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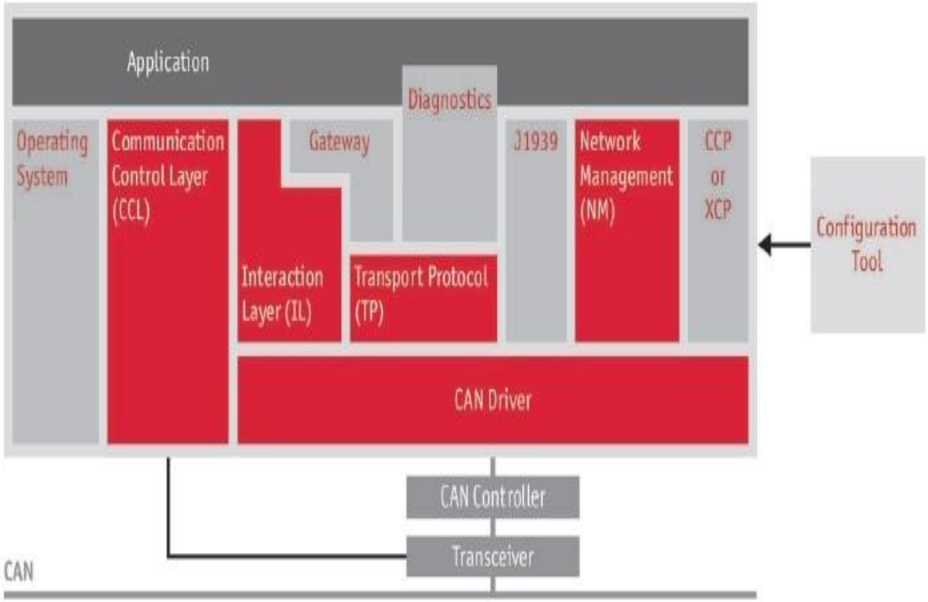

A Basic Approach to Embedded Software Architecture

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Objectives

- To introduce basic concepts and examples of software architecture applied to embedded system design and development

- To provide a basic point of view about embedded software architecture to students and other developers who are not yet involved in this product development culture

- To establish the important concepts and design methodology during undergraduate/graduate embedded systems courses

Note:

- The present material is intended for the audience attending the embedded systems workshop at Oakland University (mainly students). The content respect to methodology and source code is based on Author previous experience and current projects related to academics, it is not related to Vector CANTech Inc. products and/or tools

Definitions

Software Architecture

- The software architecture of a program or computing system is the structure or structures of the system, which comprise software elements, the externally visible properties of those elements, and the relationships among them. [Bass, Clements & Kazman, 2003]
- Collection of software components that follows an organized structure, and describes the overall system and it components behavior from a high-level design perspective

Embedded Software Architecture

- Structure and organization of multiple software components through different abstraction layers that intends to provide hardware independence, maximizes code reusability and propagates component behaviors, between multiple platforms of purpose-specific embedded computers

Definitions

“All architecture is design, but not all design is architecture. Architecture represents the significant design decisions that shape a system, where significant is measured by cost of change” [Grady Booch]

Definitions

Abstraction

- Simplified view of a system containing only the details important for a particular purpose [Berzins & Luqi, 1991]

Embedded Software Abstraction

- Design methodology used to hide hardware architecture details from the application software domain by the isolation and encapsulation of relevant parameters that describe the behavior of an specific hardware entity, in order to facilitate software component reusability and portability

Software Component

- In software system, a software component is an entity with well defined behavior and interacts with other components and modules within the system

Definitions

Software Interface

- A mechanism used by a software component or module to interact with the external world (i.e., analog/digital signals, RF) and other software components

Coupling

- Degree of dependency between different software components within a system

Cohesion

- Measures the degree of relationship between elements within a software component.

Reasons for Embedded Software Architecture

- The increasing complexity of system requirements as consequence of technology advancements in semiconductor industry

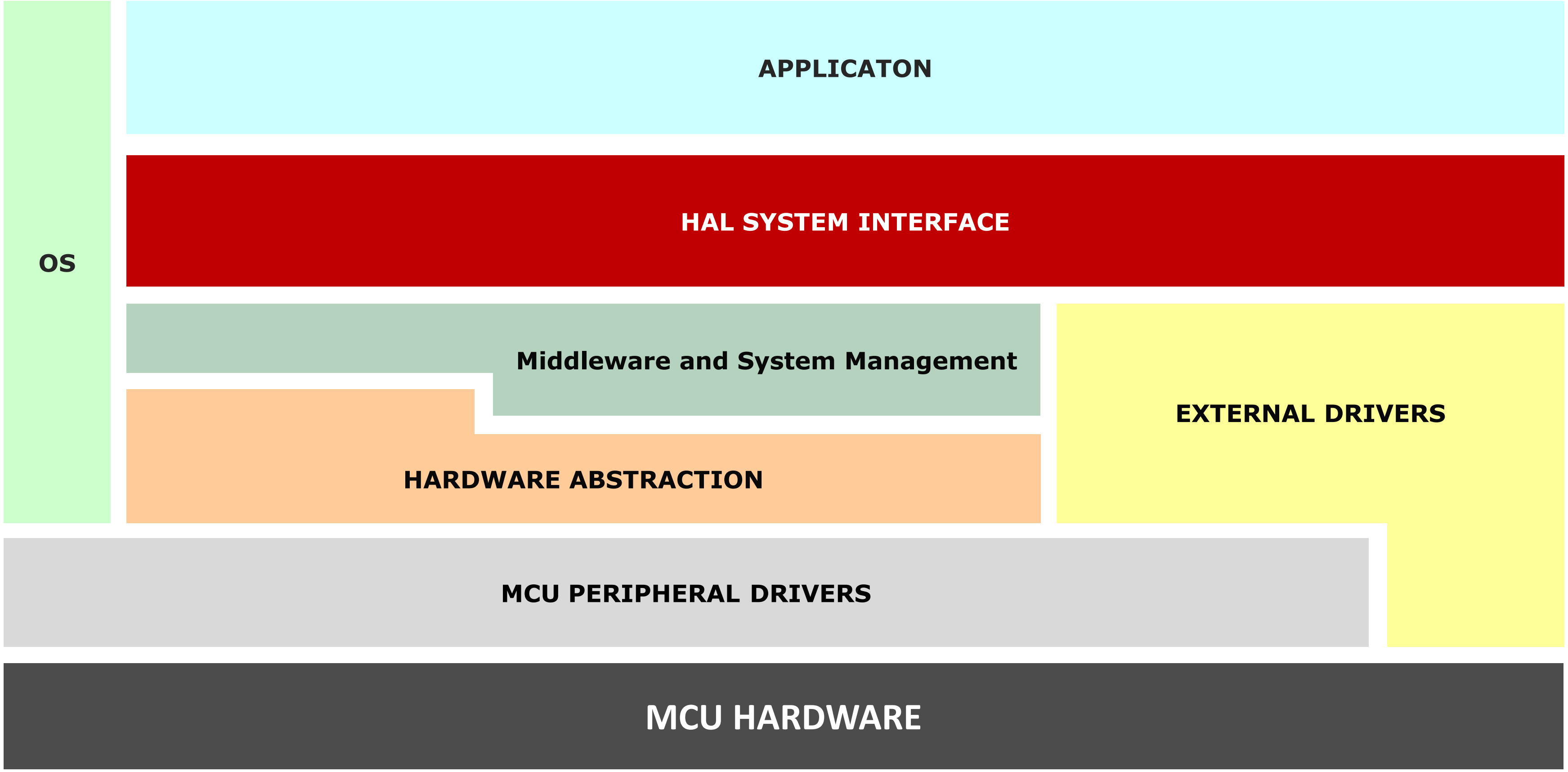
- Complex requirements critically impact the product life cycle. It is difficult to satisfy time-to-market demands (reduce development time and cost)

- Optimize and speed-up software development, without compromising safety, robustness and quality of the software components

- Improve software component reusability through multiple hardware platforms

Software Architecture Structure

Layered Architecture



OS

APPLICATON

HAL SYSTEM INTERFACE

Middleware and System Management

HARDWARE ABSTRACTION

EXTERNAL DRIVERS

MCU PERIPHERAL DRIVERS

MCU HARDWARE

Software Layers Description

MCU Peripheral Drivers

- Internal device drivers
- Hardware access to MCU peripherals
- Provide MCU low-level abstraction
- Hardware dependence is high, therefore, reuse is limited at this level
- Provide standard interfaces used by abstraction, OS and external driver layers

Software Layers Description

Hardware Abstraction Layer (HAL)

- Provides access to MCU hardware features through peripheral interfaces
- Hides hardware details not relevant to upper software layers
- Interfaces with MCU and external drivers in the low level side, and with HAL signal interface at the upper side

Middleware and System Management

- Facilitate the interaction between application components and other modules and/or components within the system:
  - Graphics Library
  - Networking
  - File Systems
  - Databases
  - Other Middleware components, i.e., off-the-shelf components

- Provides system management
  - Power Management
  - Memory management
  - Diagnostics

- Due to overhead, it is an optional layer

Software Layers Description

External Drivers

- Implements direct hardware access to external devices through MCU peripherals

- Meet all functional and timing requirements of the external devices

- Examples:
  - EEPROM (I2C™, SPI™, Microwire™, etc)
  - External ADCs (i.e. Delta-Sigma high-resolution converters)
  - Sensors and actuators

Software Layers Description

HAL System Interface

- Provides to the application one more level of abstraction and hardware independence
- Translates logical signals into a meaningful format for the application
- Facilitates the communication between application software components and/or lower layer modules
- It is application specific
- Due to overhead, it is an optional layer

Software Layers Description

Application Layer

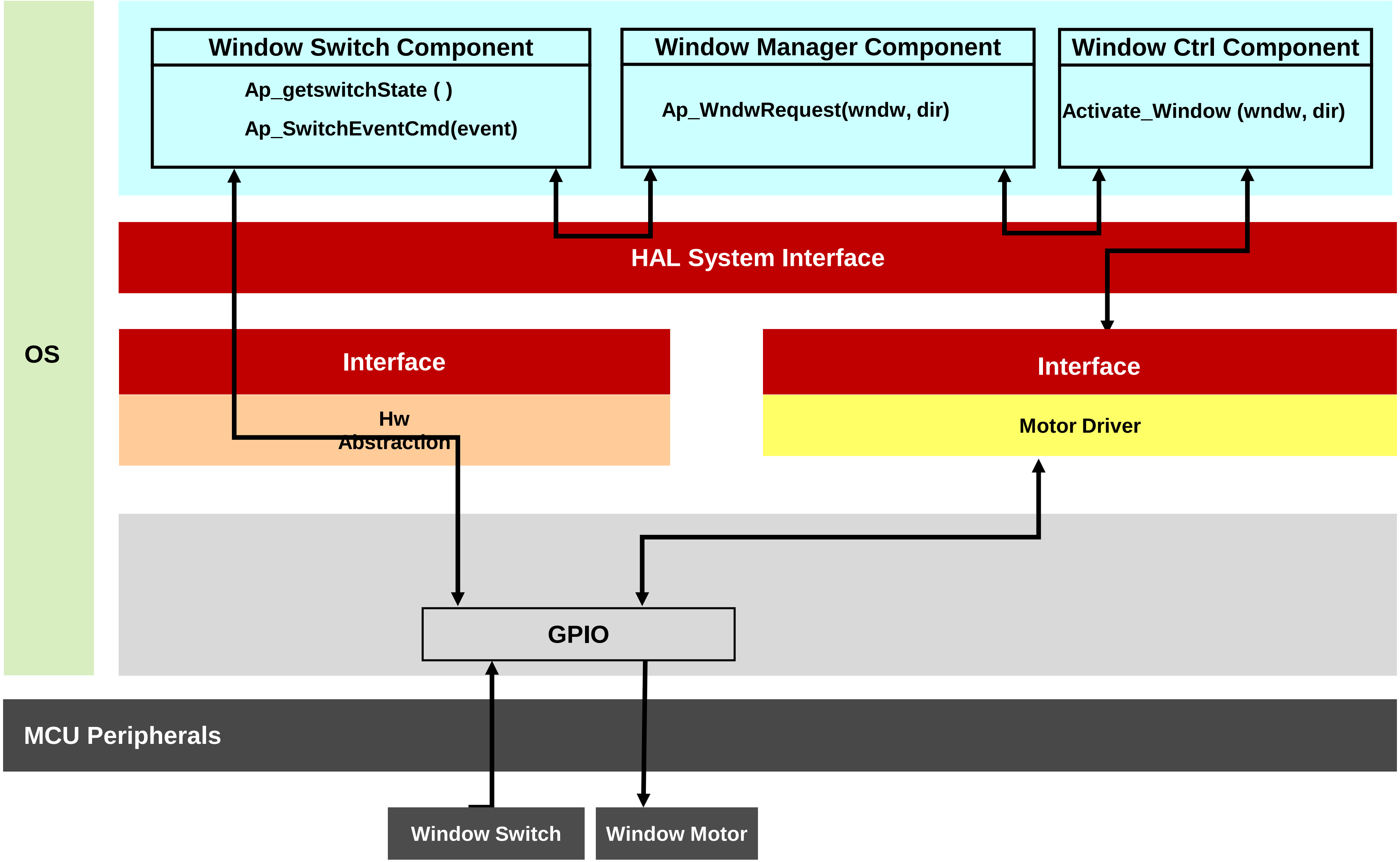
- Product specific functions
- Contains the software components that implements the desired functionality (unique) for a specific embedded computer system
- A high-level design methodology ignores the details of the hardware
- Reusability of application components strongly depends in the availability and efficiency of lower layers

