GigaDevice Semiconductor Inc.

适用于 Arm Cortex-M 处理器的 GD32 Embedded Builder 分散加载说明

应用笔记

AN311

1.0 版本

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1. 简介

ld 是 GNU binutils 工具集中的一个，是众多 Linkers（链接器）的一种。ld 把各种目标文件和库文件链接起来，并重定向它们的数据，完成符号解析。Linking 其实主要就是完成四个方面的工作：storage allocation、symbol management、libraries、relocation。因此根据工程代码的需要，我们可以通过修改该文件来实现指定代码段区的位置存储。

本应用笔记基于 GD32H75x 系列，采用 GD32H759I-EVAL 开发板，Embedded Builder 版本为 1.5.18，实现的功能主要如下：

- 实现用户定义的全局变量和数组加载到指定位置
- 实现用户定义的函数加载到指定位置
- 实现用户指定.c 文件加载到指定位置
- 实现上述功能加载到 SDRAM 指定位置

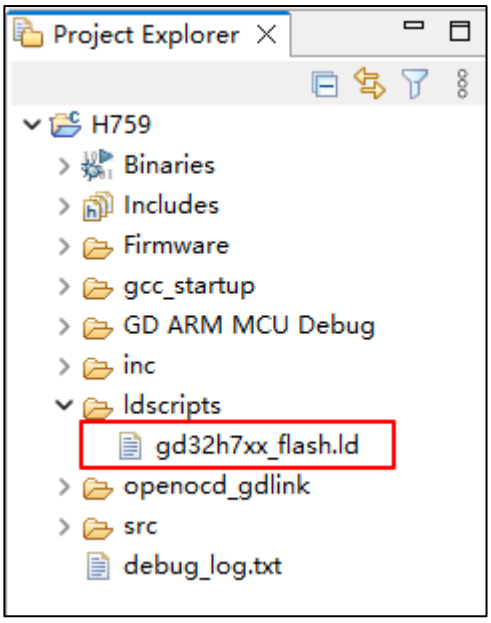
本手册同样适用于 GD32 Arm Cortex® M3/M4/M23/M33/M7 内核 MCU 产品。

2. 分散加载在 Embedded Builder 中的实现

2.1. 使用手动编写的 ld 文件

本工程直接使用手动编写的 ld 文件，在 Embedded Builder 中的“Window-> Show View-> Project Explore->ldscripts”中双击 gd32h7xx_flash.ld 文件，工程目录结构如*图 2-1 GD32 Embedded Builder 中工程目录结构*所示。同时也可到工程目录“..\ldscripts\gd32h7xx_flash.ld”下打开编辑。

图 2-1 GD32 Embedded Builder 中工程目录结构



2.2. VMA 和 LMA

在链接脚本中，VMA 和 LMA 是两个核心概念，用于控制程序段在内存中的分布。VMA (Virtual Memory Address) 即虚拟内存地址，是程序运行时段所在的内存地址，也称为运行时地址。LMA (Load Memory Address) 即加载内存地址，是程序烧录时段存储的物理地址，也称为存储地址。实现分散加载功能，需要理解 VMA 和 LMA 两个核心概念，关于 VMA 和 LMA 的具体介绍可参考*《AN200 GD32 Embedded builder 链接脚本文件说明》*。

2.3. 将全局变量和全局数组加载到指定位置

2.3.1. 自定义段

在链接脚本中添加用户自定义段，将不同类型的数据分配到指定地址，地址分配如*表 2-1. 将*

*全局变量和全局数组加载到指定位置地址分配总览*所示，链接文件代码如*表 2-2. gd32h7xx_flash.ld 中将全局变量和全局数组加载到指定位置*所示。

表 2-1. 将全局变量和全局数组加载到指定位置地址分配总览

段类型	section 名称	FLASH 地址	RAM 地址	用途
初始化变量	.data.user_vars	0x08008000	0x24008000	有初始值的变量
初始化数组	.data.user_arrays	0x08009000	0x24009000	有初始值的数组
未初始化变量	.bss.user_vars	-	0x2400A000	零初始化变量
未初始化数组	.bss.user_arrays	-	0x2400B000	零初始化数组
常量数组	.rodata.user_const_arrays	0x08007000	-	const 数组

表 2-2. gd32h7xx_flash.ld 中将全局变量和全局数组加载到指定位置

```
/* user initializes variable section */
.user_global_vars ALIGN(0x24008000, 4) : AT(ALIGN(0x08008000, 4))
{
    . = ALIGN(4);
    __user_global_vars_start__ = .;
    KEEP(*(.data.user_vars))
    . = ALIGN(4);
    __user_global_vars_end__ = .;
    __user_global_vars_size__ = __user_global_vars_end__ - __user_global_vars_start__;
}
__user_global_vars_loadaddr__ = LOADADDR(.user_global_vars);
/* user initializes array section */
.user_global_arrays ALIGN(0x24009000, 4) : AT(ALIGN(0x08009000, 4))
{
    . = ALIGN(4);
    __user_global_arrays_start__ = .;
    KEEP(*(.data.user_arrays))
    . = ALIGN(4);
    __user_global_arrays_end__ = .;
    __user_global_arrays_size__ = __user_global_arrays_end__ - __user_global_arrays_start__;
}
__user_global_arrays_loadaddr__ = LOADADDR(.user_global_arrays);
/* user uninitialized variable section */
.user_uninit_vars ALIGN(0x2400A000, 4) (NOLOAD) :
{
    . = ALIGN(4);
    __user_uninit_vars_start__ = .;
    KEEP(*(.bss.user_vars))
    . = ALIGN(4);
    __user_uninit_vars_end__ = .;
```

```
    __user_uninit_vars_size__ = __user_uninit_vars_end__ - __user_uninit_vars_start__;
}
/* user uninitialized array section */
.user_uninit_arrays ALIGN(0x2400B000, 4) (NOLOAD) :
{
    . = ALIGN(4);
    __user_uninit_arrays_start__ = .;
    KEEP(*(.bss.user_arrays))
    . = ALIGN(4);
    __user_uninit_arrays_end__ = .;
    __user_uninit_arrays_size__ = __user_uninit_arrays_end__ - __user_uninit_arrays_start__;
}
/* user constant array section */
.user_const_arrays ALIGN(0x08007000, 4) :
{
    . = ALIGN(4);
    __user_const_arrays_start__ = .;
    KEEP(*(.rodata.user_const_arrays))
    . = ALIGN(4);
    __user_const_arrays_end__ = .;
    __user_const_arrays_size__ = __user_const_arrays_end__ - __user_const_arrays_start__;
} > FLASH
```

