ECE4703 REAL-TIME DSP: INTERFACING WITH I/O, DEBUGGING, AND PROFILING
Interfacing a DSP With the Real World

ADC → DSP → DAC

- Analog input
- Digital inputs = 4 DIP switches
- Digital outputs = 4 LEDs
- Data
- Code
- ADC and DAC = AIC23 codec

**TMS320C6713 DSK:**
- Digital inputs = 4 DIP switches
- Digital outputs = 4 LEDs
DIP Switches and LEDs

LED and DIP switch interface functions are provided in `dsk6713bsl.lib`.

- Initialize the DSK with the BSL function `DSK6713_init();`
- Initialize DIP/LEDs with `DSK6713_DIP_init()` and/or `DSK6713_LED_init()`
- Read state of DIP switches with `DSK6713_DIP_get(n)`
- Change state of LEDs with `DSK6713_LED_on(n)` or `DSK6713_LED_off(n)` or `DSK6713_LED_toggle(n)`

where n=0, 1, 2, or 3.

Documentation is available in Board Support Library API (on course website).
AIC23 Codec

- AIC23 codec performs both ADC and DAC functions
- Stereo input and output (left+right channels)

Initialization steps:
- Initialize the DSK with the BSL function `DSK6713_init();`
- Open the codec with the BSL function `hCodec = DSK6713_AIC23_openCodec(0,&config);`
  - “hCodec” is the codec “handle”. You can think of this as a unique address of the codec on the McBSP bus.
  - “config” is the default configuration of the codec. See the header file `dsk6713_aic23.h` and the AIC23 codec datasheet (link on the course web page) for details.
- Optional: Set the codec sampling frequency.
- Configure the McBSP to transmit/receive 32 bits (two 16 bit samples) with the CSL function `McBSP_FSETS()`
- Set up and enable interrupts
Codec Initialization Example (from Kehtarnavaz)

Initialization steps:

1. Initialize the DSK
2. Open the codec with the default configuration.
3. Configure multi-channel buffered serial port (McBSP)
   - SPCR = serial port control register
   - RCR = receive control register
   - XCR = transmit control register
   - See SPRU508e.pdf
4. Set the sampling rate
5. Configure and enable interrupts
6. Do normal processing (we just enter a loop here)

```c
interrupt void serialPortRcvISR(void);

void main()
{
    DSK6713_init(); // Initialize the board support library, must be called first
    hCodec = DSK6713_AIC23_openCodec(0, &config); // Open the codec

    // Configure buffered serial ports for 32 bit operation
    // This allows transfer of both right and left channels in one read/write
    MCBSF_FSETS(SPCR1, RINTM, FRM);
    MCBSF_FSETS(SPCR1, XINTM, FRM);
    MCBSF_FSETS(RCR1, RWDLEN1, 32BIT);
    MCBSF_FSETS(XCR1, RWDLEN1, 32BIT);
    DSK6713_AIC23_setFreq(hCodec, DSK6713_AIC23_FREQ_48KHZ); // set the sampling rate

    // Interrupt setup
    IRQ_globalDisable(); // Globally disables interrupts
    IRQ_nmiEnable(); // Enables the NMI interrupt
    IRQ_map(IRQ_EVT_RINT1,15);
    IRQ_enable(IRQ_EVT_RINT1); // Enables the event
    IRQ_globalEnable(); // Globally enables interrupts

    while(1)
    {
    }
}
```
AIC23 Codec: Interrupts

- We will use an interrupt interface between the DSP and the codec.
- DSP can do useful things while waiting for samples to arrive from codec, e.g. check DIP switches.
- C6x interrupt basics:
  - Interrupt sources must be mapped to interrupt events
    - 16 physical “interrupt sources” (timers, serial ports, codec, ...)
    - 12 logical “interrupt events” (INT4 to INT15)
  - Interrupt events have associated “interrupt vectors”. An “interrupt vector” is a special pointer to the start of the “interrupt service routine” (ISR).
  - Interrupt vectors must be set up in your code (usually in the file “vectors.asm”).
  - You are also responsible for writing the ISR.
Interrupts

main code

physical interrupt source X linked to logical interrupt event N

interrupts enabled

interrupt event N occurs (C compiler generates code to automatically save the state)

interrupt vector N

branch to interrupt service routine

interrupt service routine

do something useful

make sure the ISR completes before the next interrupt occurs

return to main code

return to main code
Interrupt Vector

- We usually link the physical codec interrupt to INT15.
- The ISR in this example is called “serialPortRcvISR” (you can rename it if you like).
- C function “x” is called “_x” in ASM files.
- The interrupt vector is usually in the vectors.asm file:
- Each interrupt vector must be exactly 8 ASM instructions.

```
INT15:
  150  MVKL  S2 _serialPortRcvISR, B0
  151  MVKH  S2 _serialPortRcvISR, B0
  152      B   .S2 B0
  153       NOP
  154       NOP
  155       NOP
  156       NOP
  157       NOP
  158       NOP
```
A Simple Interrupt Service Routine

```c
interrupt void serialPortRcvISR()
{
    Uint32 temp;
    temp = MCBSP_read(DSK6713_AIC23_DATAHANDLE);  // read L+R channels
    MCBSP_write(DSK6713_AIC23_DATAHANDLE,temp);    // write L+R channels
}
```

