The state is maintained by the kernel.

options = A bit-mapped parameter controlling options. See “Rounding Support” section, for the definition of available modes.

3.9 Single-Pole IIR Filter API

This kernel implements the single-pole filter, which is an IIR (Infinite Impulse Response) filter with one feedback tap. The maximum gain is unity.

Format

```
int16_t R_DSCL_IIRSinglePole_i16i16 ( const r_dscl_iirsinglepole_t * handle,
const vector_t * input, vector_t * output)
```

Parameters

<i>handle</i>	Pointer to an instance of the <code>r_dscl_iirsinglepole_t</code> data structure.
<i>input</i>	Pointer to an instance of <code>vector_t</code> data structure for the input data. Neither the instance nor the actual input data will be altered by the function.
<i>input→n</i>	Number of input samples to be processed by the function. This value must be set before the function call.
<i>input→data</i>	Pointer to the input data buffer. This pointer must be set before the function call.
<i>output</i>	Pointer to an instance of <code>vector_t</code> data structure for the output data. Both the instance and the actual output data will be altered by the function.
<i>output→n</i>	Number of output samples produced by the function. This value will be filled by the function.
<i>output→data</i>	Pointer to the output data buffer. This pointer must be set before the function call. The output data buffer will be filled by the function.

Return Values

R_DSCL_STATUS_OK = Status OK, no issues encountered.

R_DSCL_ERR_HANDLE_NULL = If the pointer to the handle is NULL.

R_DSCL_ERR_INPUT_NULL = If the pointer to the input vector or the data therein is NULL.

R_DSCL_ERR_OUTPUT_NULL = If the pointer to the output vector or the data therein is NULL.

R_DSCL_ERR_INVALID_OPTIONS = options value in handle specified a mode not currently supported.

Others = Reserved.

Note: this kernel does not provide an init function. It is the user's responsibility to initialize the internal state to 0.

Description

The single-pole IIR filter is shown graphically in Figure 5 and Figure 6, low-pass and high pass respectively.