Software Layers Description

OS Layer

- Provides support for multi-tasking
- Task scheduling and synchronization
- If real-time OS (RTOS)
    - Context –switching
    - Task preemption
    - Interrupt management

Example - Software components and module interaction



Example – Device Driver Module

Methodology:

- Understand device characteristics (internal or external)
  - Read device user manual, datasheet and application notes
  - Become familiar with the device (within the family)
- Identify and extract the characteristics that describe the device behavior
- Define component data types (needed for encapsulation)
- Design software component structures and interfaces
- Component implementation and testing
- Incorporate software component into software libraries

Example – MCU SPI™ Device Driver Module

- Data Abstraction – Extract common device characteristics
  - Operation mode (Master / Slave)
  - Data width
  - Clock polarity
  - Clock edge
  - Baudrate
  - Device selection (chip select - CS)

- MCUs can incorporate additional features, not part of SPI™ standard, that need to be addressed appropriately if used (not within the scope of this example)

- Data processing configuration
  - Enable/disable interrupts
  - Polling mode

Example – MCU SPI™ Device Driver (simple case)

- Define Interfaces
  - Driver Initialization
    - Init port pins
    - Init SPI physical channel
    - Init SPI interrupts (enable/disable)
  - Data transmission
    - Tx character
    - Rx character
    - Tx data buffer
    - Rx data buffer

Module Example – MCU SPI™ Device Driver (code snippets)

Module Data types

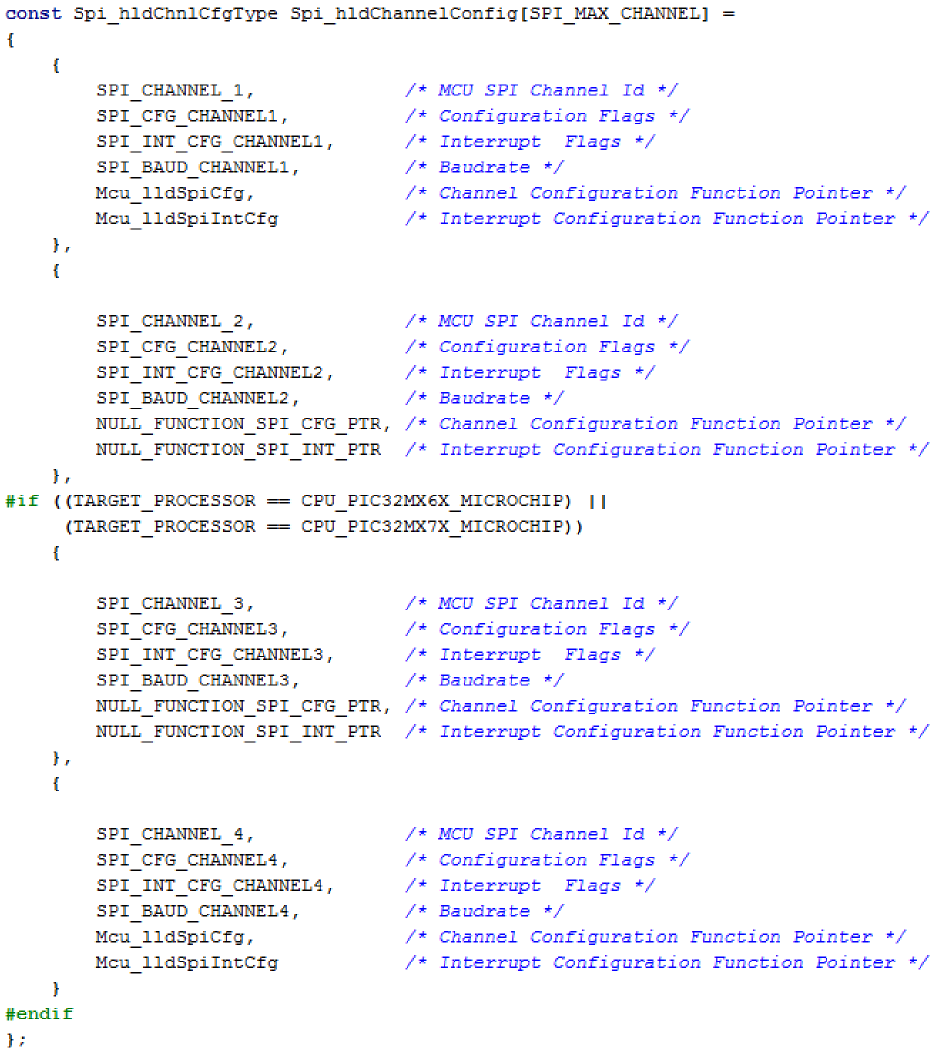
```
typedef struct Spi_hldChnlCfg
{
   Spi_hldChnlIdType                 channelId;
   Spi_hldCfgFlagType                cfgFlags;
   Spi_hldIntCfgFlagType             intCfgFlags;
   Spi_hldBaudRateType               baudRate;
   Spi_hldCallbackCfgType            cfgFnctnPtr;
   Spi_hldCallbackIntCfgType         intCfgFnctnPtr;
} Spi_hldChnlCfgType;

typedef struct Spi_hldCsCfg
{
  Spi_hldcsIndexType                 csId;
  Spi_hldCsEnType                    csEnable;
  Spi_hldCsPolType                   csPolarity;
  Spi_hldCsDlyEnType                 csDelayEn;
  Spi_hldCsDlyTimeType               csDelayTime;
  Spi_hldCsPortType                  csPort;
} Spi_hldCsCfgType;
```

Module Configuration

```
const Spi_hldCsCfgType Spi_hldCsConfig[SPI_MAX_CS_NUMBER] =
{
  {SPI_CS0, SPI_CS_ENABLE,  SPI_CS_POL_LOW, SPI_CS_DLY_DISABLE, 0, EE_CS},
  {SPI_CS1, SPI_CS_DISABLE, SPI_CS_POL_LOW, SPI_CS_DLY_DISABLE, 0, ADS124x_CS},
  {SPI_CS2, SPI_CS_DISABLE, SPI_CS_POL_LOW, SPI_CS_DLY_DISABLE, 0, GPIO_NULL},
  {SPI_CS3, SPI_CS_DISABLE, SPI_CS_POL_LOW, SPI_CS_DLY_DISABLE, 0, GPIO_NULL}
};
```

Module Example – MCU SPI™ Device Driver (code snippets)

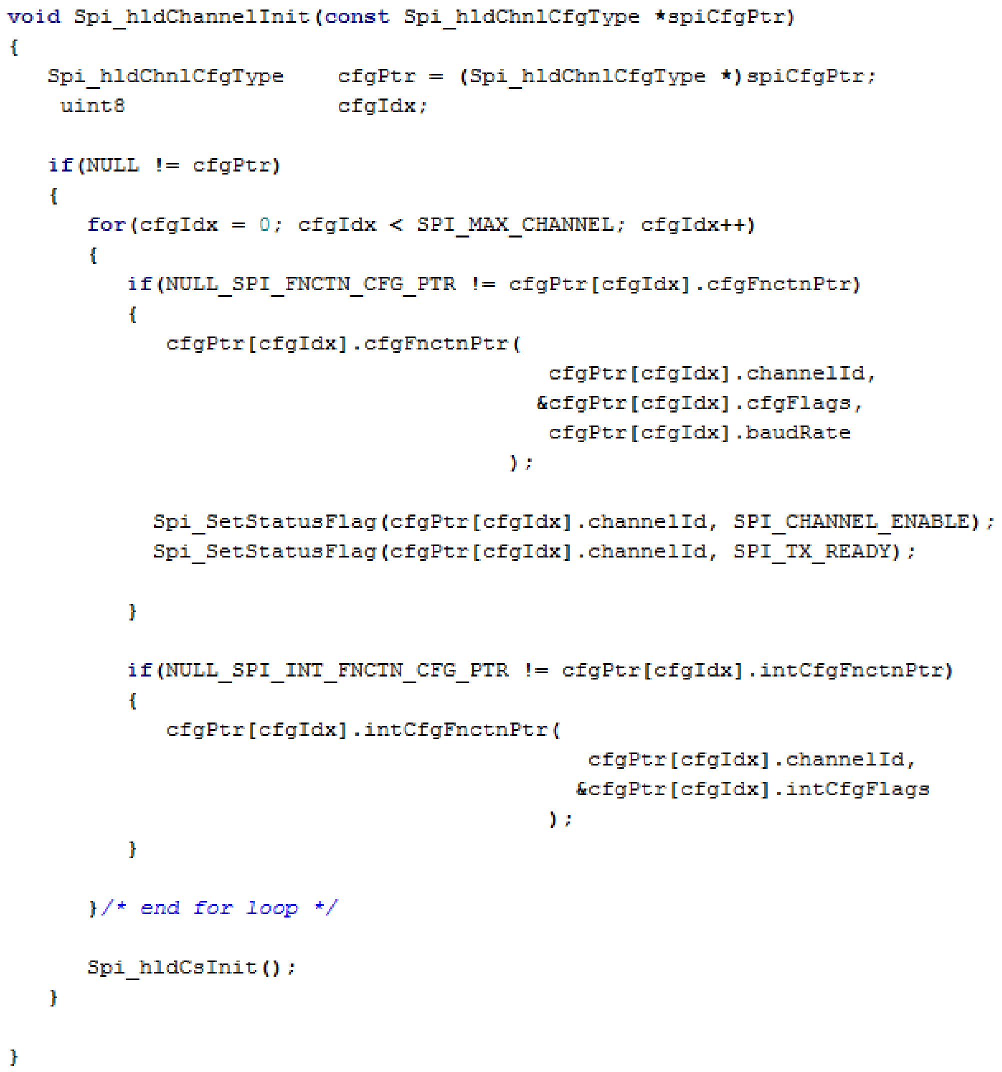
Module Configuration (Cont…)



```
const Spi_hldChnlCfgType Spi_hldChannelConfig[SPI_MAX_CHANNEL] =
{
    {
        SPI_CHANNEL_1,                 /* MCU SPI Channel Id */
        SPI_CFG_CHANNEL1,              /* Configuration Flags */
        SPI_INT_CFG_CHANNEL1,          /* Interrupt  Flags */
        SPI_BAUD_CHANNEL1,             /* Baudrate */
        Mcu_lldSpiCfg,                 /* Channel Configuration Function Pointer */
        Mcu_lldSpiIntCfg               /* Interrupt Configuration Function Pointer */
    },
    {

        SPI_CHANNEL_2,                 /* MCU SPI Channel Id */
        SPI_CFG_CHANNEL2,              /* Configuration Flags */
        SPI_INT_CFG_CHANNEL2,          /* Interrupt  Flags */
        SPI_BAUD_CHANNEL2,             /* Baudrate */
        NULL_FUNCTION_SPI_CFG_PTR,     /* Channel Configuration Function Pointer */
        NULL_FUNCTION_SPI_INT_PTR      /* Interrupt Configuration Function Pointer */
    },
#if ((TARGET_PROCESSOR == CPU_PIC32MX6X_MICROCHIP) ||
     (TARGET_PROCESSOR == CPU_PIC32MX7X_MICROCHIP))
    {

        SPI_CHANNEL_3,                 /* MCU SPI Channel Id */
        SPI_CFG_CHANNEL3,              /* Configuration Flags */
        SPI_INT_CFG_CHANNEL3,          /* Interrupt  Flags */
        SPI_BAUD_CHANNEL3,             /* Baudrate */
        NULL_FUNCTION_SPI_CFG_PTR,     /* Channel Configuration Function Pointer */
        NULL_FUNCTION_SPI_INT_PTR      /* Interrupt Configuration Function Pointer */
    },
    {

        SPI_CHANNEL_4,                 /* MCU SPI Channel Id */
        SPI_CFG_CHANNEL4,              /* Configuration Flags */
        SPI_INT_CFG_CHANNEL4,          /* Interrupt  Flags */
        SPI_BAUD_CHANNEL4,             /* Baudrate */
        Mcu_lldSpiCfg,                 /* Channel Configuration Function Pointer */
        Mcu_lldSpiIntCfg               /* Interrupt Configuration Function Pointer */
    }
#endif
};
```

Module Example – MCU SPI™ Device Driver (code snippets)