2.3.2. C 代码中的变量定义

在头文件中定义 section 属性宏，提高代码可读性，如*表 2-3. 全局变量和全局数组加载到指定位置头文件宏定义*所示：

表 2-3. 全局变量和全局数组加载到指定位置头文件宏定义

```
/* initialized data section attributes - will be loaded from FLASH to RAM */
#define USER_INIT_VAR           __attribute__((section(".data.user_vars")))
#define USER_INIT_ARRAY         __attribute__((section(".data.user_arrays")))
/* uninitialized data section attributes - only in RAM, cleared at startup */
#define USER_UNINIT_VAR         __attribute__((section(".bss.user_vars")))
#define USER_UNINIT_ARRAY       __attribute__((section(".bss.user_arrays")))

#define USER_CONST_ARRAY        __attribute__((section(".rodata.user_const_arrays")))
```

变量定义示例如*表 2-4. 全局变量和全局数组加载到指定位置变量定义*所示。

表 2-4. 全局变量和全局数组加载到指定位置变量定义

```
/* user initialized global variables definition - will be placed in .data.user_vars section */
USER_INIT_VAR int32_t     system_status = 1;
```

```
USER_INIT_VAR uint32_t    device_serial = 0x12345678;
USER_INIT_VAR uint16_t    firmware_version = 0x0102;
USER_INIT_VAR uint8_t     system_config = 0xAB;

/* user initialized global arrays definition - will be placed in .data.user_arrays section */
USER_INIT_ARRAY uint16_t calibration_data[10] = {
    100, 200, 300, 400, 500, 600, 700, 800, 900, 1000
};

USER_INIT_ARRAY uint8_t device_info[32] = {
    'G','D','3','2','H','7','x','x',' ','D','e','v','i','c','e',0
};

/* User uninitialized global variables definition - will be placed in .bss.user_vars section */
USER_UNINIT_VAR volatile uint32_t     tick_counter;
USER_UNINIT_VAR volatile uint16_t     error_code;
USER_UNINIT_VAR volatile uint8_t      system_state;
USER_UNINIT_VAR uint32_t                  runtime_config;

/* User uninitialized global arrays definition - will be placed in .bss.user_arrays section */
USER_UNINIT_ARRAY uint8_t     uart_tx_buffer[512];
USER_UNINIT_ARRAY uint8_t     uart_rx_buffer[512];
USER_UNINIT_ARRAY uint16_t    adc_samples[256];
USER_UNINIT_ARRAY char         log_buffer[1024];

/* Const array definition */
USER_CONST_ARRAY const uint16_t lookup_table[256] = {
    0x0000, 0x0001, 0x0004, 0x0009,
};
```

2.3.3. 自定义初始化实现

在系统启动时调用自定义段初始化函数，如*表 2-5. 全局变量和全局数组加载到指定位置数据段初始化实现*所示。

表 2-5. 全局变量和全局数组加载到指定位置数据段初始化实现

```
/* Data initialization function implementation */
void UserData_Init(void)
{
    uint32_t *src, *dst;
    uint32_t size;
    /* 1. Initialize user global variables segment - copy from FLASH to RAM */
```

```
    src = &__user_global_vars_loadaddr__;
    dst = &__user_global_vars_start__;
    size = ((uint32_t)&__user_global_vars_end__ - (uint32_t)&__user_global_vars_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }

    /* 2. Initialize user global arrays segment - copy from FLASH to RAM */
    src = &__user_global_arrays_loadaddr__;
    dst = &__user_global_arrays_start__;
    size = ((uint32_t)&__user_global_arrays_end__ - (uint32_t)&__user_global_arrays_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }
    /* 3. Clear user uninitialized variables segment */
    dst = &__user_uninit_vars_start__;
    size = ((uint32_t)&__user_uninit_vars_end__ - (uint32_t)&__user_uninit_vars_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = 0;
    }
    /* 4. Clear user uninitialized arrays segment */
    dst = &__user_uninit_arrays_start__;
    size = ((uint32_t)&__user_uninit_arrays_end__ - (uint32_t)&__user_uninit_arrays_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = 0;
    }
}
```

注意：

1. 初始化放在 cache 初始化函数之前。
2. 常量数组不需要初始化操作。

2.3.4. 测试验证

通过串口打印的方式，测试全局变量和全局数组加载到指定位置内存布局验证，代码如*表 2-6. 全局变量和全局数组加载到指定位置内存验证代码*所示。

表 2-6. 全局变量和全局数组加载到指定位置内存验证代码

```
void UserData_PrintMemoryInfo(void)
```

```
{
    printf("=== User-defined Memory Segments Information ===\r\n");

    printf("1. Initialized variables segment:\r\n");
    printf("    RAM address: 0x%08X - 0x%08X (%d bytes)\r\n",
           (uint32_t)&__user_global_vars_start__,
           (uint32_t)&__user_global_vars_end__,
           (uint32_t)&__user_global_vars_end__ - (uint32_t)&__user_global_vars_start__);
    printf("    FLASH source: 0x%08X\r\n", (uint32_t)&__user_global_vars_loadaddr__);

    printf("2. Initialized arrays segment:\r\n");
    printf("    RAM address: 0x%08X - 0x%08X (%d bytes)\r\n",
           (uint32_t)&__user_global_arrays_start__,
           (uint32_t)&__user_global_arrays_end__,
           (uint32_t)&__user_global_arrays_end__ - (uint32_t)&__user_global_arrays_start__);
    printf("    FLASH source: 0x%08X\r\n", (uint32_t)&__user_global_arrays_loadaddr__);

    printf("3. Uninitialized variables segment:\r\n");
    printf("    RAM address: 0x%08X - 0x%08X (%d bytes)\r\n",
           (uint32_t)&__user_uninit_vars_start__,
           (uint32_t)&__user_uninit_vars_end__,
           (uint32_t)&__user_uninit_vars_end__ - (uint32_t)&__user_uninit_vars_start__);

    printf("4. Uninitialized arrays segment:\r\n");
    printf("    RAM address: 0x%08X - 0x%08X (%d bytes)\r\n",
           (uint32_t)&__user_uninit_arrays_start__,
           (uint32_t)&__user_uninit_arrays_end__,
           (uint32_t)&__user_uninit_arrays_end__ - (uint32_t)&__user_uninit_arrays_start__);
    printf("5. Constant arrays segment:\r\n");
    printf("    FLASH address: 0x%08X - 0x%08X (%d bytes)\r\n",
           (uint32_t)&__user_const_arrays_start__,
           (uint32_t)&__user_const_arrays_end__,
           (uint32_t)&__user_const_arrays_end__ - (uint32_t)&__user_const_arrays_start__);
    printf("============================================\r\n\r\n");

}

int main(void)
{
    gd_eval_com_init(EVAL_COM);
    /*system initialization */
    printf("GD32H7xx User-defined Data Segment Example\r\n");
```

```
    printf("========================================\r\n");

    /* initialize user data segment */
    UserData_Init();
    /* enable the CPU cache */
    cache_enable();
    mpu_config();
    /* print memory information */
    UserData_PrintMemoryInfo();

    /* verify initialization data */
    printf("=== Verify Initialization Data ===\r\n");
    printf("system_status = %d (addr: 0x%08X)\r\n", system_status, (uint32_t)&system_status);
    printf("device_serial = 0x%08X (addr: 0x%08X)\r\n", device_serial, (uint32_t)&device_serial);
    printf("calibration_data[0] = %d (addr: 0x%08X)\r\n", calibration_data[0],
(uint32_t)&calibration_data[0]);
    printf("calibration_data[9] = %d (addr: 0x%08X)\r\n", calibration_data[9],
(uint32_t)&calibration_data[9]);
    printf("calibration_data array base addr: 0x%08X\r\n", (uint32_t)calibration_data);
    printf("device_info = %s (addr: 0x%08X)\r\n", (char*)device_info, (uint32_t)device_info);
    /* verify const array */
    printf("lookup_table[0] = 0x%04X (addr: 0x%08X)\r\n", lookup_table[0],
(uint32_t)&lookup_table[0]);
    printf("lookup_table[255] = 0x%04X (addr: 0x%08X)\r\n", lookup_table[255],
(uint32_t)&lookup_table[255]);
    printf("lookup_table array base addr: 0x%08X\r\n", (uint32_t)lookup_table);

    /* test uninitialized data usage */
    printf("\r\n=== Test Uninitialized Data Usage ===\r\n");

    /* buffer filling test */
    for(int i = 0; i < 10; i++) {
        uart_tx_buffer[i] = i + 0x30;    // '0' to '9'
        adc_samples[i] = i * 100;
    }
    uart_tx_buffer[10] = '\0';

    printf("uart_tx_buffer = %s (addr: 0x%08X)\r\n", (char*)uart_tx_buffer, (uint32_t)uart_tx_buffer);
    printf("adc_samples[5] = %d (addr: 0x%08X)\r\n", adc_samples[5], (uint32_t)&adc_samples[5]);
    printf("adc_samples array base addr: 0x%08X\r\n", (uint32_t)adc_samples);

    printf("\r\n=== System Ready ===\r\n");
```

```
    printf("User-defined data segments test completed successfully!\r\n");

    /* main loop - simple endless loop */
    while(1) {
    }
}
```