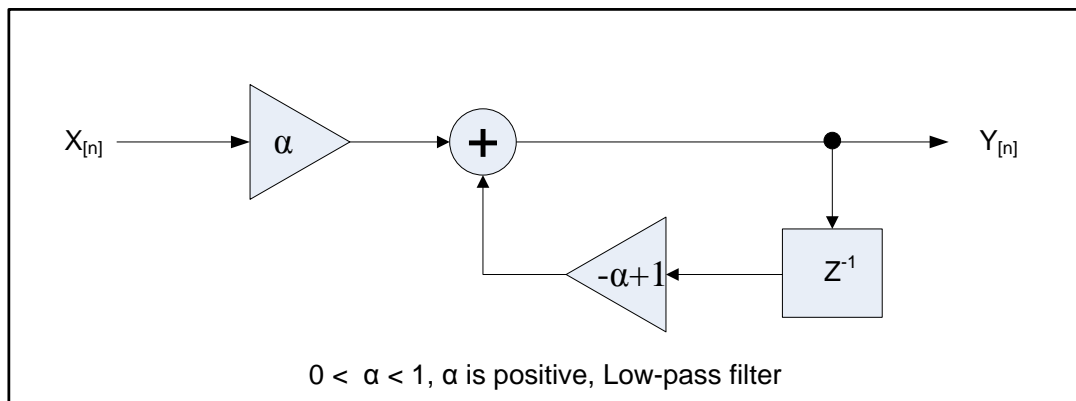


Figure 5: Low-pass Single Pole IIR

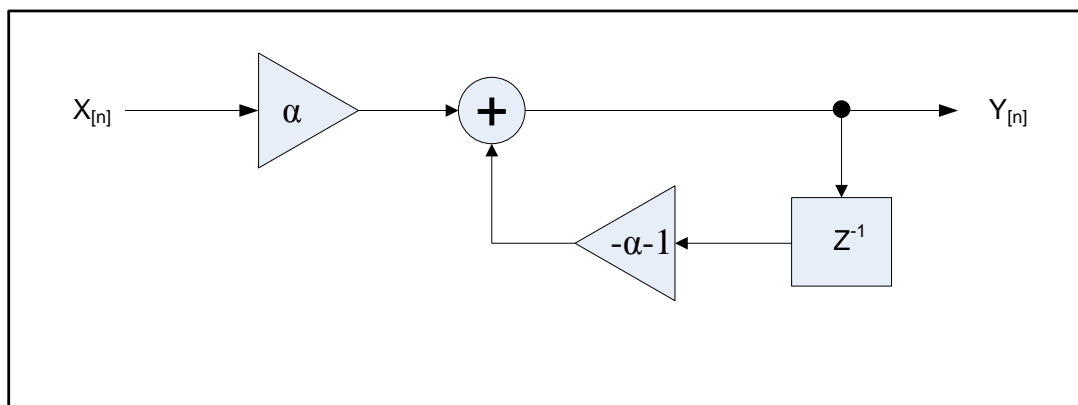


Figure 6: High-Pass Single Pole IIR

The single-pole low-pass IIR filter has the following transfer function:

$$H(z) = \frac{a}{1 - (1-a)z^{-1}}$$

where the coefficient a is always positive and determines the filter characteristic. When a is 1.0, the filter passes the input signal unchanged. As a decreases toward zero, greater attenuation of high frequencies results. The output of the single-pole low-pass filter can be computed as follows:

$$y_n = y_{n-1}(1 - a) + x_n a$$

or

$$y_n = y_{n-1} + (x_n - y_{n-1})a$$

where x_n is the input signal and y_n is the filter output.

A single-pole high-pass filter can be implemented with the transfer function:

$$H(z) = \frac{a}{1 + (a+1)z^{-1}}$$

However, this high-pass filter tends to oscillate at the Nyquist frequency as a approaches zero. Because this property of the filter is undesirable in many applications, a single-pole high-pass filter is often implemented by subtracting the output of a single-pole low-pass filter from the input signal. Thus the high-pass output is the simple difference:

$$y'_n = x_n - y_n$$

where x_n is the input signal, y_n is the low-pass filter output computed as describe above, and y'_n is the high-pass filter output.

Fixed-point Behavior

Since the function is implemented by fixed point, the behavior of fixed point must be taken. Following issues must be considered:

- Scaling
- Overflow

Scaling: The scaling factor “*IIR_SP_SCALE_A*” for the output data is defined in “*r_dscl_filter_asm.inc*”. Results are right-shifted by scale prior to writing the output to memory.

The scale must be equal to the number of fraction bits of coefficient. For example:

If the filter coefficients are in Q4.12 format and the filter’s input is in Q2.14 format, then the accumulated result for each output sample is in Q6.26 format. The scale value of 12 should be set, such that it will perform the required conversion by discarding 12 LSBs of the accumulated result, leaving 14 fractional bits in the final output word.

The default value of this scaling factor is 15. If the value is changed, the library needs to be compiled again.

Overflow: The function is optimized for speed at the cost of precision and overflow protection. It’s implemented by using multiply-accumulate operations. The accumulator is just 32 bit, overflows may happen. After accumulations, the

final result is converted to 16 bit, precision is also lost. To avoid overflows completely, the input data must be scaled down by 1 bit (Maximum is 15 bits).

Example

The following is an example showing how to use the single-pole IIR function with real 16-bit fixed-point input and output data.

```

r_dscl_iirsinglepole_t  myFilterHandle;
vector_t               myInput; // See introduction section describing the API document
vector_t               myOutput; // for a definition of the "vector_t" data type.
int16_t                inputData[NUM_SAMPLES];
int16_t                outputData[NUM_SAMPLES];
int16_t                myIIRFlags;
int16_t                mystate;
int16_t                mycoeff;

/*----- Set up the single-pole IIR filter -----*/
mystate = 0; // initialize state
mycoeff = (int16_t) (-0.15 * 0x7FFF);
myFilterHandle.coefs = &mycoeff;
myFilterHandle.state = &mystate;
myFilterHandle.options = R_DSCL_ROUNDING_TRUNC;

/*----- Set up the input/output -----*/
myInput.n = NUM_SAMPLES;
myInput.data = (void *)inputData;
myOutput.data = (void *)outputData;

/*----- Wait for input data -----*/

/*----- Main library function call -----*/
myIIRFlags = R_DSCL_IIRSinglePole_i16i16(&myFilterHandle, &myInput,
&myOutput);

/*----- Output data are now ready -----*/
/* Note: At this point myOutput.n holds the number of output samples generated
by
* the library, where the data are written to the array pointed to by
myOutput.data.
*-----*/