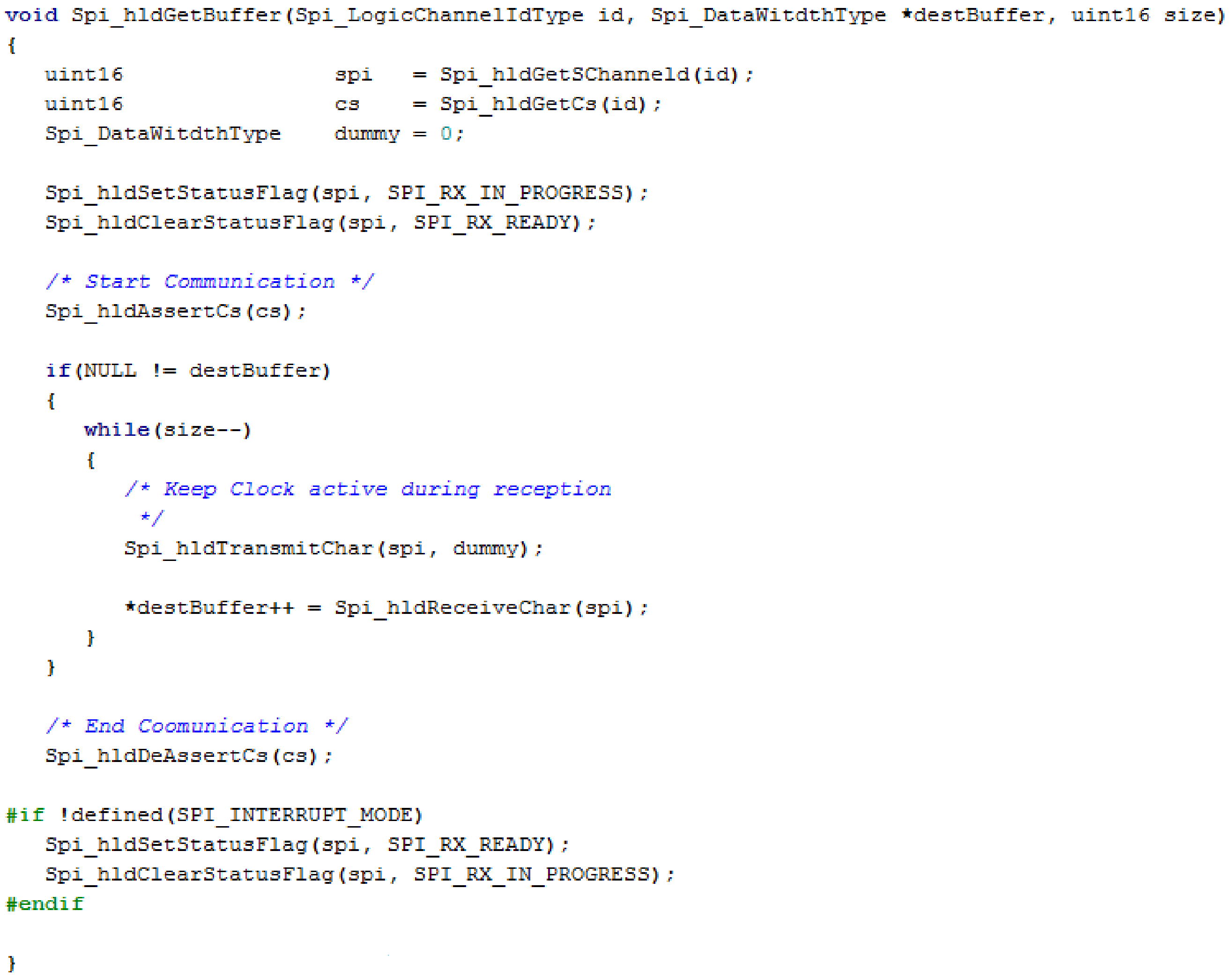
Module Interfaces - Initialization



```
void Spi_hldChannelInit(const Spi_hldChnlCfgType *spiCfgPtr)
{
   Spi_hldChnlCfgType     cfgPtr = (Spi_hldChnlCfgType *)spiCfgPtr;
    uint8                 cfgIdx;

   if(NULL != cfgPtr)
   {
      for(cfgIdx = 0; cfgIdx < SPI_MAX_CHANNEL; cfgIdx++)
      {
         if(NULL_SPI_FNCTN_CFG_PTR != cfgPtr[cfgIdx].cfgFnctnPtr)
         {
            cfgPtr[cfgIdx].cfgFnctnPtr(
                                         cfgPtr[cfgIdx].channelId,
                                        &cfgPtr[cfgIdx].cfgFlags,
                                         cfgPtr[cfgIdx].baudRate
                                      );

           Spi_SetStatusFlag(cfgPtr[cfgIdx].channelId, SPI_CHANNEL_ENABLE);
           Spi_SetStatusFlag(cfgPtr[cfgIdx].channelId, SPI_TX_READY);

         }

         if(NULL_SPI_INT_FNCTN_CFG_PTR != cfgPtr[cfgIdx].intCfgFnctnPtr)
         {
            cfgPtr[cfgIdx].intCfgFnctnPtr(
                                            cfgPtr[cfgIdx].channelId,
                                           &cfgPtr[cfgIdx].intCfgFlags
                                         );
         }

      }/* end for loop */

      Spi_hldCsInit();
   }

}
```

Module Example – MCU SPI™ Device Driver (code snippets)

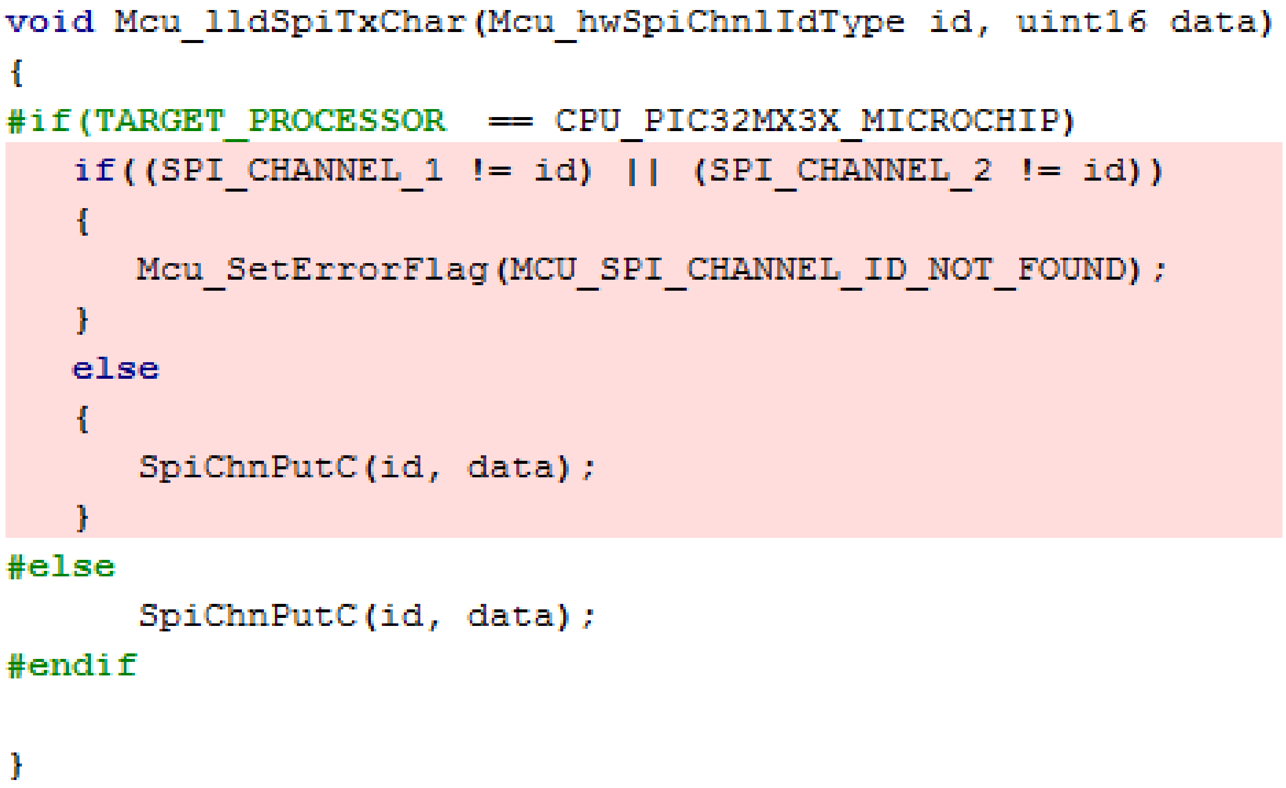
Module Interfaces – Rx Buffer



```
void Spi_hldGetBuffer(Spi_LogicChannelIdType id, Spi_DataWitdthType *destBuffer, uint16 size)
{
   uint16                  spi    = Spi_hldGetSChanneld(id);
   uint16                  cs     = Spi_hldGetCs(id);
   Spi_DataWitdthType      dummy = 0;

   Spi_hldSetStatusFlag(spi, SPI_RX_IN_PROGRESS);
   Spi_hldClearStatusFlag(spi, SPI_RX_READY);

   /* Start Communication */
   Spi_hldAssertCs(cs);

   if(NULL != destBuffer)
   {
      while(size--)
      {
         /* Keep Clock active during reception
          */
         Spi_hldTransmitChar(spi, dummy);

         *destBuffer++ = Spi_hldReceiveChar(spi);
      }
   }

   /* End Coomunication */
   Spi_hldDeAssertCs(cs);

#if !defined(SPI_INTERRUPT_MODE)
   Spi_hldSetStatusFlag(spi, SPI_RX_READY);
   Spi_hldClearStatusFlag(spi, SPI_RX_IN_PROGRESS);
#endif

}
```

Module Example – MCU SPI™ Device Driver (code snippets)

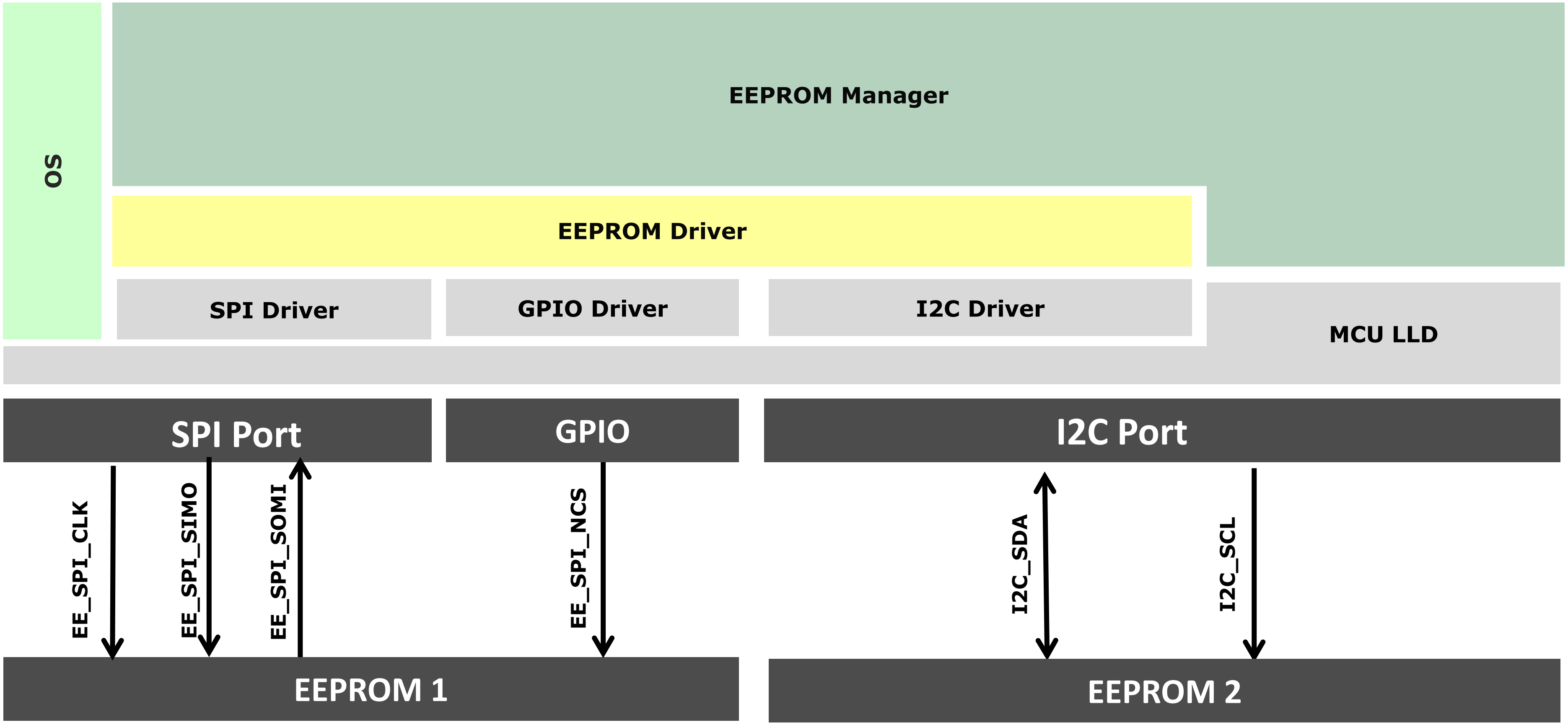
Module Interfaces – LLD SPI Rx interface



```
void Mcu_lldSpiTxChar(Mcu_hwSpiChnlIdType id, uint16 data)
{
#if(TARGET_PROCESSOR  == CPU_PIC32MX3X_MICROCHIP)
    if((SPI_CHANNEL_1 != id) || (SPI_CHANNEL_2 != id))
    {
        Mcu_SetErrorFlag(MCU_SPI_CHANNEL_ID_NOT_FOUND);
    }
    else
    {
        SpiChnPutC(id, data);
    }
#else
        SpiChnPutC(id, data);
#endif

}
```