测试打印日志如*表 2-7. 将全局变量和全局数组加载到指定位置日志*所示，测试结果与实际分配保持一致。

表 2-7. 将全局变量和全局数组加载到指定位置日志

```
GD32H7xx User-defined Data Segment Example
==========================================
Starting initialization of user-defined data segments...
Initializing user global variables segment...
  Address range: 0x24008000 - 0x2400800C
  Data size: 12 bytes
Initializing user global arrays segment...
  Address range: 0x24009000 - 0x24009034
  Data size: 52 bytes
Clearing user uninitialized variables segment...
  Address range: 0x2400A000 - 0x2400A00C
  Data size: 12 bytes
Clearing user uninitialized arrays segment...
  Address range: 0x2400B000 - 0x2400BA00
  Data size: 2560 bytes
User data segments initialization completed!

=== User-defined Memory Segments Information ===
1. Initialized variables segment:
    RAM address: 0x24008000 - 0x2400800C (12 bytes)
    FLASH source: 0x08008000
2. Initialized arrays segment:
    RAM address: 0x24009000 - 0x24009034 (52 bytes)
    FLASH source: 0x08009000
3. Uninitialized variables segment:
    RAM address: 0x2400A000 - 0x2400A00C (12 bytes)
4. Uninitialized arrays segment:
    RAM address: 0x2400B000 - 0x2400BA00 (2560 bytes)
5. Constant arrays segment:
    FLASH address: 0x0800A000 - 0x0800A200 (512 bytes)
==========================================
```

```
=== Verify Initialization Data ===
system_status = 1 (addr: 0x24008000)
device_serial = 0x12345678 (addr: 0x24008004)
calibration_data[0] = 100 (addr: 0x24009000)
calibration_data[9] = 1000 (addr: 0x24009012)
calibration_data array base addr: 0x24009000
device_info = GD32H7xx Device (addr: 0x24009014)
lookup_table[0] = 0xA55A (addr: 0x0800A000)
lookup_table[255] = 0x0000 (addr: 0x0800A0FE)
lookup_table array base addr: 0x0800A000

=== Test Uninitialized Data Usage ===
uart_tx_buffer = 0123456789 (addr: 0x2400B000)
adc_samples[5] = 500 (addr: 0x2400B40A)
adc_samples array base addr: 0x2400B400

=== System Ready ===
User-defined data segments test completed successfully!
```

2.4. 将函数加载到指定位置

2.4.1. 自定义段

在链接脚本中添加用户自定义段，将函数分配到指定地址，地址分配如*表 2-8. 将函数加载到指定位置地址分配总览*所示，链接文件代码如*表 2-9. gd32h7xx_flash.ld 中将全局变量和全局数组加载到指定位置*所示。

表 2-8. 将函数加载到指定位置地址分配总览

段类型	section 名称	FLASH 地址	RAM 地址	用途
FLASH 函数	.text.flash_functions	0x08010000	-	直接在 FLASH 中执行
RAM 函数	.text.ram_functions	自动分配	0x2400C000	复制到 RAM 中执行
ITCM 函数	.text.itcm_functions	自动分配	0x00001000	复制到 ITCMRAM 中执行
DTCM 函数	.text.dtcm_functions	自动分配	0x20001000	复制到 DTCMRAM 中执行

表 2-9. gd32h7xx_flash.ld 中将全局变量和全局数组加载到指定位置

```
/* User custom function scatter loading */
.user_flash_functions 0x08010000 :
{
    . = ALIGN(4);
    __user_flash_functions_start__ = .;
    KEEP(*(.text.flash_functions))
```

```
    . = ALIGN(4);
    __user_flash_functions_end__ = .;
    __user_flash_functions_size__ = __user_flash_functions_end__ -
__user_flash_functions_start__;
} > FLASH

.user_ram_functions 0x2400C000 :
{
    . = ALIGN(4);
    __user_ram_functions_start__ = .;
    KEEP(*(.text.ram_functions))
    . = ALIGN(4);
    __user_ram_functions_end__ = .;
    __user_ram_functions_size__ = __user_ram_functions_end__ -
__user_ram_functions_start__;
} > AXISRAM AT> FLASH
__user_ram_functions_loadaddr__ = LOADADDR(.user_ram_functions);

.user_itcm_functions 0x00001000 :
{
    . = ALIGN(4);
    __user_itcm_functions_start__ = .;
    KEEP(*(.text.itcm_functions))
    . = ALIGN(4);
    __user_itcm_functions_end__ = .;
    __user_itcm_functions_size__ = __user_itcm_functions_end__ -
__user_itcm_functions_start__;
} > ITCMRAM AT> FLASH
__user_itcm_functions_loadaddr__ = LOADADDR(.user_itcm_functions);

.user_dtcm_functions 0x20001000 :
{
    . = ALIGN(4);
    __user_dtcm_functions_start__ = .;
    KEEP(*(.text.dtcm_functions))
    . = ALIGN(4);
    __user_dtcm_functions_end__ = .;
    __user_dtcm_functions_size__ = __user_dtcm_functions_end__ -
__user_dtcm_functions_start__;
} > DTCMRAM AT> FLASH
__user_dtcm_functions_loadaddr__ = LOADADDR(.user_dtcm_functions);
```