```


Processing Flow

The example above just gives an example to do all the filter sample once, in this case, the input buffer and output buffer should sufficient to hold all the data, if not, we need to filter the input sample into several times. The processing flow is shown in **Figure 7**, including the setting of scaling factor.

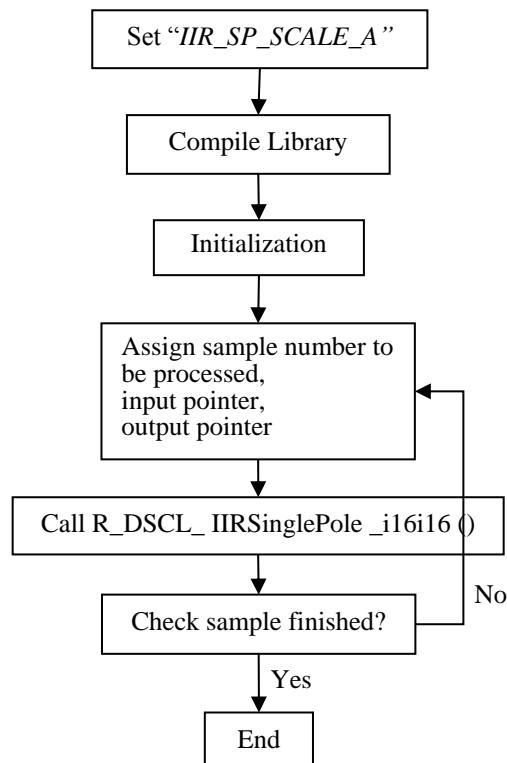


Figure 7: Processing flow

Restrictions

- The magnitude of the coefficient must be less than 1.0.

4. Sample Workspace on CubeSuite+

4.1 16-bit Fixed-point library only

The following include file and library files are provided.

When using this library alone, include the file indicated in table 1, and link the library file (corresponding to the compiler option) indicated in table 2.

Table 1. Include File for Fixed-point Library

Library	Function	
Fixed-point library	Implements fixed-point operations	"r_dscl_filters.h"

Table 2. Fixed-point Libraries

Library name	Compiler Option Cpu
R_dscl_filter_rl78.lib	RL78/G14

Before using, copy these files into your local include or library directories.

include directory	—	r_dscl_filters.h, r_dscl_types.h, r_stdint.h
library	—————	R_dsp_rl78.lib

Example of Usage

The following example shows a program using IIR Single Pole and how to specify the library under CubeSuite+.