Example – Module interaction

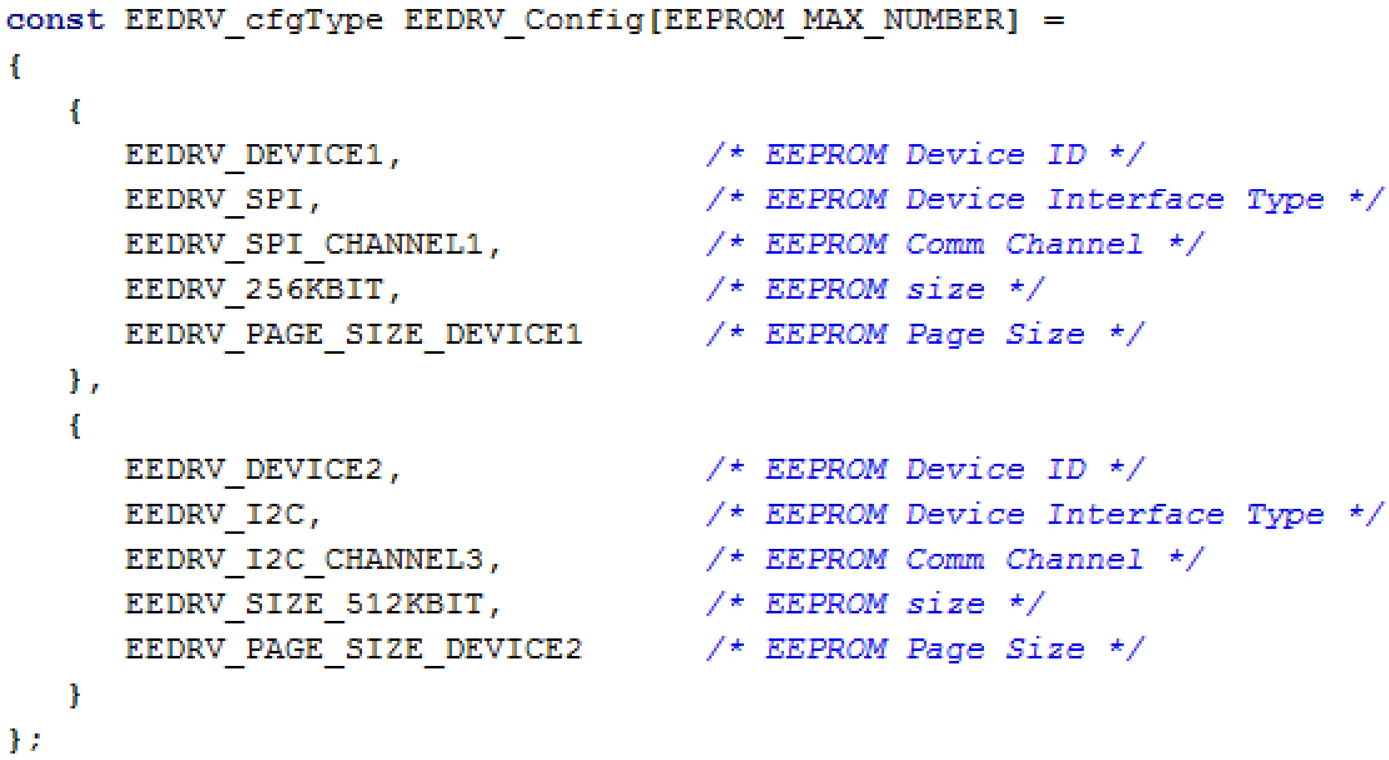
Inter-module interaction - EEPROM Module (External device)



Example – Module Interaction (code snippets)

Inter-module interaction - EEPROM Module (External device)

EEPROM Driver Initialization

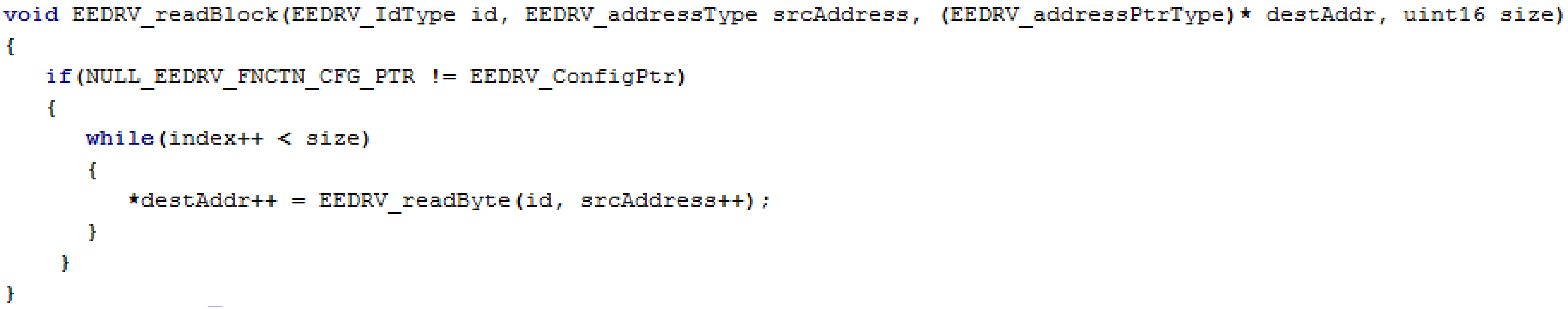


```
const EEDRV_cfgType EEDRV_Config[EEPROM_MAX_NUMBER] =
{
    {
        EEDRV_DEVICE1,                  /* EEPROM Device ID */
        EEDRV_SPI,                      /* EEPROM Device Interface Type */
        EEDRV_SPI_CHANNEL1,             /* EEPROM Comm Channel */
        EEDRV_256KBIT,                  /* EEPROM size */
        EEDRV_PAGE_SIZE_DEVICE1         /* EEPROM Page Size */
    },
    {
        EEDRV_DEVICE2,                  /* EEPROM Device ID */
        EEDRV_I2C,                      /* EEPROM Device Interface Type */
        EEDRV_I2C_CHANNEL3,             /* EEPROM Comm Channel */
        EEDRV_SIZE_512KBIT,             /* EEPROM size */
        EEDRV_PAGE_SIZE_DEVICE2         /* EEPROM Page Size */
    }
};
```

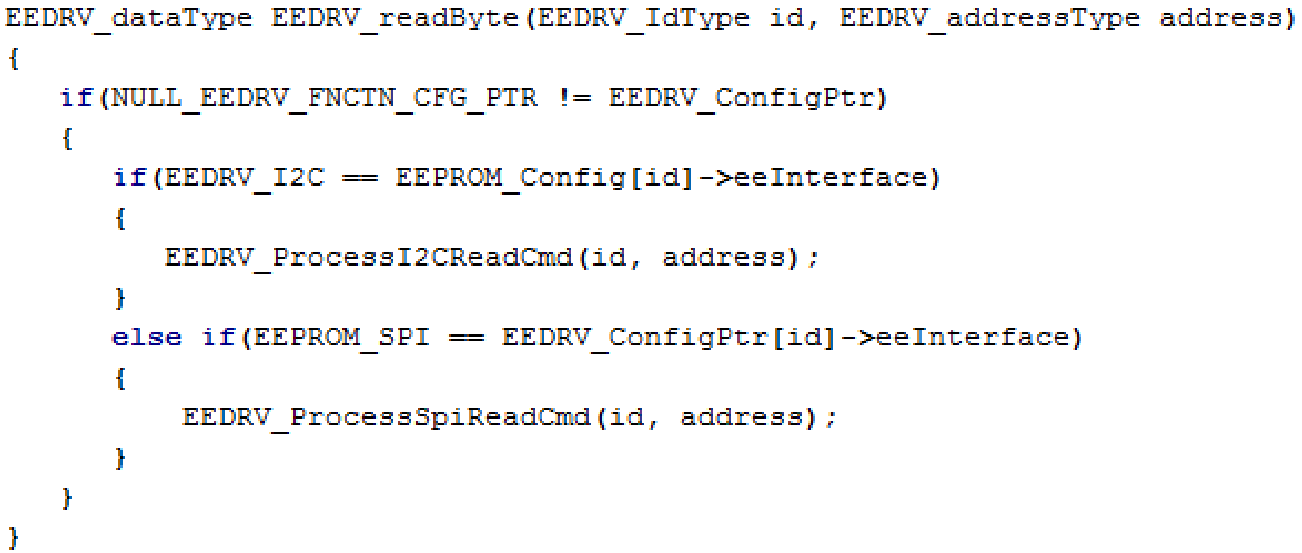
Example – Module Interaction (code snippets)

Inter-module interaction - EEPROM Module (External device)

EEPROM Driver – Read Memory Block



```
void EEDRV_readBlock(EEDRV_IdType id, EEDRV_addressType srcAddress, (EEDRV_addressPtrType)* destAddr, uint16 size)
{
    if(NULL_EEDRV_FNCTN_CFG_PTR != EEDRV_ConfigPtr)
    {
        while(index++ < size)
        {
            *destAddr++ = EEDRV_readByte(id, srcAddress++);
        }
    }
}
```

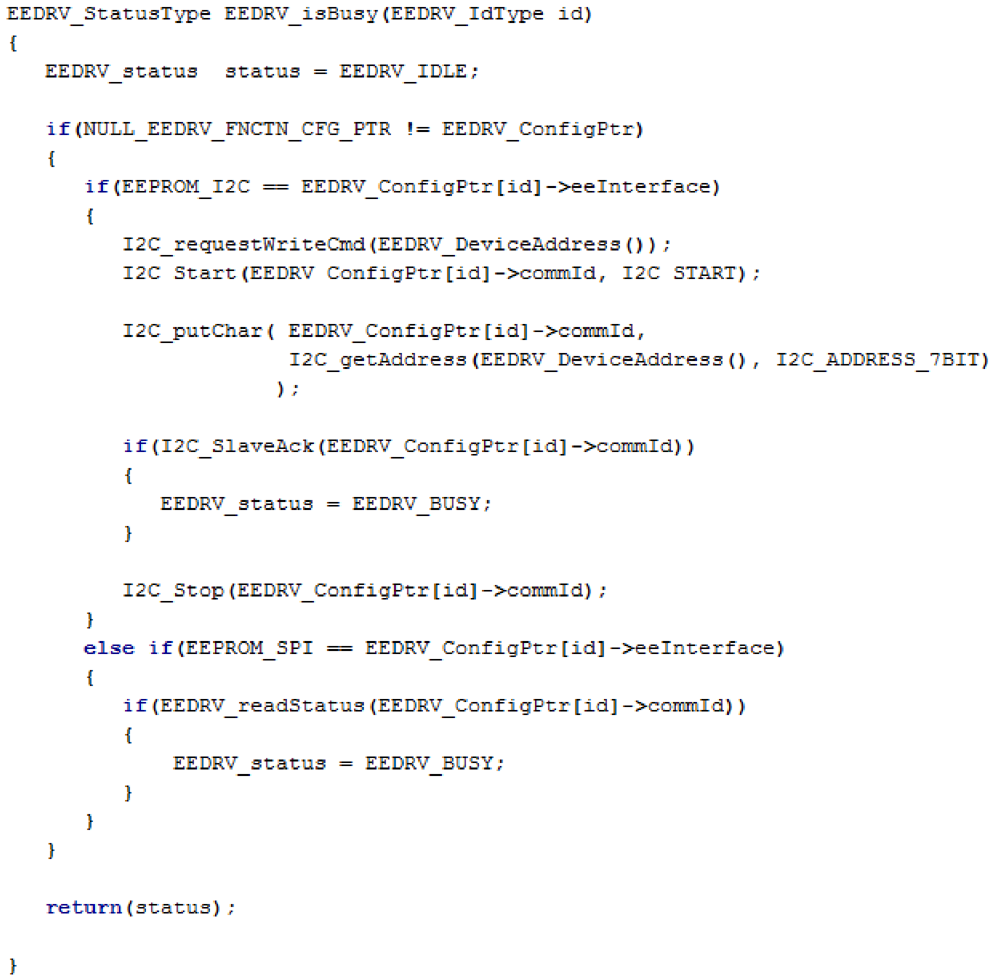


```
EEDRV_dataType EEDRV_readByte(EEDRV_IdType id, EEDRV_addressType address)
{
    if(NULL_EEDRV_FNCTN_CFG_PTR != EEDRV_ConfigPtr)
    {
        if(EEDRV_I2C == EEPROM_Config[id]->eeInterface)
        {
            EEDRV_ProcessI2CReadCmd(id, address);
        }
        else if(EEPROM_SPI == EEDRV_ConfigPtr[id]->eeInterface)
        {
            EEDRV_ProcessSpiReadCmd(id, address);
        }
    }
}
```