2.4.2. C 代码中的函数定义

在头文件中定义 section 属性宏，提高代码可读性，如*表 2-10. 将函数加载到指定位置头文件宏定义*所示：

表 2-10. 将函数加载到指定位置头文件宏定义

```
/* Function section attributes */
#define FLASH_FUNCTION        __attribute__((section(".text.flash_functions")))
#define RAM_FUNCTION          __attribute__((section(".text.ram_functions")))
#define ITCM_FUNCTION         __attribute__((section(".text.itcm_functions")))
#define DTCM_FUNCTION         __attribute__((section(".text.dtcm_functions")))
```

变量定义示例如*表 2-11. 将函数加载到指定位置函数定义与实现*所示。

表 2-11. 将函数加载到指定位置函数定义与实现

```
FLASH_FUNCTION int FlashFunction_Calculate(int a, int b)
{
    printf("FlashFunction_Calculate: a=%d, b=%d\r\n", a, b);
    int result = 0;
    for(int i = 0; i < 50; i++) {
        result += (a * b) + (i % 10);
    }
    printf("FlashFunction_Calculate result: %d\r\n", result);
    return result;
}

FLASH_FUNCTION void FlashFunction_ProcessData(uint8_t* data, uint32_t len)
{
    printf("FlashFunction_ProcessData: processing %d bytes\r\n", len);
    for(uint32_t i = 0; i < len; i++) {
        data[i] = data[i] ^ 0x5A;
    }
    printf("Data processing completed\r\n");
}

RAM_FUNCTION int RamFunction_FastProcess(int data)
{
    //printf("RamFunction_FastProcess: input=0x%08X\r\n", data);
    volatile int temp = data;
    temp = (temp << 1) ^ 0xA5A5;
    temp = (temp >> 1) | 0x5A5A0000;
    //printf("RamFunction_FastProcess result: 0x%08X\r\n", temp);
    return temp;
```

```
}

RAM_FUNCTION void RamFunction_ProcessBuffer(uint16_t* buffer, uint32_t size)
{
    printf("RamFunction_ProcessBuffer: processing %d elements\r\n", size);
    for(uint32_t i = 0; i < size; i++) {
        buffer[i] = (buffer[i] << 1) | (buffer[i] >> 15);
    }
    printf("Buffer processing completed\r\n");
}

ITCM_FUNCTION int ItcmFunction_CriticalTask(int input)
{
    printf("ItcmFunction_CriticalTask: input=%d\r\n", input);
    register int result = input;
    result = (result * 3) + 7;
    result = result ^ 0x12345678;
    result = (result << 4) | (result >> 28);
    printf("ItcmFunction_CriticalTask result: %d\r\n", result);
    return result;
}

ITCM_FUNCTION uint32_t ItcmFunction_BitOperation(uint32_t value)
{
    printf("ItcmFunction_BitOperation: input=0x%08X\r\n", value);
    uint32_t result = value;
    result = ~result;
    result = (result & 0xAAAAAAAA) | ((result & 0x55555555) << 1);
    result = (result & 0xCCCCCCCC) | ((result & 0x33333333) << 2);
    printf("ItcmFunction_BitOperation result: 0x%08X\r\n", result);
    return result;
}

DTCM_FUNCTION int DtcmFunction_DataProcess(int value)
{
    printf("DtcmFunction_DataProcess: input=%d\r\n", value);
    static int buffer[32];
    for(int i = 0; i < 32; i++) {
        buffer[i] = value + (i * 10);
    }
    int sum = 0;
    for(int i = 0; i < 32; i++) {
```

```
        sum += buffer[i];
    }
    printf("DtcmFunction_DataProcess result: %d\r\n", sum);
    return sum;
}

DTCM_FUNCTION void DtcmFunction_ArrayOperation(uint32_t* array, uint32_t count)
{
    printf("DtcmFunction_ArrayOperation: processing %d elements\r\n", count);
    for(uint32_t i = 0; i < count; i++) {
        array[i] = array[i] * 2 + 1;
    }
    printf("Array operation completed\r\n");
}
```

2.4.3. 自定义初始化实现

在系统启动时调用自定义代码段初始化函数，如*表 2-12. 函数加载到指定位置初始化实现*所示。

表 2-12. 函数加载到指定位置初始化实现

```
void UserFunctions_Init(void)
{
    uint32_t *src, *dst;
    uint32_t size;

    /* Copy RAM functions */
    src = &__user_ram_functions_loadaddr__;
    dst = &__user_ram_functions_start__;
    size = ((uint32_t)&__user_ram_functions_end__ - (uint32_t)&__user_ram_functions_start__) /
4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }
    /* Copy ITCM functions */
    src = &__user_itcm_functions_loadaddr__;
    dst = &__user_itcm_functions_start__;
    size = ((uint32_t)&__user_itcm_functions_end__ - (uint32_t)&__user_itcm_functions_start__) /
4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
```

```
    }

    /* Copy DTCM functions */
    printf("Copying DTCM functions...\r\n");
    src = &__user_dtcm_functions_loadaddr__;
    dst = &__user_dtcm_functions_start__;
    size = ((uint32_t)&__user_dtcm_functions_end__ - (uint32_t)&__user_dtcm_functions_start__)
/ 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }
}
```