Remarks:
- **MCBSP_read()** requests L+R samples from the codec’s ADC
- **MCBSP_write()** sends L+R samples to the codec’s DAC
- This ISR simply reads in samples and then sends them back out.
Setting the Codec Sampling Frequency

Here we open the codec with the default configuration:

```c
hCodec = DSK6713_AIC23_openCodec(0, &config); // Open the codec
```

The structure “config” is declared in `dsk6713_aic23.h`

Rather than editing the default configuration in the header file, we can change the sampling frequency after the initial configuration:

```c
DSK6713_AIC23_setFreq(hCodec, DSK6713_AIC23_FREQ_48KHZ); // set the sampling rate
```

Frequency definitions are in `dsk6713_aic.h`

```c
#ifndef DSK6713_AIC23_FREQ_H
#define DSK6713_AIC23_FREQ_H

#define DSK6713_AIC23_FREQ_8KHZ 1
#define DSK6713_AIC23_FREQ_16KHZ 2
#define DSK6713_AIC23_FREQ_24KHZ 3
#define DSK6713_AIC23_FREQ_32KHZ 4
#define DSK6713_AIC23_FREQ_44KHZ 5
#define DSK6713_AIC23_FREQ_48KHZ 6
#define DSK6713_AIC23_FREQ_96KHZ 7

#endif
```

This is actually 44.1kHz
Other Codec Configuration

- Line input volume level (individually controllable for left and right channels)
- Headphone output volume level (individually controllable for left and right channels)
- Digital word size (16, 20, 24, or 32 bit)
- Other settings, e.g. byte order, etc. For more details, see:
  - dsk6713_aic23.h
  - AIC23 codec datasheet (link on course web page)
Codec Data Format and How To Separate the Left/Right Channels

// we can use the union construct in C to have
// the same memory referenced by two different variables
union {Uint32 combo; short channel[2];} temp;

// the McBSP functions require that we
// read/write data to/from the Uint32 variable
temp.combo = MCBSP_read(DSK6713_AIC23_DATAHANDLE);
MCBSP_write(DSK6713_AIC23_DATAHANDLE, temp.combo);

// but if we want to access the left/right channels individually
// we can do this through the short variables
Leftchannel = temp.channel[1];
Rightchannel = temp.channel[0];
Final Remarks on DSP/Codec Interface

- In most real-time DSP applications, you process samples as they become available from the codec’s ADC (sample-by-sample operation).
- This means that **all processing will be done in the ISR**.
  - `MCBSP_read()`
  - `--- processing here ---`
  - `MCBSP_write()`
- The ISR must run in real-time, i.e. the total execution time must be less than one sampling period.
- You can do DIP/LED processing outside of the ISR (in your main code).
C6713 DSK Memory Architecture

- TSM320C6713 DSP chip has 256kB internal SRAM
  - Up to 64kB of this SRAM can be configured as shared L2 cache
- DSK provides additional 16MB external RAM (SDRAM)
- DSK also provides 512kB external FLASH memory
- Code location (.text in linker command file)
  - internal SRAM memory (fast)
  - external SDRAM memory (typically 2-4x slower, depends on cache configuration)
- Data location (.data in linker command file)
  - internal SRAM memory (fast)
  - external SDRAM memory (slower, depends on datatypes and cache configuration)
- Code+data for all projects assigned in ECE4703 should fit in the C6713 internal SRAM
TMS320C6713 DSK Memory Map

0000 0000
0003 FFFF
0003 FFFF
8000 0000
8000 0000
8007 FFFF
8007 FFFF
FFFF FFFF

Internal SRAM (256kB)
External SDRAM (16MB)
FLASH

your code+data here

192K-Byte RAM
16K-Byte RAM
16K-Byte RAM
16K-Byte RAM
16K-Byte RAM
Linker Command File Example

MEMORY
{
  vecs: o = 00000000h  l = 00000200h
  IRAM: o = 00000200h  l = 0002FE00h
  CEO: o = 80000000h  l = 01000000h
}

SECTIONS
{
  .vectors > vecs
  .cinit > IRAM
  .text > IRAM
  .stack > IRAM
  .bss > IRAM
  .const > IRAM
  .data > IRAM
  .far > IRAM
  .switch > IRAM
  .sysmem > IRAM
  .tables > IRAM
  .cio > IRAM
}

Addresses 00000000-0002FFFF correspond to the lowest 192kB of internal memory (SRAM) and are labeled “IRAM”.

External memory is mapped to address range 80000000 – 80FFFFFF. This is 16MB and is labeled “CEO”.

Both code and data are placed in the C6713 internal SRAM in this example. Interrupt vectors are also in SRAM.
vectors.asm

- This file contains your interrupt vectors
- "sect" directive at top of file tells linker where (in memory) to put the code
- Each interrupt vector is composed of exactly 8 assembly language instructions
- Example:

```
INT15:
MVKL .S2 _serialPortRcvISR, B0
MVKH .S2 _serialPortRcvISR, B0
B .S2 B0
NOP
NOP
NOP
NOP
```
Debugging and Other Useful Features of the CCS IDE

- Breakpoints and stepping through your code
- Watch variables
- Registers
- Plotting arrays of data
Breakpoints: stop code execution at this point to allow state examination and step-by-step execution.