Example – Module Interaction (code snippets)

Interaction with other modules - EEPROM Module

EEPROM Driver– Write Cycle Status

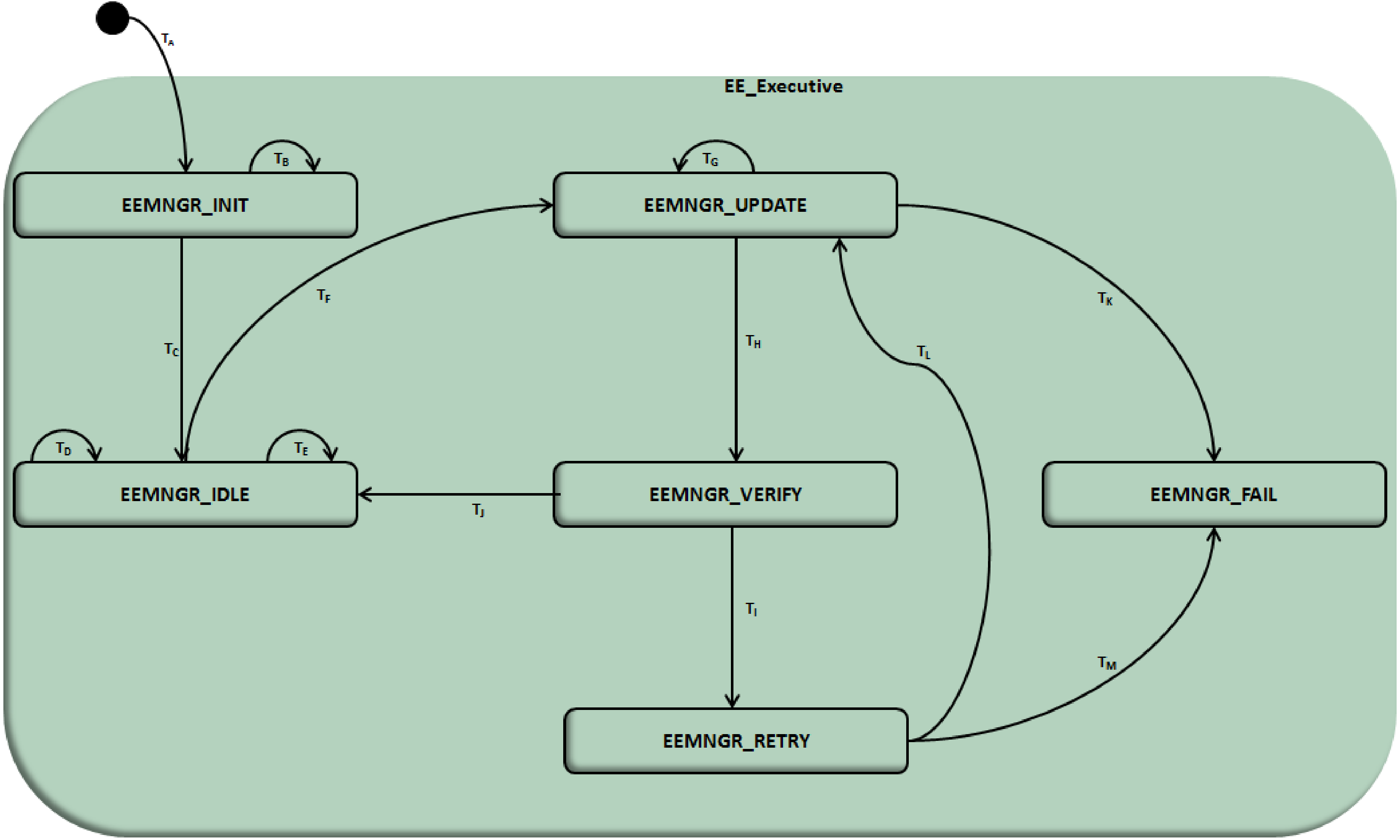


```
EEDRV_StatusType EEDRV_isBusy(EEDRV_IdType id)
{
   EEDRV_status  status = EEDRV_IDLE;

   if(NULL_EEDRV_FNCTN_CFG_PTR != EEDRV_ConfigPtr)
   {
      if(EEPROM_I2C == EEDRV_ConfigPtr[id]->eeInterface)
      {
         I2C_requestWriteCmd(EEDRV_DeviceAddress());
         I2C Start(EEDRV ConfigPtr[id]->commId, I2C START);

         I2C_putChar( EEDRV_ConfigPtr[id]->commId,
                      I2C_getAddress(EEDRV_DeviceAddress(), I2C_ADDRESS_7BIT)
                     );

         if(I2C_SlaveAck(EEDRV_ConfigPtr[id]->commId))
         {
            EEDRV_status = EEDRV_BUSY;
         }

         I2C_Stop(EEDRV_ConfigPtr[id]->commId);
      }
      else if(EEPROM_SPI == EEDRV_ConfigPtr[id]->eeInterface)
      {
         if(EEDRV_readStatus(EEDRV_ConfigPtr[id]->commId))
         {
             EEDRV_status = EEDRV_BUSY;
         }
      }
   }

   return(status);

}
```

Example – Module interaction

Interaction with other modules - EEPROM Module

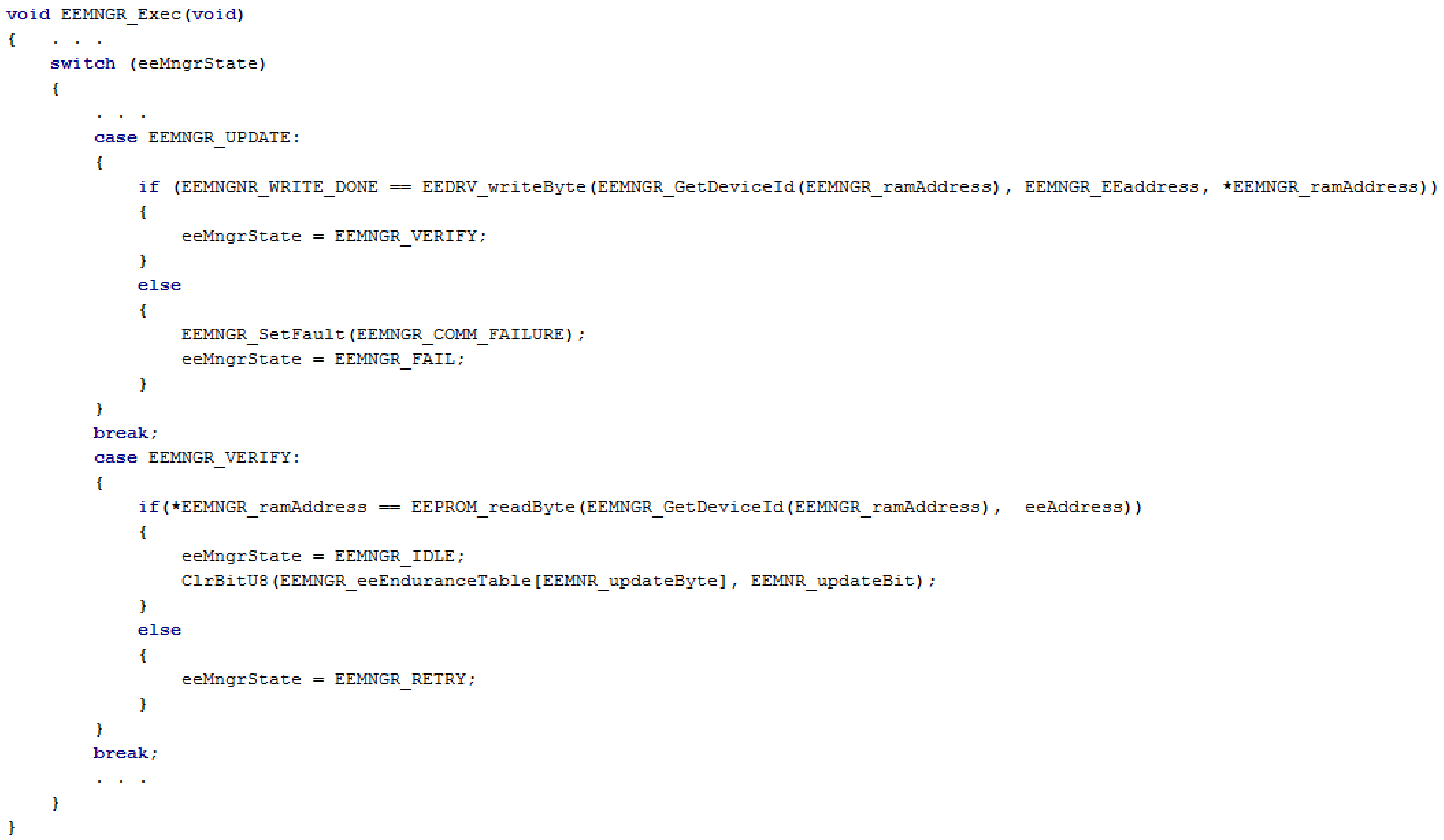
EEPROM Manager



Example – Module Interaction (code snippets)