注意：初始化放在 cache 初始化函数之前。

2.4.4. 测试验证

通过串口打印的方式，测试将函数加载到指定位置内存布局验证，代码如*表 2-13. 函数加载到指定位置内存验证代码*所示。

表 2-13. 函数加载到指定位置内存验证代码

```
void TestUserFunctions(void)
{
    printf("=== Testing User Functions ===\r\n");

    uint8_t test_data[16] = {0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07, 0x08,
                             0x09, 0x0A, 0x0B, 0x0C, 0x0D, 0x0E, 0x0F, 0x10};

    uint16_t test_buffer[8] = {100, 200, 300, 400, 500, 600, 700, 800};
    uint32_t test_array[5] = {10, 20, 30, 40, 50};

    printf("\n--- Testing FLASH Functions ---\r\n");
    FlashFunction_Calculate(15, 25);
    FlashFunction_ProcessData(test_data, 8);

    printf("\n--- Testing RAM Functions ---\r\n");
    RamFunction_FastProcess(0x12345678);
    RamFunction_ProcessBuffer(test_buffer, 8);

    printf("\n--- Testing ITCM Functions ---\r\n");
    ItcmFunction_CriticalTask(42);
    ItcmFunction_BitOperation(0xAAAA5555);
```

```
    printf("\n--- Testing DTCM Functions ---\r\n");
    DtcmFunction_DataProcess(100);
    DtcmFunction_ArrayOperation(test_array, 5);

    printf("\n================================\r\n\r\n");
}

/*!
    \brief      main function
    \param[in]  none
    \param[out] none
    \retval     none
*/
void main(void)
{
    gd_eval_com_init(EVAL_COM);
    printf("GD32H7xx User Functions Address Test\r\n");
    printf("====================================\r\n");
    /* initialize user functions */
    UserFunctions_Init();
    /* enable the CPU cache */
    cache_enable();
    mpu_config();

    /* print all function addresses */
    PrintFunctionAddresses();
    /* test all functions */
    TestUserFunctions();

    printf("All function tests completed!\r\n");
    printf("Function address verification complete.\r\n\r\n");

    /* main application loop with periodic address display */
    uint32_t counter = 0;

    while(1) {
        counter++;

        if(counter % 5 == 1) {
            /* periodically show function addresses */
            printf("=== Periodic Address Check %d ===\r\n", counter);
```

```
            printf("FlashFunction_Calculate: 0x%08X\r\n", (uint32_t)FlashFunction_Calculate);
            printf("RamFunction_FastProcess:                    0x%08X\r\n",
(uint32_t)RamFunction_FastProcess);
            printf("ItcmFunction_CriticalTask: 0x%08X\r\n", (uint32_t)ItcmFunction_CriticalTask);
            printf("DtcmFunction_DataProcess:                   0x%08X\r\n",
(uint32_t)DtcmFunction_DataProcess);
            printf("==============================\r\n\r\n");
        }

        /* call functions to verify they work at reported addresses */
        FlashFunction_Calculate(counter, counter + 10);
        RamFunction_FastProcess(counter * 0x1000);
        ItcmFunction_CriticalTask(counter + 100);
        DtcmFunction_DataProcess(counter * 50);

        /* delay between iterations */
        for(volatile int i = 0; i < 2000000; i++);

        /* stop after several iterations */
        if(counter >= 3) {
            printf("Address verification demo completed.\r\n");
            break;
        }
    }

    while(1) {
    }
}
```

测试打印日志如*表 2-14. 将函数加载到指定位置日志*所示，测试结果与实际分配保持一致。

表 2-14. 将函数加载到指定位置日志

```
GD32H7xx User Functions Address Test
==================================
Initializing user functions...
Copying RAM functions...
  RAM functions: 0x2400C000 - 0x2400C0B0 (176 bytes)
Copying ITCM functions...
  ITCM functions: 0x00001000 - 0x000010A0 (160 bytes)
Copying DTCM functions...
  DTCM functions: 0x20001000 - 0x200010E0 (224 bytes)
User functions initialization completed!
```

```
=== Function Entry Addresses ===

--- FLASH Functions (Direct Execution) ---
Section Range: 0x08010000 - 0x080100C4
FlashFunction_Calculate        : 0x08010001
FlashFunction_ProcessData      : 0x08010071

--- RAM Functions (Copied from FLASH) ---
FLASH Source: 0x080100C4
RAM Target    : 0x2400C000 - 0x2400C0B0
RamFunction_FastProcess        : 0x2400C001
RamFunction_ProcessBuffer      : 0x2400C035

--- ITCM Functions ---
FLASH Source: 0x08010174
ITCM Target : 0x00001000 - 0x000010A0
ItcmFunction_CriticalTask      : 0x00001001
ItcmFunction_BitOperation      : 0x00001049

--- DTCM Functions ---
FLASH Source: 0x08010214
DTCM Target : 0x20001000 - 0x200010E0
DtcmFunction_DataProcess       : 0x20001001
DtcmFunction_ArrayOperation : 0x2000107D

================================

=== Testing User Functions ===

--- Testing FLASH Functions ---
FlashFunction_Calculate: a=15, b=25
FlashFunction_Calculate result: 18975
FlashFunction_ProcessData: processing 8 bytes
Data processing completed

--- Testing RAM Functions ---
RamFunction_ProcessBuffer: processing 8 elements
Buffer processing completed

--- Testing ITCM Functions ---
ItcmFunction_CriticalTask: input=42
```

```
ItcmFunction_CriticalTask result: 591753169
ItcmFunction_BitOperation: input=0xAAAA5555
ItcmFunction_BitOperation result: 0x88888888

--- Testing DTCM Functions ---
DtcmFunction_DataProcess: input=100
DtcmFunction_DataProcess result: 8160
DtcmFunction_ArrayOperation: processing 5 elements
Array operation completed

==============================

All function tests completed!
Function address verification complete.

=== Periodic Address Check 1 ===
FlashFunction_Calculate: 0x08010001
RamFunction_FastProcess: 0x2400C001
ItcmFunction_CriticalTask: 0x00001001
DtcmFunction_DataProcess: 0x20001001
==============================

FlashFunction_Calculate: a=1, b=11
FlashFunction_Calculate result: 775
ItcmFunction_CriticalTask: input=101
ItcmFunction_CriticalTask result: 591754465
DtcmFunction_DataProcess: input=50
DtcmFunction_DataProcess result: 6560
FlashFunction_Calculate: a=2, b=12
FlashFunction_Calculate result: 1425
ItcmFunction_CriticalTask: input=102
ItcmFunction_CriticalTask result: 591754257
DtcmFunction_DataProcess: input=100
DtcmFunction_DataProcess result: 8160
FlashFunction_Calculate: a=3, b=13
FlashFunction_Calculate result: 2175
ItcmFunction_CriticalTask: input=103
ItcmFunction_CriticalTask result: 591754305
DtcmFunction_DataProcess: input=150
DtcmFunction_DataProcess result: 9760
Address verification demo completed.
```

2.5. 将.c 文件代码段加载到指定位置

2.5.1. 自定义段

在链接脚本中添加用户自定义段，将.c 文件代码段分配到指定地址，地址分配如*表 2-15. 将.c 加载到指定位置地址分配总览*所示，链接文件代码如*表 2-16. gd32h7xx_flash.ld 中将全局变量和全局数组加载到指定位置*所示。