[Source Program]

```
#include <stdlib.h>
#include "r_dscl_filters.h"

/*****
Macro definitions
*****/
#define INPUT_N (10)

/*****
Typedef definitions
*****/
static int16_t sp_buff_out16[INPUT_N];

/*****
Exported global variables (to be accessed by other files)
*****/

/*****
Private global variables and functions
*****/
static const int16_t sp_buff_in[INPUT_N] =
{ (int16_t) (1.0000000000000000 *0x7FFF)
, (int16_t) (0.0710197609601031 *0x7FFF)
, (int16_t) (0.5590169943749470 *0x7FFF)
, (int16_t) (0.4484011233337100 *0x7FFF)
, (int16_t) (-0.2500000000000000 *0x7FFF)
, (int16_t) (0.5000000000000000 *0x7FFF)
, (int16_t) (-0.5590169943749470 *0x7FFF)
, (int16_t) (-0.1393841289587630 *0x7FFF)
, (int16_t) (-0.2500000000000000 *0x7FFF)
, (int16_t) (-0.8800367553350520 *0x7FFF)
};
```

```

/*****
* Function Name: sample_dscl_iirsinglepole
* Description  : Sample code to demonstrate single-pole IIR filter
* Arguments    : none
* Return Value : r_dsp_status_t   Function status code
*****/

int16_t sample_dscl_iirsinglepole (void)
{
    int16_t    result;
    vector_t   input;
    vector_t * input_ptr;
    vector_t   output;
    vector_t * output_ptr;

    int16_t state;
    int16_t coeff;

    /*-----*/
    /* Single-pole IIR filter */
    /*-----*/
    r_dscl_iirsinglepole_t sp_handle;
    r_dscl_iirsinglepole_t * sp_handle_ptr;

    /*-----*/
    /* Single-pole IIR filter */
    /*-----*/
    state                = 0;
    coeff                = (int16_t) (-0.15 * 0x7FFF);
    sp_handle.options    = R_DSCL_ROUNDING_TRUNC;
    sp_handle.coefs     = &coeff;
    sp_handle.state     = &state;
    sp_handle_ptr       = &sp_handle;

    input.n             = INPUT_N;
    input.data          = (void*) (&sp_buff_in[0]);
    input_ptr           = &input;

    output_ptr         = &output;
    output.data         = (void *) sp_buff_out16;
    result              = R_DSCL_IIRSinglePole_i16i16 (sp_handle_ptr, input_ptr, output_ptr);

    return (result);
}

```

[How to specify the library under CubeSuite+]

Select [Property] of [CA78K0R] in project tree menu. In the dialog box [Property], select tab [Frequently Used Options (for Link)], and specify the library in "Using libraries" and the library path in "Additional library paths".