Inter-module interaction - EEPROM Manager

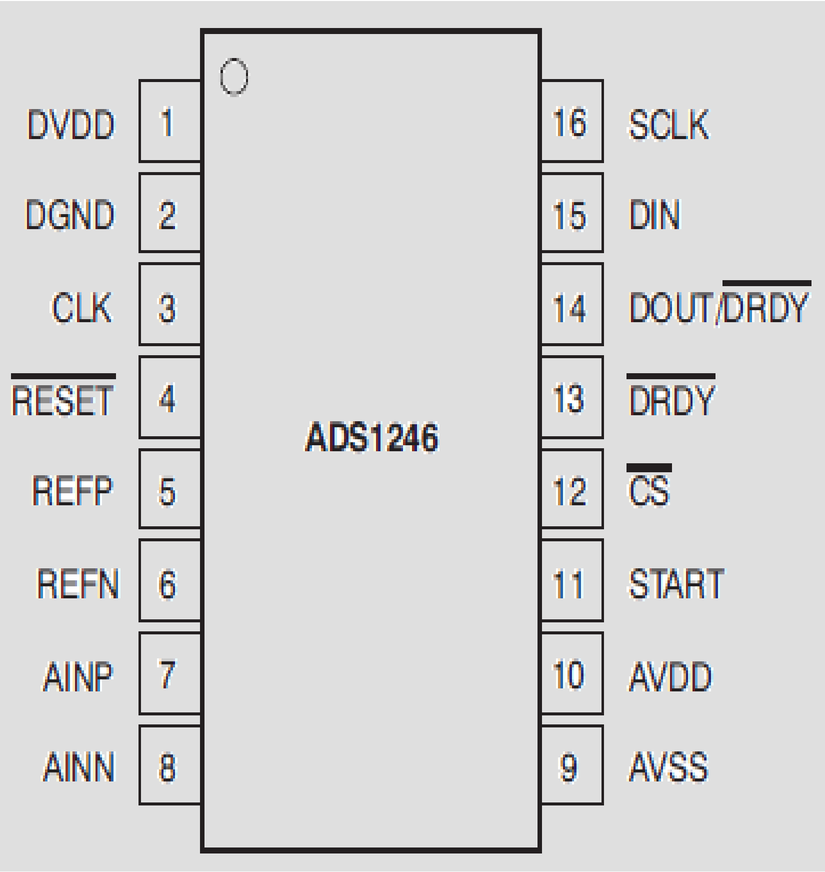
EEPROM Manager– Executive

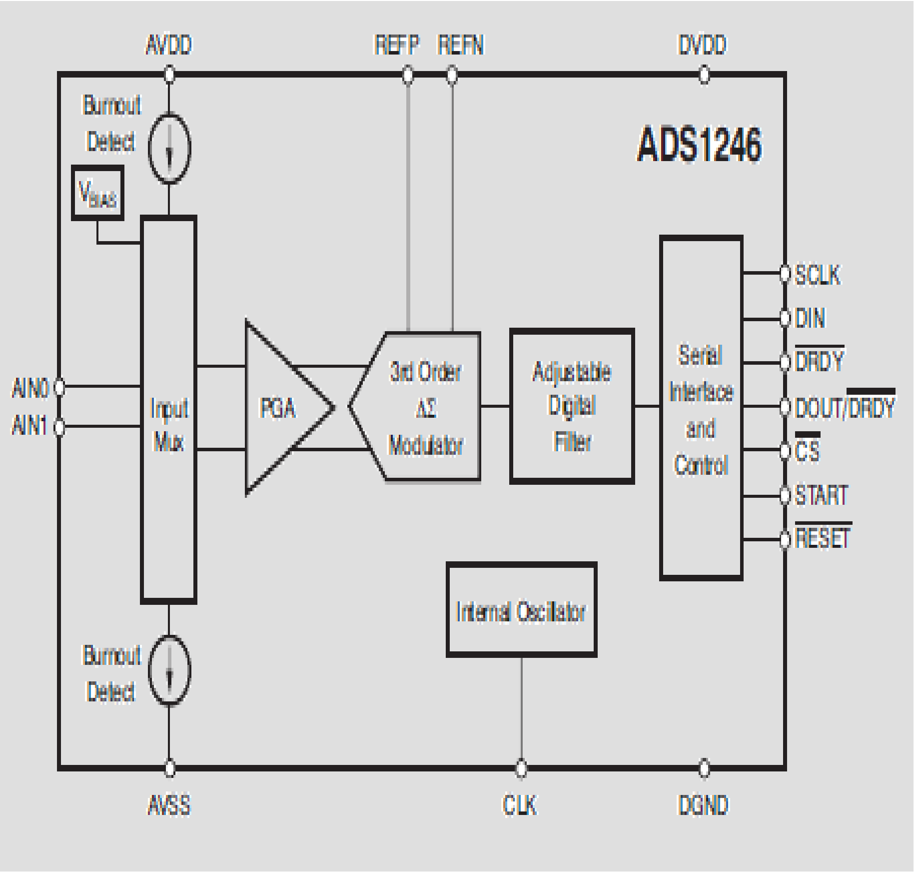


```
void EEMNGR_Exec(void)
{    . . .
    switch (eeMngrState)
    {
        . . .
        case EEMNGR_UPDATE:
        {
            if (EEMNGNR_WRITE_DONE == EEDRV_writeByte(EEMNGR_GetDeviceId(EEMNGR_ramAddress), EEMNGR_EEaddress, *EEMNGR_ramAddress))
            {
                eeMngrState = EEMNGR_VERIFY;
            }
            else
            {
                EEMNGR_SetFault(EEMNGR_COMM_FAILURE);
                eeMngrState = EEMNGR_FAIL;
            }
        }
        break;
        case EEMNGR_VERIFY:
        {
            if(*EEMNGR_ramAddress == EEPROM_readByte(EEMNGR_GetDeviceId(EEMNGR_ramAddress),  eeAddress))
            {
                eeMngrState = EEMNGR_IDLE;
                ClrBitU8(EEMNGR_eeEnduranceTable[EEMNR_updateByte], EEMNR_updateBit);
            }
            else
            {
                eeMngrState = EEMNGR_RETRY;
            }
        }
        break;
        . . .
    }
}
```