表 2-15. 将.c 加载到指定位置地址分配总览

模块文件	section 名称	FLASH 地址	RAM 地址	用途
flash_module.c	.flash_module_functions	0x08020000	-	直接在 FLASH 中执行
ram_module.c	.ram_module_functions	自动分配	0x2400D000	复制到 RAM 中执行
itcm_module.c	.itcm_module_functions	自动分配	0x00002000	复制到 ITCMRAM 中执行
dtcm_module.c	.dtcm_module_functions	自动分配	0x20002000	复制到 DTCMRAM 中执行
sram0_module.c	.sram0_module_functions	自动分配	0x3000800	复制到 SRAM0 中执行

表 2-16. gd32h7xx_flash.ld 中将全局变量和全局数组加载到指定位置

```
/* user file-based function scatter loading */
.flash_module_functions ALIGN(0x08020000, 4) :
{
    . = ALIGN(4);
    __flash_module_functions_start__ = .;
    KEEP(*flash_module.o(.text))
    KEEP(*flash_module.o(.text*))
    . = ALIGN(4);
    __flash_module_functions_end__ = .;
} > FLASH

.ram_module_functions ALIGN(0x2400D000,4):
{
    . = ALIGN(4);
    __ram_module_functions_start__ = .;
    KEEP(*ram_module.o(.text))
    KEEP(*ram_module.o(.text*))
    . = ALIGN(4);
    __ram_module_functions_end__ = .;
} > AXISRAM AT> FLASH
__ram_module_functions_loadaddr__ = LOADADDR(.ram_module_functions);

.itcm_module_functions   ALIGN(0x00002000,4):
{
    . = ALIGN(4);
```

```
    __itcm_module_functions_start__ = .;
    KEEP(*itcm_module.o(.text))
    KEEP(*itcm_module.o(.text*))
    . = ALIGN(4);
    __itcm_module_functions_end__ = .;
} > ITCMRAM AT> FLASH
__itcm_module_functions_loadaddr__ = LOADADDR(.itcm_module_functions);

.dtcm_module_functions    ALIGN(0x20002000,4):
{
    . = ALIGN(4);
    __dtcm_module_functions_start__ = .;
    KEEP(*dtcm_module.o(.text))
    KEEP(*dtcm_module.o(.text*))
    . = ALIGN(4);
    __dtcm_module_functions_end__ = .;
} > DTCMRAM AT> FLASH
__dtcm_module_functions_loadaddr__ = LOADADDR(.dtcm_module_functions);

.sram0_module_functions    ALIGN(0x30000800,4):
{
    . = ALIGN(4);
    __sram0_module_functions_start__ = .;
    KEEP(*sram0_module.o (.text))
    KEEP(*sram0_module.o(.text*))
    . = ALIGN(4);
    __sram0_module_functions_end__ = .;
} > SRAM0 AT> FLASH
__sram0_module_functions_loadaddr__ = LOADADDR(.sram0_module_functions);
```

2.5.2. C 代码中的文件定义

新建 dtcm_module.c、flash_module.c、itcm_module.c、ram_module.c 和 sram0_module.c 文件以及对应的头文件，并在每个 c 文件中定义各自的函数。主要如*表 2-17. .c 文件定义*所示。

表 2-17. .c 文件定义

```
/* dtcm_module.c */
int DtcmModule_Function1(int a, int b)
{
    /* Function with fast data access */
    printf("DtcmModule_Function1: a=%d, b=%d\r\n", a, b);
    dtcm_buffer[dtcm_counter % 64] = a + b;
```

```
    dtcm_counter++;
    return dtcm_buffer[(dtcm_counter - 1) % 64];
}
int DtcmModule_Function2(int x)
{
    /* Data-intensive function */
    printf("DtcmModule_Function2: x=%d\r\n", x);
    for(int i = 0; i < 32; i++) {
        dtcm_buffer[i] = x * i;
    }
    int sum = 0;
    for(int i = 0; i < 32; i++) {
        sum += dtcm_buffer[i];
    }
    return sum;
}
/* flash_module.c */
int FlashModule_Function1(int a, int b)
{
    /* Complex calculation function executed from FLASH */
    printf("FlashModule_Function1: a=%d, b=%d\r\n", a, b);
    int result = 0;
    for(int i = 0; i < 50; i++) {
        result += (a * b) + (i % 7);
    }
    return result;
}

int FlashModule_Function2(int x)
{
    /* Mathematical processing function */
    printf("FlashModule_Function2: x=%d\r\n", x);
    int temp = x;
    temp = temp * temp + 100;
    temp = temp % 1000;
    return temp;
}
/* itcm_module.c */
int ItcmModule_Function1(int a, int b)
{
    /* Ultra-fast critical function in ITCM */
    register int result = a * b;
```

```
    result = result + (result >> 4);
    result = result ^ 0x12345678;
    return result;
}

int ItcmModule_Function2(int x)
{
    /* Real-time processing function */
    register int temp = x;
    temp = (temp * 7) + 13;
    temp = temp & 0xFFFF;
    return temp;
}
/* ram_module.c */
int RamModule_Function1(int a, int b)
{
    /* Fast calculation function executed from RAM */
    printf("RamModule_Function1: a=%d, b=%d\r\n", a, b);
    register int result = a + b;
    result = result << 2;
    result = result ^ 0xAAAA;
    return result;
}

int RamModule_Function2(int x)
{
    /* High-speed processing function */
    printf("RamModule_Function2: x=%d\r\n", x);
    volatile int temp = x;
    for(int i = 0; i < 20; i++) {
        temp = (temp << 1) | (temp >> 31);
    }
    return temp;
}
/* sram0_module.c */
int Sram0Module_Function1(int a, int b)
{
    /* Function executed from SRAM0 */
    printf("Sram0Module_Function1: a=%d, b=%d\r\n", a, b);
    int result = a - b;
    if(result < 0) result = -result;
    return result * 2;
```

```
}
int Sram0Module_Function2(int x)
{
    /* Special processing function */
    printf("Sram0Module_Function2: x=%d\r\n", x);
    int temp = x;
    temp = temp + 0x1000;
    temp = temp & 0x7FFF;
    return temp;
}
```

2.5.3. 自定义初始化实现

在系统启动时调用自定义代码段初始化函数，如*表 2-18. .c 文件加载到指定位置初始化实现*所示。

表 2-18. .c 文件加载到指定位置初始化实现

```
void ModuleLoader_Init(void)
{
    uint32_t *src, *dst;
    uint32_t size;
    /* copy RAM module functions */
    src = &__ram_module_functions_loadaddr__;
    dst = &__ram_module_functions_start__;
    size = ((uint32_t)&__ram_module_functions_end__ -
(uint32_t)&__ram_module_functions_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }

    /* copy ITCM module functions */
    src = &__itcm_module_functions_loadaddr__;
    dst = &__itcm_module_functions_start__;
    size = ((uint32_t)&__itcm_module_functions_end__ -
(uint32_t)&__itcm_module_functions_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }

    /* copy DTCM module functions */
```

```
    src = &__dtcm_module_functions_loadaddr__;
    dst = &__dtcm_module_functions_start__;
    size = ((uint32_t)&__dtcm_module_functions_end__ -
(uint32_t)&__dtcm_module_functions_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }

    /* copy SRAM0 module functions */
    src = &__sram0_module_functions_loadaddr__;
    dst = &__sram0_module_functions_start__;
    size = ((uint32_t)&__sram0_module_functions_end__ -
(uint32_t)&__sram0_module_functions_start__) / 4;

    for(uint32_t i = 0; i < size; i++) {
        *dst++ = *src++;
    }
}
```