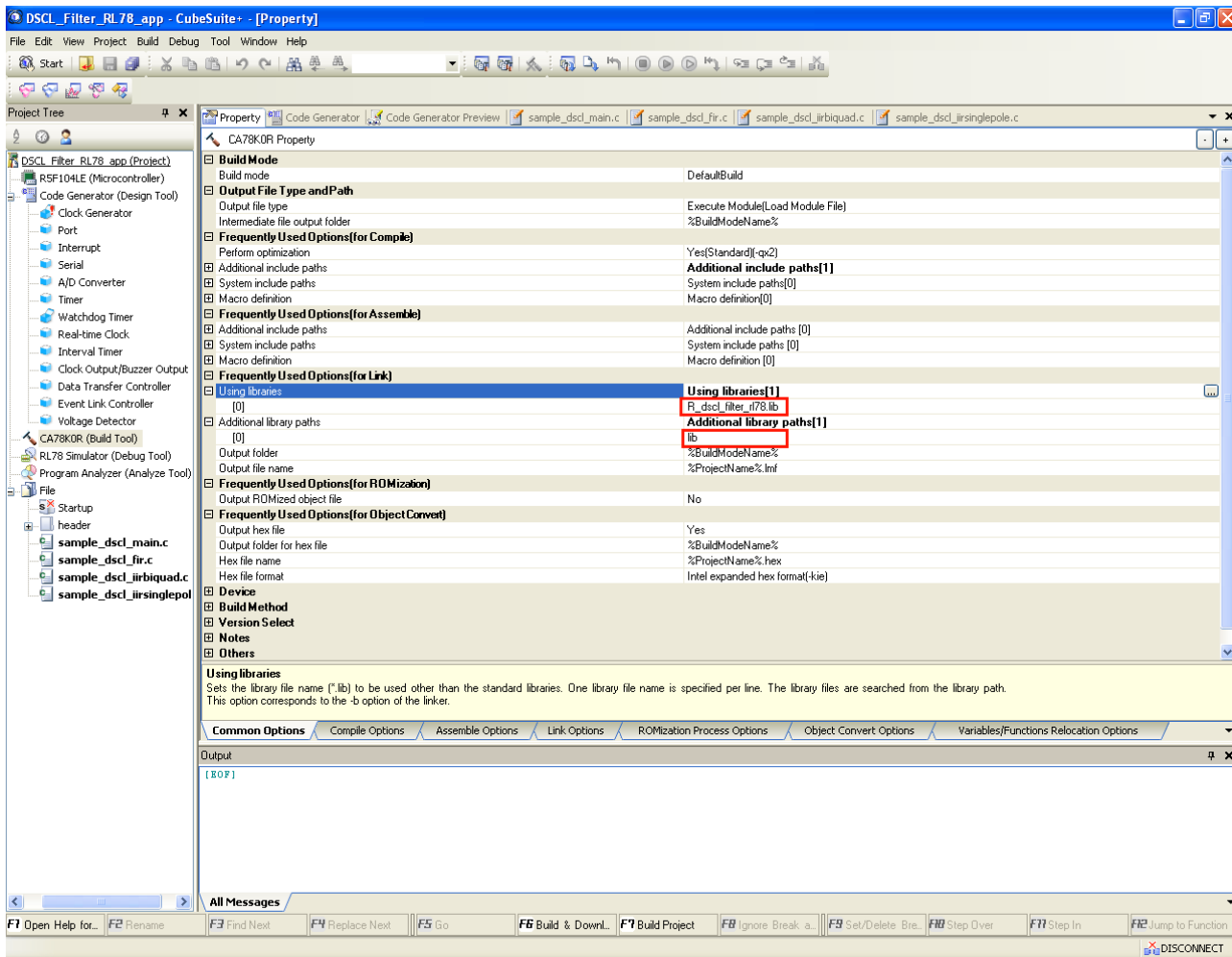


Figure 8. Specifying library

4.2 Resource Requirements

4.2.1 Code Size and Stack Size

No.	Kernel Category	Kernel Type	In/Out Format	Function	Options	Code size (Dec)	Total Code size (Dec)	Stack size (Dec)	Overall Stack size (Dec)
1	Filter	Generic FIR	i16i16	R_DSP_FIR_StateSize_i16i16	-	13	13	4	4
				R_DSP_FIR_Init_i16i16	-	111	111	8	8
				R_DSP_FIR_i16i16	c interface	189	477	4	26
				R_DSP_FIR_i16i16	nr	137		20	
				R_DSP_FIR_i16i16	r	151		22	
		IIR-Biquad	i16i16	R_DSP_IIRBiquad_StateSize_i16i16	-	8	8	2	4
				R_DSP_IIRBiquad_Init_i16i16	-	109	109	12	4
				R_DSP_IIRBiquad_i16i16	c interface	174	635	4	34
				R_DSP_IIRBiquad_i16i16	nr	222		28	
				R_DSP_IIRBiquad_i16i16	r	239		30	
		Single-pole-IIR	i16i16	R_DSP_IIRSinglePole_i16i16	c interface	173	488	6	32
				R_DSP_IIRSinglePole_i16i16	nr	143		22	
				R_DSP_IIRSinglePole_i16i16	r	172		26	

Notes:

nr = R_DSP_ROUNDING_TRUNC (or no option)

r = R_DSP_ROUNDING_NEAREST

4.2.2 Cycles and Accuracy

N.O	Filter	Samples	Taps	Options	Cycles	Max Err	Ave Err	
1	Generic FIR	200	64	nr	354,215	3.03E-05	1.58E-05	
2		200	64	r	354,503	1.53E-05	8.43E-06	
3	IIR Single pole	low pass	200	1	nr	8,191	3.02E-04	2.20E-04
4			200	1	r	9,915	4.44E-05	1.99E-05
5		high pass	200	1	nr	8,482	4.20E-05	1.86E-05
6			200	1	r	9,789	4.24E-05	1.48E-05
7	IIR Biquad	200	4	nr	81,235	5.32E-04	4.00E-04	
8		200	4	r	82,131	1.66E-04	4.82E-05	

Notes:

nr = R_DSP_ROUNDING_TRUNC (or no option)

- r = R_DSP_ROUNDING_NEAREST

5. Sample Workspace on IAR Embedded Workbench

5.1 16-bit Fixed-point library only

The following include files and library file are provided.

When using this library alone, include the file indicated in table 3, and add the library file (corresponding to the compiler option) indicated in table 4.