Also try View->Breakpoints
Using Breakpoints

- Run
- Halt
- Source step into
- Source step over
- ASM step into
- ASM step over
- Step out
Watch Variables

- View->Watch

- Type in any variable name currently in scope.
- Tip: Right click on <new> to easily add global variables.
Registers: View->Registers
Plotting Arrays of Data

- Tools -> Graph -> (Typically Single Time)

Can type array name here
Graph Windows: Plotting Arrays of Data

Right click for lots of options.
Profiling Your Code and Making it More Efficient

- How to estimate the execution time of your code.
- How to use the optimizing compiler to produce more efficient code.
- Other factors affecting the efficiency of your code.
How to estimate code execution time when connected to the DSK

1. Open the source file you wish to profile
2. Set two breakpoints for the start/end of the code range you wish to profile
3. Build it and load .out file to the DSK
4. Target -> Clock -> Enable
5. Target -> Clock -> View
6. Run to the first breakpoint
7. Target -> Clock -> Reset (or double click the clock to reset the clock to zero)
8. Run to the second breakpoint
9. Clock will show raw number of execution cycles between breakpoints.
Optimizing Compiler

![Properties for stereoloop dialog box](image_url)

- **Project Type:** C6000
- **Configuration:** Debug
- **Optimization level:** 3

**Tags:**
- C/C++ Build
- C6000 Compiler
- C6000 Linker
- Optimization level
Profiling results after compiler optimization

- Rebuild and reload the program to the DSK
- Use your breakpoint/clock method to profile the execution time
- In this example, we get a 5x-6x improvement with Level-3 Optimization
- Optimization gains can be much larger, e.g. 20x
Limitations of hardware profiling

- Variability of results
- Profiling is known to be somewhat inaccurate when connected to real hardware
- Breakpoint/clock profiling method may not always work with compiler-optimized code
- For the best results, TI recommends profiling your code in a cycle accurate simulator:
  - New target configuration:
    - Connection = Texas Instruments Simulator
    - Device = C6713 Device Cycle Accurate Simulator, Little Endian
  - Need to create a new project for the simulator and copy your functions/code for profiling to this project without calls to board-specific functions
  - Tools -> Profile -> Setup and then Tools-> Profile -> View
Code from ISR placed in a regular function called from main()

All calls to BSL functions removed

Not running on DSK
Tools -> Profile -> Setup, then Tools-> Profile -> View
Other factors affecting code efficiency

- **Memory**
  - Code location (.text in linker command file)
    - internal SRAM memory (fast)
    - external SDRAM memory (typically 2-4x slower, depends on cache configuration)
  - Data location (.data in linker command file)
    - internal SRAM memory (fast)
    - external SDRAM memory (slower, depends on datatypes and cache configuration)

- **Data types**
  - Slowest execution is double-precision floating point
  - Fastest execution is fixed point, e.g. short

Example: Stereoloop project, changing .text and .data to external SDRAM: About 2.5x slower than SRAM (can be worse)
## TMS320C6000 C/C++ Data Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Representation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>char, signed char</td>
<td>8 bits</td>
<td>ASCII</td>
<td>-128</td>
<td>127</td>
</tr>
<tr>
<td>unsigned char</td>
<td>8 bits</td>
<td>ASCII</td>
<td>0</td>
<td>255</td>
</tr>
<tr>
<td>short</td>
<td>16 bits</td>
<td>2s complement</td>
<td>-32768</td>
<td>32767</td>
</tr>
<tr>
<td>unsigned short</td>
<td>16 bits</td>
<td>Binary</td>
<td>0</td>
<td>65535</td>
</tr>
<tr>
<td>int, signed int</td>
<td>32 bits</td>
<td>2s complement</td>
<td>-2147483648</td>
<td>214783647</td>
</tr>
<tr>
<td>unsigned int</td>
<td>32 bits</td>
<td>Binary</td>
<td>0</td>
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</tr>
<tr>
<td>long, signed long</td>
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<td>2s complement</td>
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<td>549755813887</td>
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<tr>
<td>enum</td>
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<td>-2147483648</td>
<td>214783647</td>
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<td>float</td>
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<td>IEEE 32-bit</td>
<td>1.175494e-38†</td>
<td>3.40282346e+38</td>
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<td>double</td>
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<td>IEEE 64-bit</td>
<td>2.22507385e-308†</td>
<td>1.79769313e+308</td>
</tr>
<tr>
<td>long double</td>
<td>64 bits</td>
<td>IEEE 32-bit</td>
<td>2.22507385e-308†</td>
<td>1.79769313e+308</td>
</tr>
</tbody>
</table>
Final Remarks

- You should have enough information to complete Lab 1
  - Lab/lecture slides
  - Reference material noted in slides
  - Textbooks listed in syllabus
  - Please make sure you understand what you are doing. Please ask questions if you are unsure.