注意：初始化放在 cache 初始化函数之前。

2.5.4. 测试验证

通过串口打印的方式，测试将函数加载到指定位置内存布局验证，代码如*表 2-19. .c 文件加载到指定位置内存验证代码*所示。

表 2-19. .c 文件加载到指定位置内存验证代码

```
void TestAllModules(void)
{
    int result;
    uint8_t test_data[16] = {0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07, 0x08,
                             0x09, 0x0A, 0x0B, 0x0C, 0x0D, 0x0E, 0x0F, 0x10};

    printf("=== Testing C File-based Module Functions ===\r\n");

    /* Test FLASH module */
    printf("\n--- Testing FLASH Module (flash_module.c) ---\r\n");
    printf("Executing FlashModule_Function1 at 0x%08X\r\n", (uint32_t)FlashModule_Function1);
    result = FlashModule_Function1(15, 25);
    printf("Result: %d\r\n", result);

    printf("Executing FlashModule_Function2 at 0x%08X\r\n", (uint32_t)FlashModule_Function2);
```

```
    result = FlashModule_Function2(100);
    printf("Result: %d\r\n", result);

    printf("Executing FlashModule_ProcessData at 0x%08X\r\n",
(uint32_t)FlashModule_ProcessData);
    FlashModule_ProcessData(test_data, 8);

    /* Test RAM module */
    printf("\n--- Testing RAM Module (ram_module.c) ---\r\n");
    printf("Executing RamModule_Function1 at 0x%08X\r\n", (uint32_t)RamModule_Function1);
    result = RamModule_Function1(10, 20);
    printf("Result: %d\r\n", result);

    printf("Executing RamModule_Function2 at 0x%08X\r\n", (uint32_t)RamModule_Function2);
    result = RamModule_Function2(0x1234);
    printf("Result: 0x%08X\r\n", result);

    printf("Executing RamModule_ProcessData at 0x%08X\r\n",
(uint32_t)RamModule_ProcessData);
    RamModule_ProcessData(test_data, 8);

    /* Test ITCM module */
    printf("\n--- Testing ITCM Module (itcm_module.c) ---\r\n");
    printf("Executing ItcmModule_Function1 at 0x%08X\r\n", (uint32_t)ItcmModule_Function1);
    result = ItcmModule_Function1(7, 11);
    printf("Result: %d\r\n", result);

    printf("Executing ItcmModule_Function2 at 0x%08X\r\n", (uint32_t)ItcmModule_Function2);
    result = ItcmModule_Function2(500);
    printf("Result: %d\r\n", result);

    printf("Executing ItcmModule_ProcessData at 0x%08X\r\n",
(uint32_t)ItcmModule_ProcessData);
    ItcmModule_ProcessData(test_data, 8);

    /* Test DTCM module */
    printf("\n--- Testing DTCM Module (dtcm_module.c) ---\r\n");
    printf("Executing DtcmModule_Function1 at 0x%08X\r\n", (uint32_t)DtcmModule_Function1);
    result = DtcmModule_Function1(33, 44);
    printf("Result: %d\r\n", result);

    printf("Executing DtcmModule_Function2 at 0x%08X\r\n", (uint32_t)DtcmModule_Function2);
```

```
    result = DtcmModule_Function2(200);
    printf("Result: %d\r\n", result);

    printf("Executing DtcmModule_ProcessData at 0x%08X\r\n",
(uint32_t)DtcmModule_ProcessData);
    DtcmModule_ProcessData(test_data, 8);

    /* Test SRAM0 module */
    printf("\n--- Testing SRAM0 Module (sram0_module.c) ---\r\n");
    printf("Executing Sram0Module_Function1 at 0x%08X\r\n", (uint32_t)Sram0Module_Function1);
    result = Sram0Module_Function1(60, 40);
    printf("Result: %d\r\n", result);

    printf("Executing Sram0Module_Function2 at 0x%08X\r\n", (uint32_t)Sram0Module_Function2);
    result = Sram0Module_Function2(0x8000);
    printf("Result: 0x%04X\r\n", result);

    printf("Executing Sram0Module_ProcessData at 0x%08X\r\n",
(uint32_t)Sram0Module_ProcessData);
    Sram0Module_ProcessData(test_data, 8);

    printf("\n==========================================\r\n\r\n");
}

/*!
    \brief      main function
    \param[in]  none
    \param[out] none
    \retval     none
*/
void main(void)
{
    gd_eval_com_init(EVAL_COM);

    printf("GD32H7xx C File-based Scatter Loading Example\r\n");
    printf("==========================================\r\n");
    printf("This example demonstrates loading entire C files\r\n");
    printf("to different memory regions for optimized execution.\r\n\r\n");

    /* Initialize all modules */
    ModuleLoader_Init();
```

```
/* Enable the CPU cache */
cache_enable();
mpu_config();

/* Print all module function addresses */
PrintModuleAddresses();

/* Test all modules */
TestAllModules();

printf("All C file-based module tests completed!\r\n");
printf("Each module file is loaded to its designated memory region.\r\n");

uint32_t loop_count = 0;

while(1) {
    loop_count++;

    /* Periodic address verification */
    if(loop_count % 10 == 1) {
        printf("\n=== Periodic Address Verification (Loop %d) ===\r\n", loop_count);
        printf("flash_module.c functions in FLASH:\r\n");
        printf("    FlashModule_Function1: 0x%08X\r\n", (uint32_t)FlashModule_Function1);

        printf("ram_module.c functions in AXISRAM:\r\n");
        printf("    RamModule_Function1    : 0x%08X\r\n", (uint32_t)RamModule_Function1);

        printf("itcm_module.c functions in ITCMRAM:\r\n");
        printf("    ItcmModule_Function1 : 0x%08X\r\n", (uint32_t)ItcmModule_Function1);

        printf("dtcm_module.c functions in DTCMRAM:\r\n");
        printf("    DtcmModule_Function1 : 0x%08X\r\n", (uint32_t)DtcmModule_Function1);

        printf("sram0_module.c functions in SRAM0:\r\n");
        printf("    Sram0Module_Function1: 0x%08X\r\n", (uint32_t)Sram0Module_Function1);
        printf("============================================\r\n\r\n");
    }

    /* Simple delay */
    for(volatile int i = 0; i < 2000000; i++);

    /* Stop after a few loops for demonstration */
```

```
            if(loop_count >= 3) {
                printf("C file-based scatter loading demonstration completed.\r\n");
                break;
            }
        }

        while(1) {

        }
}
```