Table 3. Include File for Fixed-point Library

Library	Function	
Fixed-point library	Implements fixed-point operations	"r_dscl_filters.h"

Table 4. Fixed-point Libraries

Library name	Compiler Option Cpu
R_dscl_filter_rl78.r87	RL78 core S3 - Unspecified

Before using, copy these files into your local include and library directories.

include directory	—	r_dscl_filters.h, r_dscl_types.h, r_stdint.h
library	—————	R_dscl_filter_rl78.r87

Example of Usage

The following example shows a program using IIR Single Pole and how to specify the library under IAR Embedded Workbench.

[Source Program]

```
#include <stdlib.h>
#include "r_dscl_filters.h"

/*****
Macro definitions
*****/
#define INPUT_N (10)

/*****
Typedef definitions
*****/
static int16_t sp_buff_out16[INPUT_N];

/*****
Exported global variables (to be accessed by other files)
*****/

/*****
Private global variables and functions
*****/
static const int16_t sp_buff_in[INPUT_N] =
{ (int16_t) (1.0000000000000000 * 0x7FFF)
, (int16_t) (0.0710197609601031 * 0x7FFF)
, (int16_t) (0.5590169943749470 * 0x7FFF)
, (int16_t) (0.4484011233337100 * 0x7FFF)
, (int16_t) (-0.2500000000000000 * 0x7FFF)
, (int16_t) (0.5000000000000000 * 0x7FFF)
}
```

```

, (int16_t) (-0.5590169943749470*0x7FFF)
, (int16_t) (-0.1393841289587630*0x7FFF)
, (int16_t) (-0.2500000000000000*0x7FFF)
, (int16_t) (-0.8800367553350520*0x7FFF)
};

/*****
* Function Name: sample_dscl_iirsinglepole
* Description  : Sample code to demonstrate single-pole IIR filter
* Arguments    : none
* Return Value : r_dsp_status_t   Function status code
*****/

int16_t sample_dscl_iirsinglepole (void)
{
    int16_t    result;
    vector_t   input;
    vector_t * input_ptr;
    vector_t   output;
    vector_t * output_ptr;

    int16_t state;
    int16_t coeff;

    /*-----*/
    /* Single-pole IIR filter */
    /*-----*/
    r_dscl_iirsinglepole_t sp_handle;
    r_dscl_iirsinglepole_t * sp_handle_ptr;

    /*-----*/
    /* Single-pole IIR filter */
    /*-----*/
    state                = 0;
    coeff                 = (int16_t) (-0.15 * 0x7FFF);
    sp_handle.options    = R_DSCL_ROUNDING_TRUNC;
    sp_handle.coefs      = &coeff;
    sp_handle.state      = &state;
    sp_handle_ptr        = &sp_handle;

    input.n              = INPUT_N;
    input.data           = (void*) (&sp_buff_in[0]);
    input_ptr            = &input;

    output_ptr          = &output;
    output.data          = (void *) sp_buff_out16;
    result               = R_DSCL_IIRSinglePole_i16i16 (sp_handle_ptr, input_ptr, output_ptr);

    return (result);
}

```


[How to specify the library under IAR Embedded Workbench]

Right click on the project [R_dsp_r178] in project tree menu. Choose [Add] → [Add Files...]. In the dialog box, browse to folder “lib” that contains the library file, select the library file, then click [Open].