Module Example – External Software Driver

Sigma-Delta ADC TI ADS124x Family

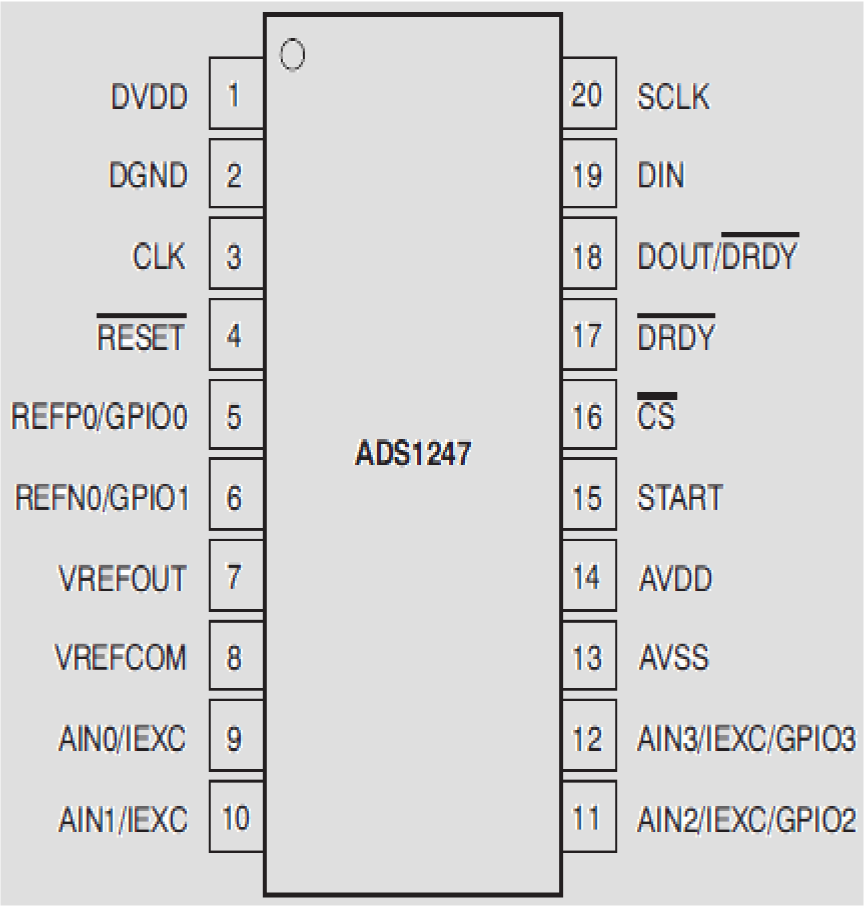


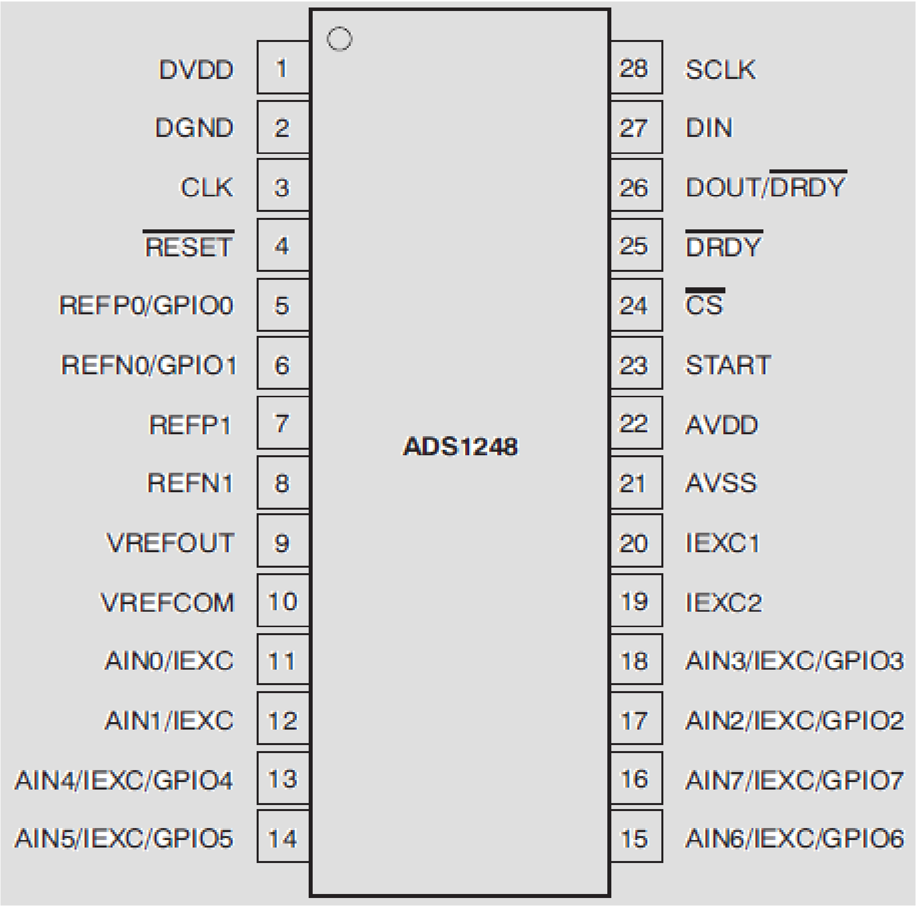


Source: ADS1246, ADS1247, ADS1248 datasheet, August 2008, Revised October 2011

Module Example – External Software Driver

Sigma-Delta ADC TI ADS124x Family

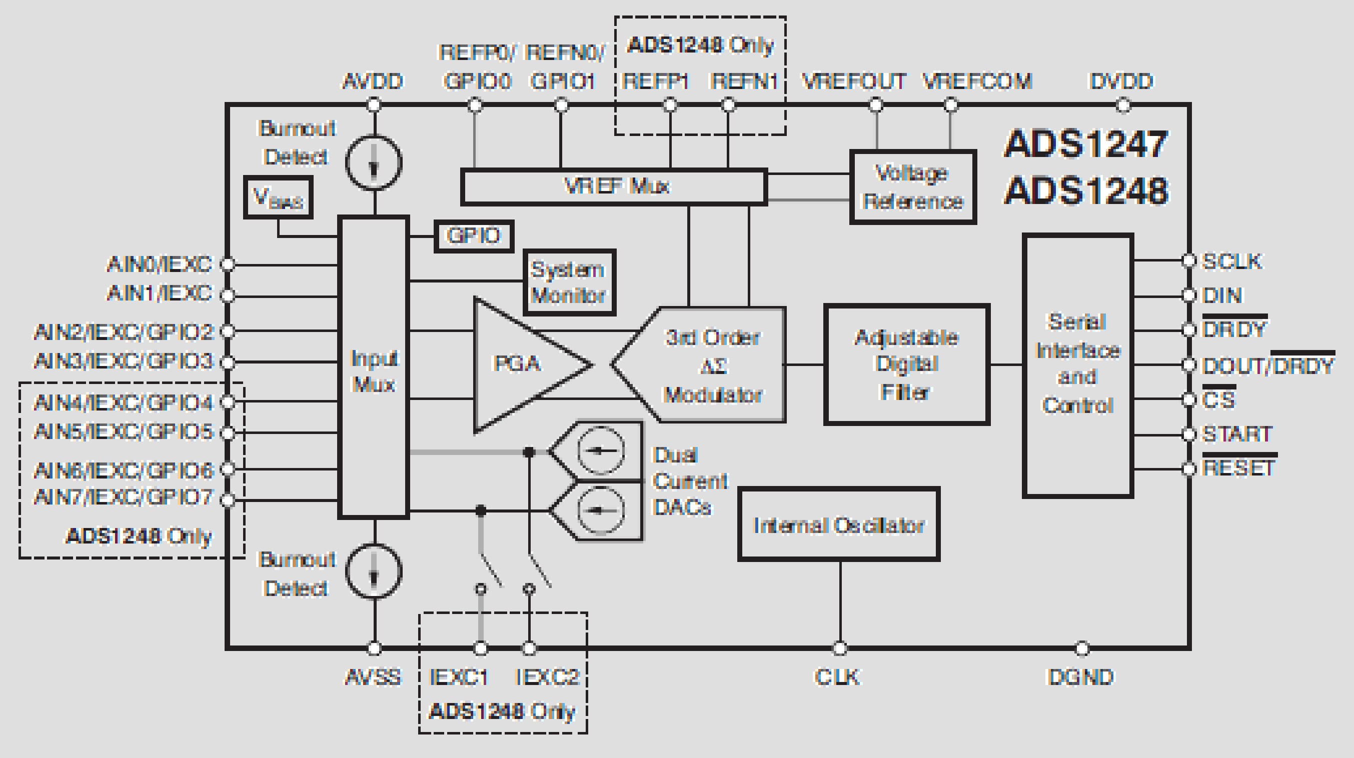




Source: ADS1246, ADS1247, ADS1248 datasheet, August 2008, Revised October 2011

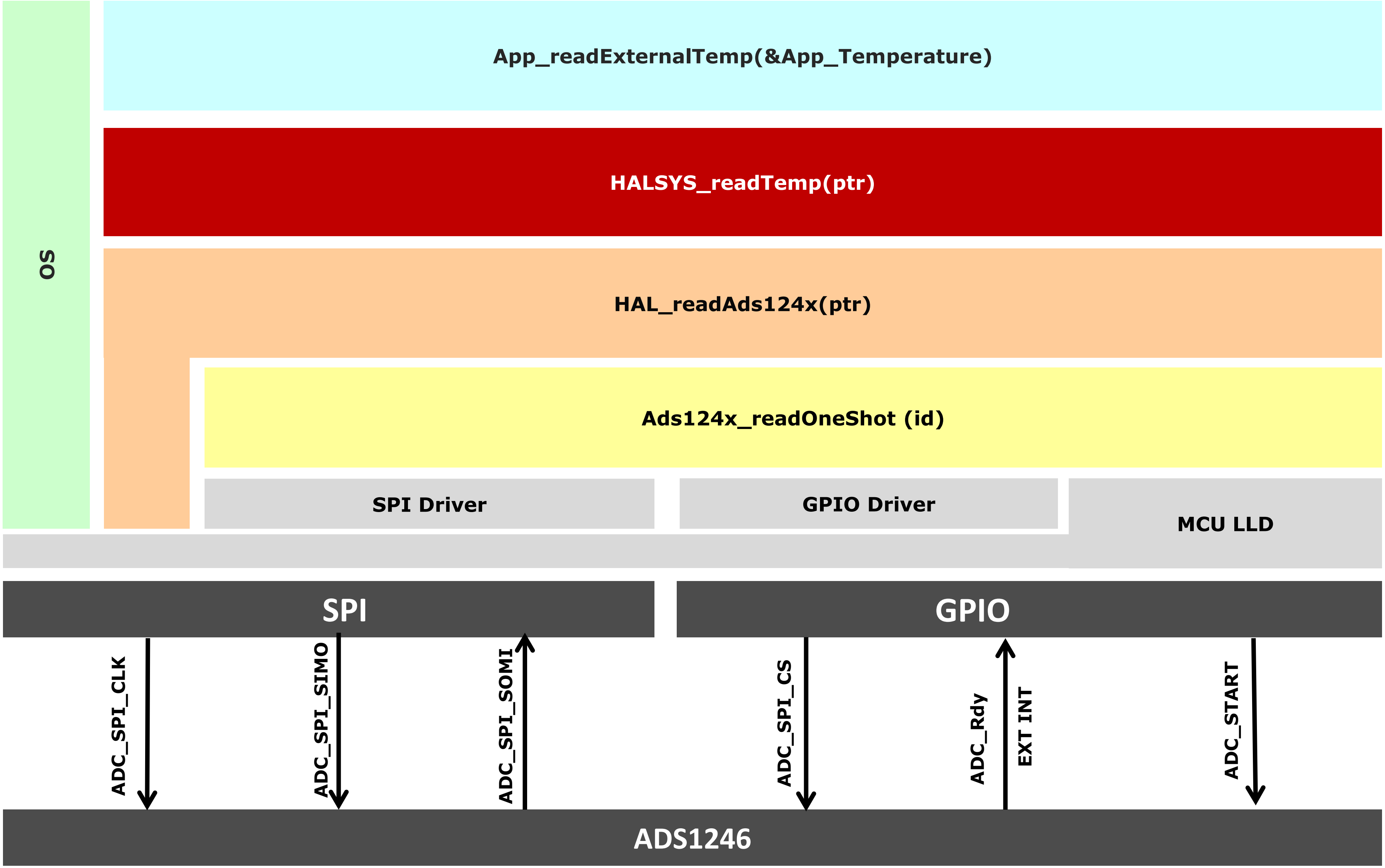
Module Example – External Software Driver

Sigma-Delta ADC TI ADS124x Family



Source: ADS1246, ADS1247, ADS1248 datasheet, August 2008, Revised October 2011

Module Example – External Software Driver



OS

App_readExternalTemp(&App_Temperature)

HALSYS_readTemp(ptr)

HAL_readAds124x(ptr)

Ads124x_readOneShot (id)

SPI Driver

GPIO Driver

MCU LLD

SPI

GPIO

ADC_SPI_CLK

ADC_SPI_SIMO

ADC_SPI_SOMI

ADC_SPI_CS

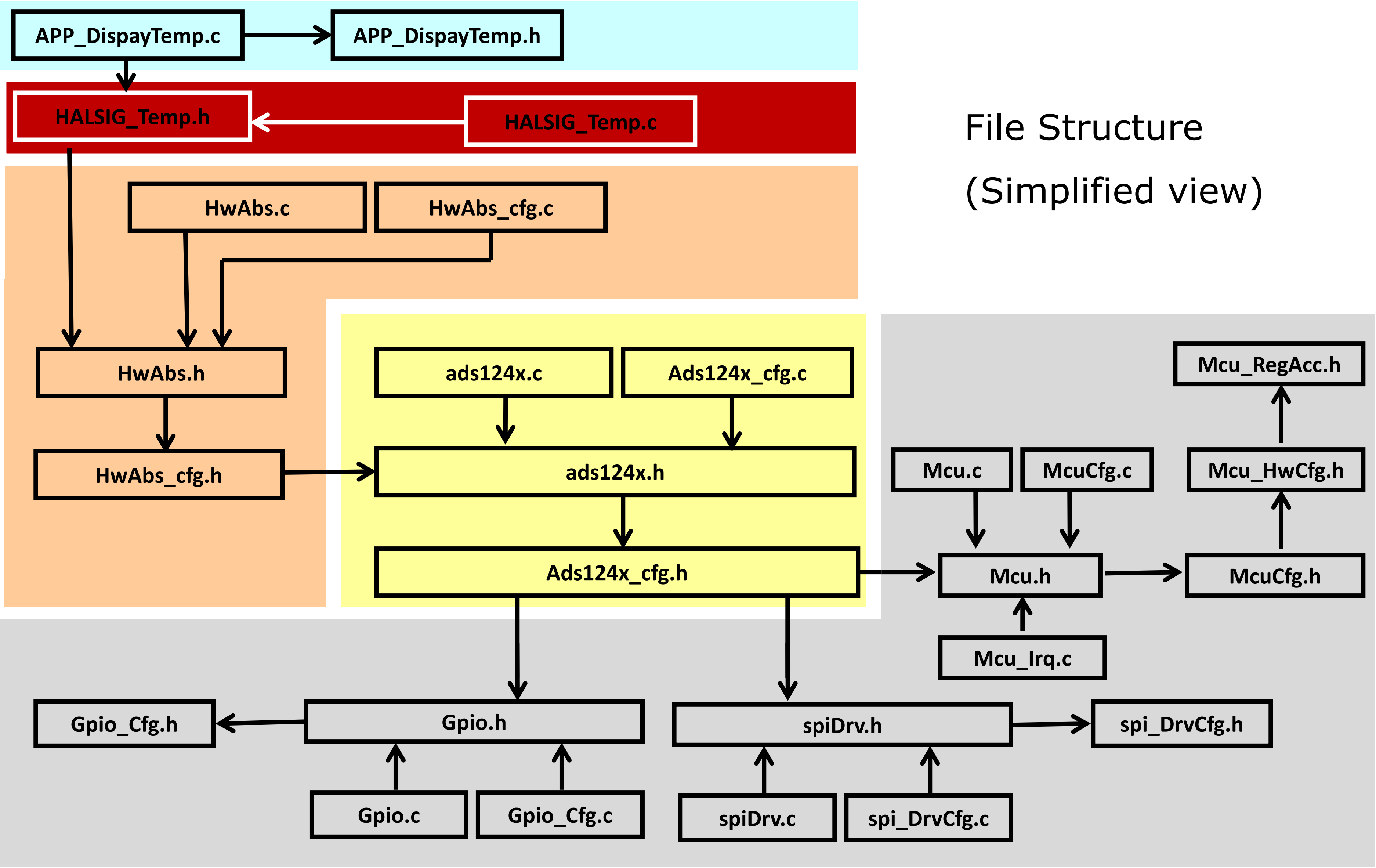
ADC_Rdy

EXT INT

ADC_START

ADS1246

Module Example – External Software Driver



APP_DispayTemp.c

APP_DispayTemp.h

HALSIG_Temp.h

HALSIG_Temp.c

HwAbs.c

HwAbs_cfg.c

HwAbs.h

HwAbs_cfg.h

ads124x.c

Ads124x_cfg.c

ads124x.h

Ads124x_cfg.h

Mcu_RegAcc.h

Mcu.c

McuCfg.c

Mcu_HwCfg.h

Mcu.h

McuCfg.h

Mcu_Irq.c

Gpio_Cfg.h

Gpio.h

spiDrv.h

spi_DrvCfg.h

Gpio.c

Gpio_Cfg.c

spiDrv.c

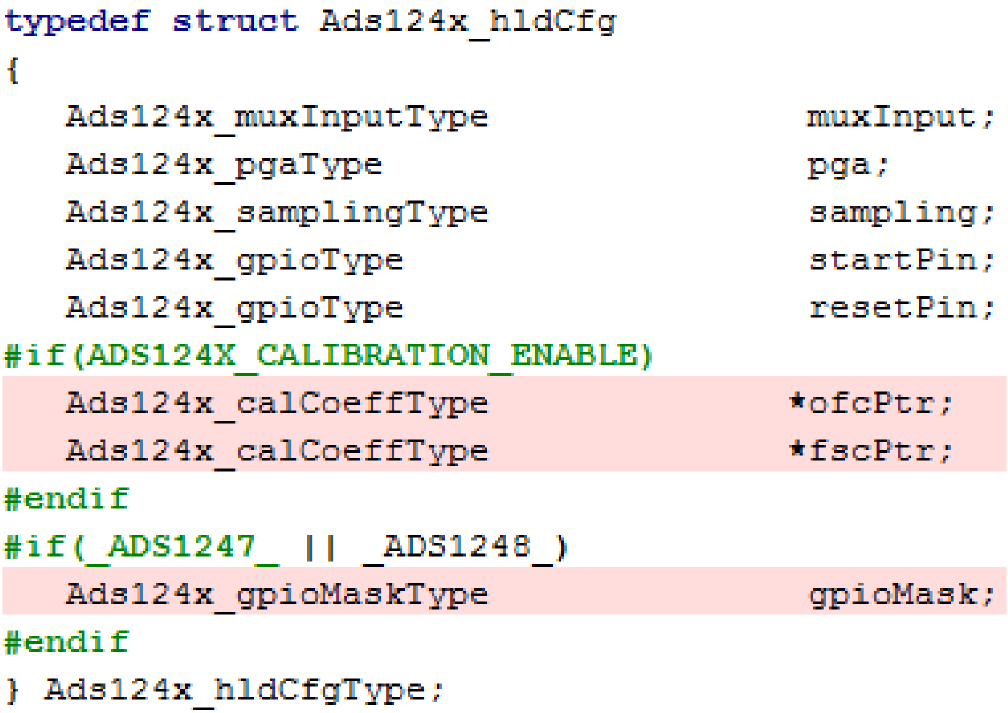
spi_DrvCfg.c

File Structure

(Simplified view)

Example – External Driver development example

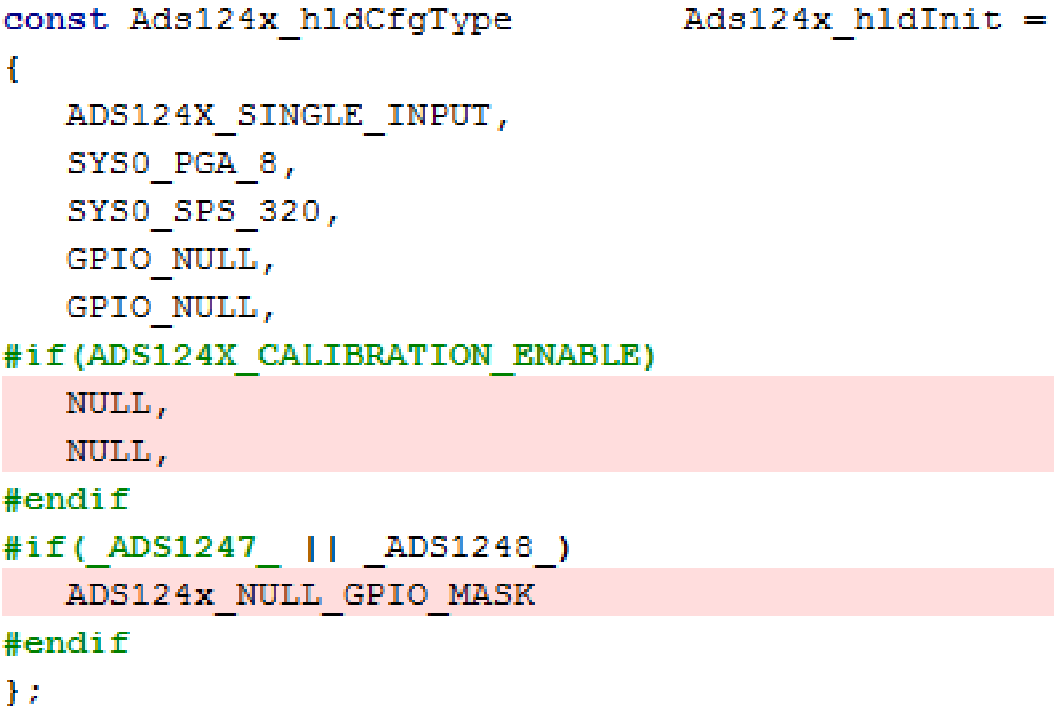
Module Data Types



```
typedef struct Ads124x_hldCfg
{
   Ads124x_muxInputType               muxInput;
   Ads124x_pgaType                    pga;
   Ads124x_samplingType               sampling;
   Ads124x_gpioType                   startPin;
   Ads124x_gpioType                   resetPin;
#if(ADS124X_CALIBRATION_ENABLE)
   Ads124x_calCoeffType              *ofcPtr;
   Ads124x_calCoeffType              *fscPtr;
#endif
#if(_ADS1247_ || _ADS1248_)
   Ads124x_gpioMaskType               gpioMask;
#endif
} Ads124x_hldCfgType;
```