测试打印日志如*表 2-20. 将.c 文件加载到指定位置日志*所示，测试结果与实际分配保持一致。

表 2-20. 将.c 文件加载到指定位置日志

```
GD32H7xx C File-based Scatter Loading Example
==============================================
This example demonstrates loading entire C files
to different memory regions for optimized execution.

Initializing C file-based module functions...
Copying RAM module functions...
   RAM module: 0x2400D000 - 0x2400D158 (344 bytes)
Copying ITCM module functions...
   ITCM module: 0x00002000 - 0x000020E0 (224 bytes)
Copying DTCM module functions...
   DTCM module: 0x20002000 - 0x20002198 (408 bytes)
Copying SRAM0 module functions...
   SRAM0 module: 0x30000800 - 0x30000928 (296 bytes)
C file-based module functions initialization completed!


=== Module Function Entry Addresses ===

--- FLASH Module (flash_module.c) ---
Section Range: 0x08020000 - 0x08020130
FlashModule_Function1          : 0x08020001
FlashModule_Function2          : 0x08020065
FlashModule_ProcessData        : 0x080200B1
FlashModule_GetProcessedValue: 0x08020115

--- RAM Module (ram_module.c) ---
FLASH Source: 0x08020130
```

```
RAM Target    : 0x2400D000 - 0x2400D158
RamModule_Function1              : 0x2400D001
RamModule_Function2              : 0x2400D035
RamModule_ProcessData            : 0x2400D075
RamModule_SortArray              : 0x2400D11F

--- ITCM Module (itcm_module.c) ---
FLASH Source: 0x08020288
ITCM Target : 0x00002000 - 0x000020E0
ItcmModule_Function1             : 0x00002001
ItcmModule_Function2             : 0x0000202D
ItcmModule_ProcessData           : 0x0000204F
ItcmModule_CriticalCalculation: 0x000020B3

--- DTCM Module (dtcm_module.c) ---
FLASH Source: 0x08020368
DTCM Target : 0x20002000 - 0x20002198
DtcmModule_Function1             : 0x20002001
DtcmModule_Function2             : 0x2000206D
DtcmModule_ProcessData           : 0x200020D9
DtcmModule_GetBufferSum          : 0x20002155

--- SRAM0 Module (sram0_module.c) ---
FLASH Source: 0x08020500
SRAM0 Target: 0x30000800 - 0x30000928
Sram0Module_Function1            : 0x30000801
Sram0Module_Function2            : 0x30000839
Sram0Module_ProcessData          : 0x3000086D
Sram0Module_ValidateAndProcess: 0x300008F9

========================================

=== Testing C File-based Module Functions ===

--- Testing FLASH Module (flash_module.c) ---
Executing FlashModule_Function1 at 0x08020001
FlashModule_Function1: a=15, b=25
Result: 18897
Executing FlashModule_Function2 at 0x08020065
FlashModule_Function2: x=100
Result: 100
Executing FlashModule_ProcessData at 0x080200B1
```

```
FlashModule_ProcessData: processing 8 bytes

--- Testing RAM Module (ram_module.c) ---
Executing RamModule_Function1 at 0x2400D001
RamModule_Function1: a=10, b=20
Result: 43730
Executing RamModule_Function2 at 0x2400D035
RamModule_Function2: x=4660
Result: 0xFFFFFFFF
Executing RamModule_ProcessData at 0x2400D075
RamModule_ProcessData: processing 8 bytes

--- Testing ITCM Module (itcm_module.c) ---
Executing ItcmModule_Function1 at 0x00002001
Result: 305419817
Executing ItcmModule_Function2 at 0x0000202D
Result: 3513
Executing ItcmModule_ProcessData at 0x0000204F

--- Testing DTCM Module (dtcm_module.c) ---
Executing DtcmModule_Function1 at 0x20002001
DtcmModule_Function1: a=33, b=44
Result: 77
Executing DtcmModule_Function2 at 0x2000206D
DtcmModule_Function2: x=200
Result: 99200
Executing DtcmModule_ProcessData at 0x200020D9
DtcmModule_ProcessData: processing 8 bytes

--- Testing SRAM0 Module (sram0_module.c) ---
Executing Sram0Module_Function1 at 0x30000801
Sram0Module_Function1: a=60, b=40
Result: 40
Executing Sram0Module_Function2 at 0x30000839
Sram0Module_Function2: x=32768
Result: 0x1000
Executing Sram0Module_ProcessData at 0x3000086D
Sram0Module_ProcessData: processing 8 bytes

==========================================

All C file-based module tests completed!
```

```
Each module file is loaded to its designated memory region.

=== Periodic Address Verification (Loop 1) ===
flash_module.c functions in FLASH:
   FlashModule_Function1: 0x08020001
ram_module.c functions in AXISRAM:
   RamModule_Function1    : 0x2400D001
itcm_module.c functions in ITCMRAM:
   ItcmModule_Function1 : 0x00002001
dtcm_module.c functions in DTCMRAM:
   DtcmModule_Function1 : 0x20002001
sram0_module.c functions in SRAM0:
   Sram0Module_Function1: 0x30000801
================================================

C file-based scatter loading demonstration completed.
```

2.6. SDRAM 分散加载实现

SDRAM 分散加载的实现可参考 *2.3*、*2.4*、*2.5* 章节描述，在进行自定义初始化之前，需要实现 EXMC 初始化和 MPU 的相关配置，代码如*表 2-21. SDRAM 初始化代码*所示。

表 2-21. SDRAM 初始化代码

```
#include "exmc_sdram.h"
/*!
    \brief        initialize the sdram
    \param[in]    none
    \param[out] none
    \retval       none
*/
void DoInit(void)
{
    /* configure the clock of EXMC */
    rcu_exmc_config();
    /* configure the MPU */
    mpu_config();
    /* configure the EXMC access mode */
    exmc_synchronous_dynamic_ram_init(EXMC_SDRAM_DEVICE0);
    __IO int i,j;
    for(i=0;i<500;i++){
        for(j=0;j<5000;j++);
    }
```

```
}
```

注意 ：在 M7 内核的默认配置中，某些地址位于禁止指令执行的区域。因此，如果将代码加载到这些区域，在执行过程中会发生错误。GD32H7xx 的 EXMC 中的 SDRAM 地址分配范围为 0xC0000000-0xDFFFFFFF，该范围属于禁止指令执行的地址区域。需要配置 MPU（内存保护单元）寄存器，以启用 0xC0000000 地址范围内的指令执行。

3. 版本历史

表 3-1. 版本历史

版本号	说明	日期
1.0	首次发布	2025 年 12 月 31 日

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