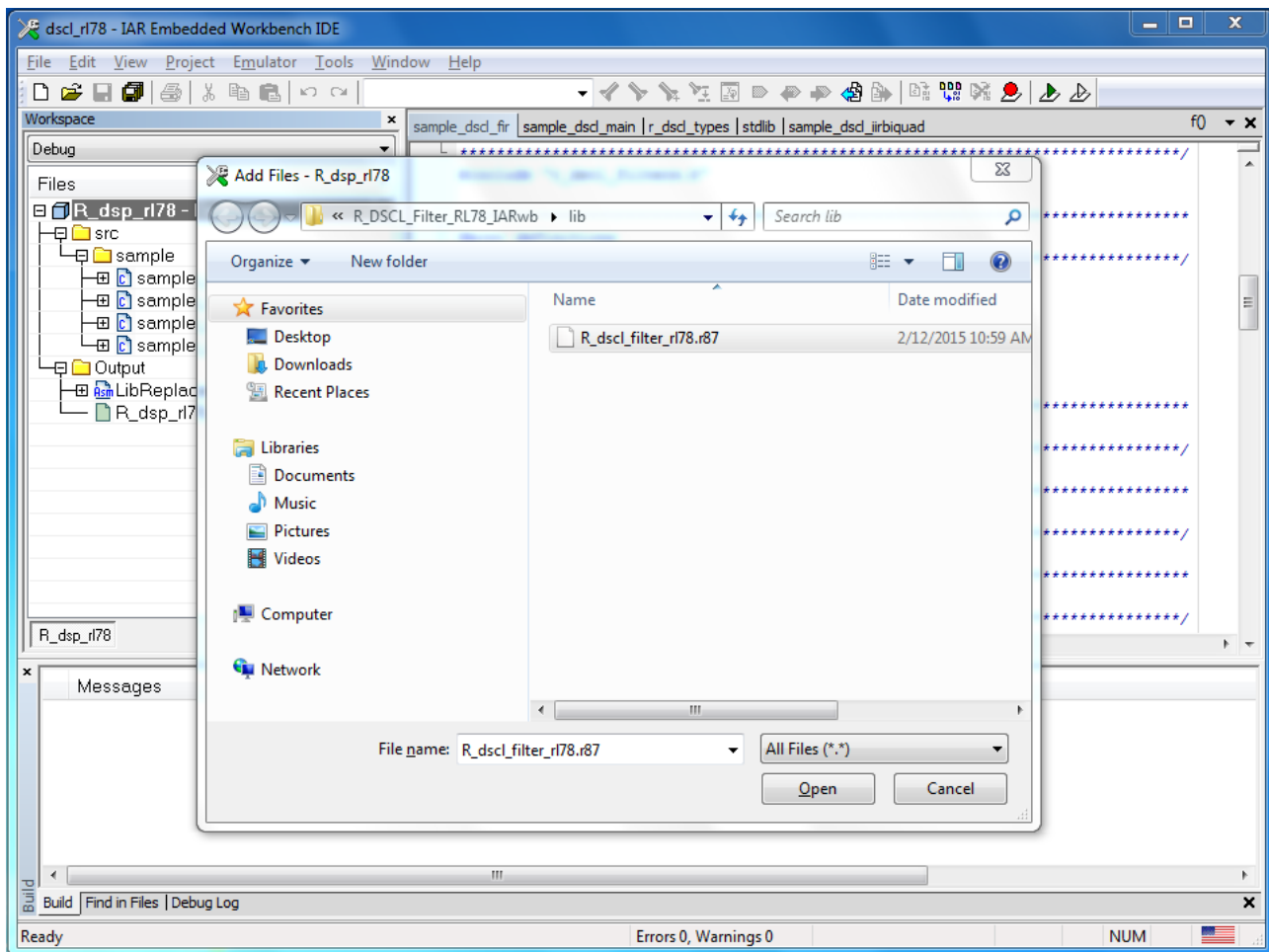


Figure 9. Select library

5.2 Resource Requirements

5.2.1 Code Size and Stack Size

No.	Kernel Category	Kernel Type	In/Out Format	Function	Options	Code size (Dec)	Total Code size (Dec)	Stack size (Dec)	Overall Stack size (Dec)
1	Filter	Generic FIR	i16i16	R_DSP_FIR_StateSize_i16i16	-	2	2	0	0
				R_DSP_FIR_Init_i16i16	-	49	49	8	8
				R_DSP_FIR_i16i16	c interface	47	348	2	30
				R_DSP_FIR_i16i16	nr	143		20	
				R_DSP_FIR_i16i16	r	158		22	
		IIR-Biquad	i16i16	R_DSP_IIRBiquad_StateSize_i16i16	-	5	5	0	0
				R_DSP_IIRBiquad_Init_i16i16	-	147	147	12	12
				R_DSP_IIRBiquad_i16i16	c interface	64	536	4	42
				R_DSP_IIRBiquad_i16i16	nr	227		34	
				R_DSP_IIRBiquad_i16i16	r	245		38	
		Single-pole-IIR	i16i16	R_DSP_IIRSinglePole_i16i16	c interface	64	398	4	40
				R_DSP_IIRSinglePole_i16i16	nr	152		32	
				R_DSP_IIRSinglePole_i16i16	r	182		36	