Example – External Driver development example

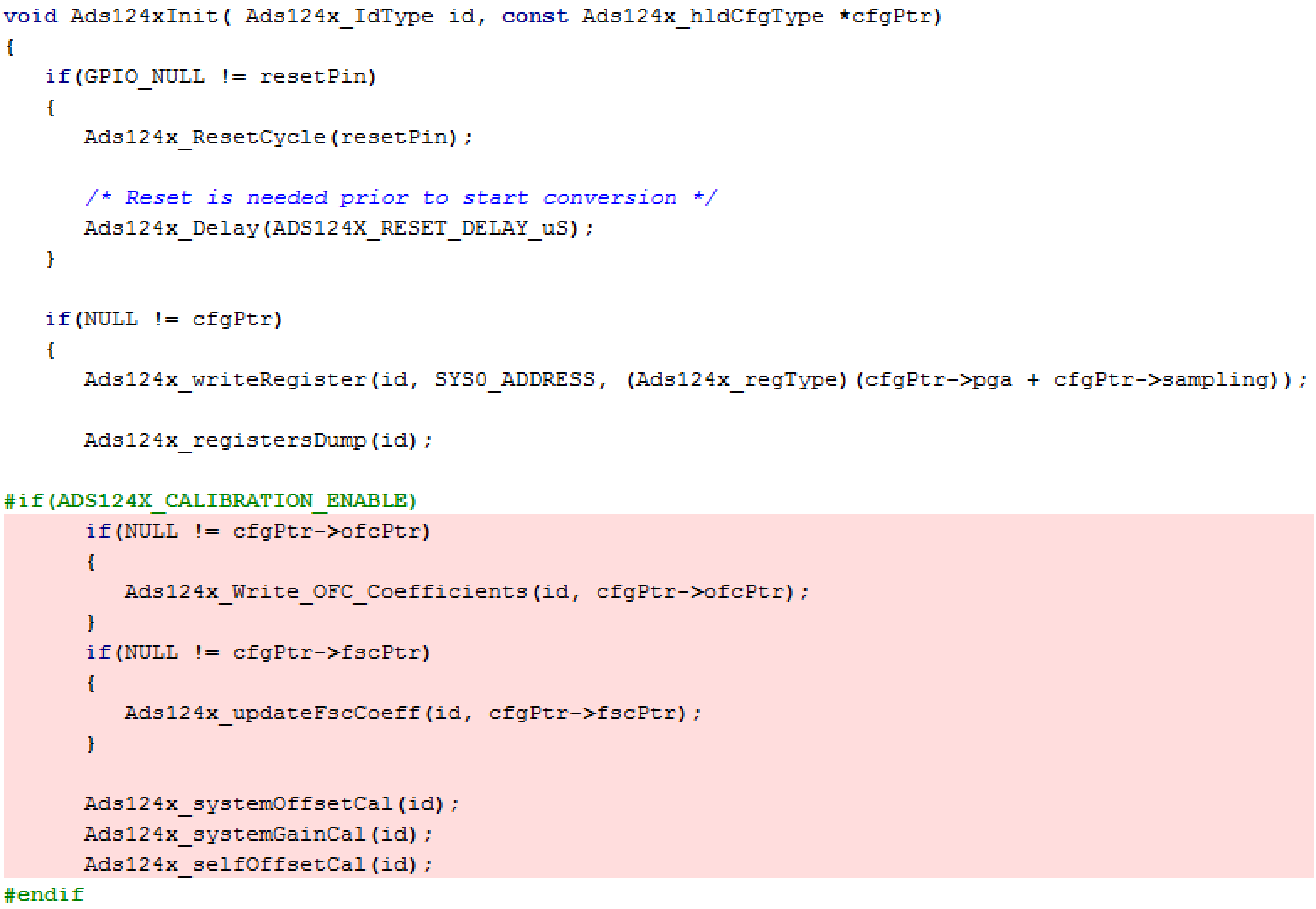
Module Initialization



```
const Ads124x_hldCfgType        Ads124x_hldInit =
{
   ADS124X_SINGLE_INPUT,
   SYS0_PGA_8,
   SYS0_SPS_320,
   GPIO_NULL,
   GPIO_NULL,
#if(ADS124X_CALIBRATION_ENABLE)
   NULL,
   NULL,
#endif
#if(_ADS1247_ || _ADS1248_)
   ADS124x_NULL_GPIO_MASK
#endif
};
```

Example – External Driver development example

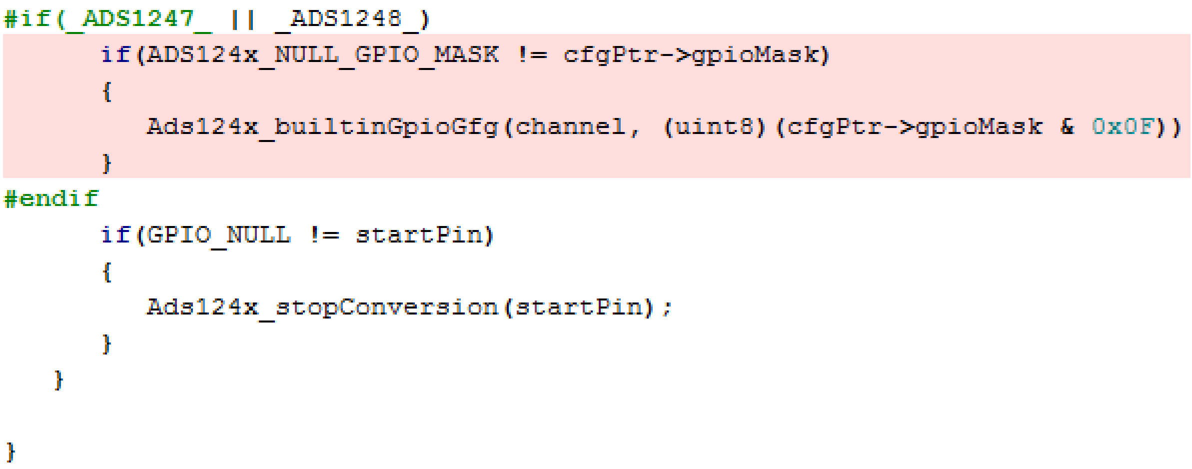
Module Initialization (cont.)



```
void Ads124xInit( Ads124x_IdType id, const Ads124x_hldCfgType *cfgPtr)
{
   if(GPIO_NULL != resetPin)
   {
      Ads124x_ResetCycle(resetPin);

      /* Reset is needed prior to start conversion */
      Ads124x_Delay(ADS124X_RESET_DELAY_uS);
   }

   if(NULL != cfgPtr)
   {
      Ads124x_writeRegister(id, SYS0_ADDRESS, (Ads124x_regType)(cfgPtr->pga + cfgPtr->sampling));

      Ads124x_registersDump(id);

#if(ADS124X_CALIBRATION_ENABLE)
      if(NULL != cfgPtr->ofcPtr)
      {
         Ads124x_Write_OFC_Coefficients(id, cfgPtr->ofcPtr);
      }
      if(NULL != cfgPtr->fscPtr)
      {
         Ads124x_updateFscCoeff(id, cfgPtr->fscPtr);
      }

      Ads124x_systemOffsetCal(id);
      Ads124x_systemGainCal(id);
      Ads124x_selfOffsetCal(id);
#endif
```

Example – External Driver development example

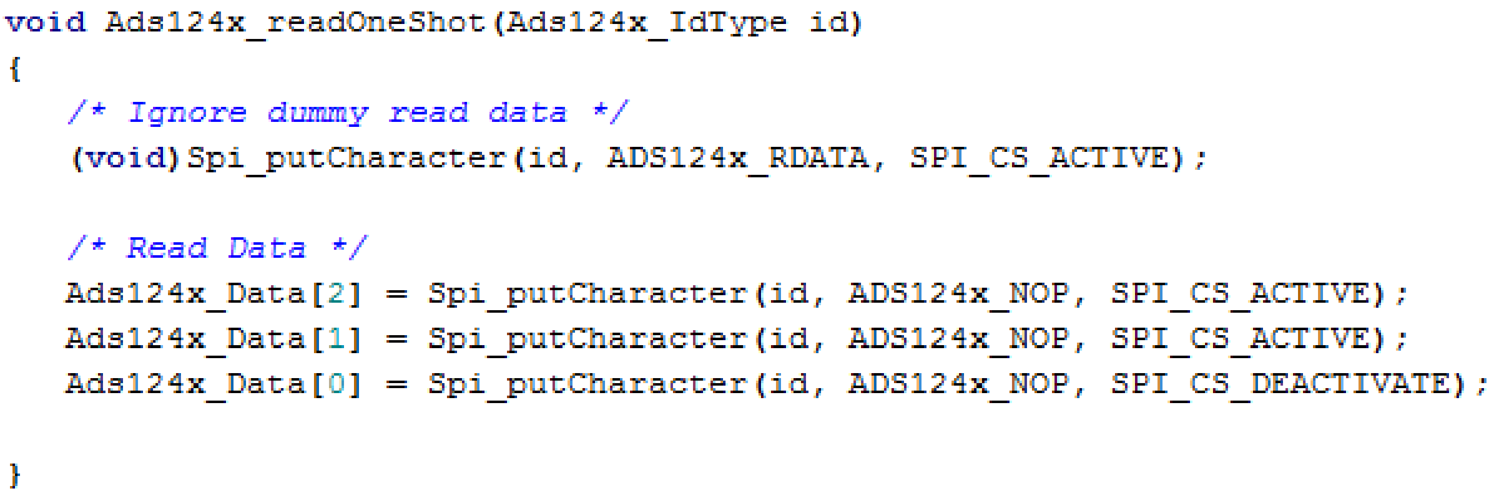
Module Initialization (cont.)



```
#if(_ADS1247_ || _ADS1248_)
      if(ADS124x_NULL_GPIO_MASK != cfgPtr->gpioMask)
      {
         Ads124x_builtinGpioGfg(channel, (uint8)(cfgPtr->gpioMask & 0x0F))
      }
#endif
      if(GPIO_NULL != startPin)
      {
         Ads124x_stopConversion(startPin);
      }
   }

}
```

Example – External Driver development example

Module Interfaces Examples

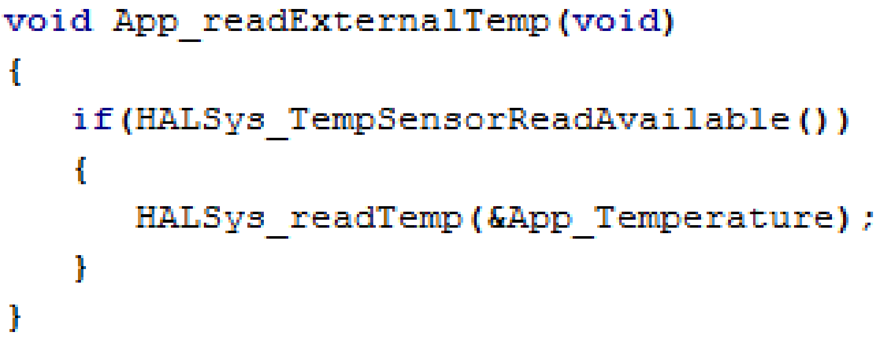


```
void Ads124x_readOneShot(Ads124x_IdType id)
{
   /* Ignore dummy read data */
   (void)Spi_putCharacter(id, ADS124x_RDATA, SPI_CS_ACTIVE);

   /* Read Data */
   Ads124x_Data[2] = Spi_putCharacter(id, ADS124x_NOP, SPI_CS_ACTIVE);
   Ads124x_Data[1] = Spi_putCharacter(id, ADS124x_NOP, SPI_CS_ACTIVE);
   Ads124x_Data[0] = Spi_putCharacter(id, ADS124x_NOP, SPI_CS_DEACTIVATE);

}
```

Example – External Driver development example

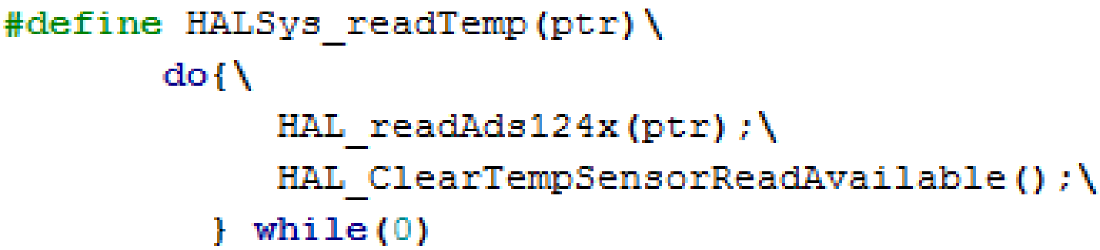
Inter-Module Interaction

Application:



```
void App_readExternalTemp(void)
{
    if(HALSys_TempSensorReadAvailable())
    {
        HALSys_readTemp(&App_Temperature);
    }
}
```

HAL System Interface



```
#define HALSys_readTemp(ptr)\
        do{\
             HAL_readAds124x(ptr);\
             HAL_ClearTempSensorReadAvailable();\
          } while(0)
```

Conclusions

- The more complex requirements the more complex software implementation
- The evolvement of embedded software requires the application of software engineering concepts
- Reusable software components demands a higher amount of MCU resources (measures in memory size and execution cycles)
- A well defined software architecture allows the creation of truly reusable software components that can be effectively ported to different hardware architectures
- The effective implementation of software architecture requires a culture of discipline and commitment

Thank you for your attention.

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