Notes:

nr = R_DSP_ROUNDING_TRUNC (or no option)

r = R_DSP_ROUNDING_NEAREST

5.2.2 Cycles and Accuracy

N.O	Filter	Samples	Taps	Options	Cycles	Max Err	Ave Err	
1	Generic FIR	200	64	nr	354,804	3.03E-05	1.58E-05	
2		200	64	r	355,105	1.53E-05	8.43E-06	
3	IIR Single Pole	low pass	200	0	nr	8,495	3.02E-04	2.20E-04
4			200	0	r	9,805	4.44E-05	1.99E-05
5		high pass	200	0	nr	8,499	4.20E-05	1.86E-05
6			200	0	r	9,806	4.24E-05	1.48E-05
7	IIR Biquad	1000	4	nr	406,693	5.32E-04	4.00E-04	
8		1000	4	r	410,837	1.66E-04	4.82E-05	

Notes:

nr = R_DSP_ROUNDING_TRUNC (or no option)

- r = R_DSP_ROUNDING_NEAREST

Website and Support

Renesas Electronics Website

<http://www.renesas.com/>

Inquiries

<http://www.renesas.com/contact/>

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Revision Record

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		Page	Summary
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1.01	March 6, 2015	-	Second Edition

General Precautions in the Handling of MPU/MCU Products

The following usage notes are applicable to all MPU/MCU products from Renesas. For detailed usage notes on the products covered by this document, refer to the relevant sections of the document as well as any technical updates that have been issued for the products.

1. Handling of Unused Pins

Handle unused pins in accordance with the directions given under Handling of Unused Pins in the manual.

- The input pins of CMOS products are generally in the high-impedance state. In operation with an unused pin in the open-circuit state, extra electromagnetic noise is induced in the vicinity of LSI, an associated shoot-through current flows internally, and malfunctions occur due to the false recognition of the pin state as an input signal become possible. Unused pins should be handled as described under Handling of Unused Pins in the manual.

2. Processing at Power-on

The state of the product is undefined at the moment when power is supplied.

- The states of internal circuits in the LSI are indeterminate and the states of register settings and pins are undefined at the moment when power is supplied.
In a finished product where the reset signal is applied to the external reset pin, the states of pins are not guaranteed from the moment when power is supplied until the reset process is completed. In a similar way, the states of pins in a product that is reset by an on-chip power-on reset function are not guaranteed from the moment when power is supplied until the power reaches the level at which resetting has been specified.

3. Prohibition of Access to Reserved Addresses

Access to reserved addresses is prohibited.

- The reserved addresses are provided for the possible future expansion of functions. Do not access these addresses; the correct operation of LSI is not guaranteed if they are accessed.

4. Clock Signals

After applying a reset, only release the reset line after the operating clock signal has become stable. When switching the clock signal during program execution, wait until the target clock signal has stabilized.

- When the clock signal is generated with an external resonator (or from an external oscillator) during a reset, ensure that the reset line is only released after full stabilization of the clock signal. Moreover, when switching to a clock signal produced with an external resonator (or by an external oscillator) while program execution is in progress, wait until the target clock signal is stable.

5. Differences between Products

Before changing from one product to another, i.e. to a product with a different part number, confirm that the change will not lead to problems.

- The characteristics of an MPU or MCU in the same group but having a different part number may differ in terms of the internal memory capacity, layout pattern, and other factors, which can affect the ranges of electrical characteristics, such as characteristic values, operating margins, immunity to noise, and amount of radiated noise. When changing to a product with a different part number, implement a system-evaluation test for the given product.

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