Todo list

CENG 355 Microprocessor-Based Systems Lab Project

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Nov 28, 2016

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Abbreviations

ADC analog-to-digital converter. v, 2, 4, 15

CPHA clock phase. 6, *see:* SPI

CPOL clock polarity. 6, *see:* SPI

CR control register. 4

CRC cyclic redundancy check. 6

DAC digital-to-analog converter. 2, 4, 15, 16

EXTI1 external interrupt line 1. 9, 11

GPIO general purpose input output. 3, 16

GPIOx GPIO port x. 1, *see:* GPIO

IC integrated circuit. 1

LCD liquid crystal display. iv, 1, 2, 5, 7, 10, 13, 15–17, *Glossary:* liquid crystal display

LCK lock. 5, 10

MOSI master output, slave input. 5, *see:* SPI

MSB most significant bit. 6

NVIC nested vector interrupt controller. 8, 9

PWM pulse-width modulation. iv, 13, 15–17, *Glossary:* pulse-width modulation

RS register select. 10

SCK serial clock. 5, *see:* SPI

SoC system on a chip. v

SPI serial peripheral interface. 1, 5, 6, 10, 16

TIM2 general purpose timer 2. 7–9, 11, 13

TIM3 general purpose timer 3. 5, 6, 10, 13

UI user interface. 7, 10

Glossary

HSI14

The 14 MHz high speed interconnect clock supplying the analog-to-digital converter (ADC)'s clock. 4

liquid crystal display

a visual display utilizing a layer of liquid crystal between two electrodes that become opaque when a voltage is applied. iv, 1

pulse-width modulation

a common control scheme in which a signal is pulsed on and off with a variable duty-cycle, and potentially frequency, generally to provide a control or reference signal. iv, 13

STM32F0DISCOVERY

A system on a chip (SoC) developed by STMicroelectronics providing a development board based on a Cortex-M0 microprocessor. 1, 15, 16

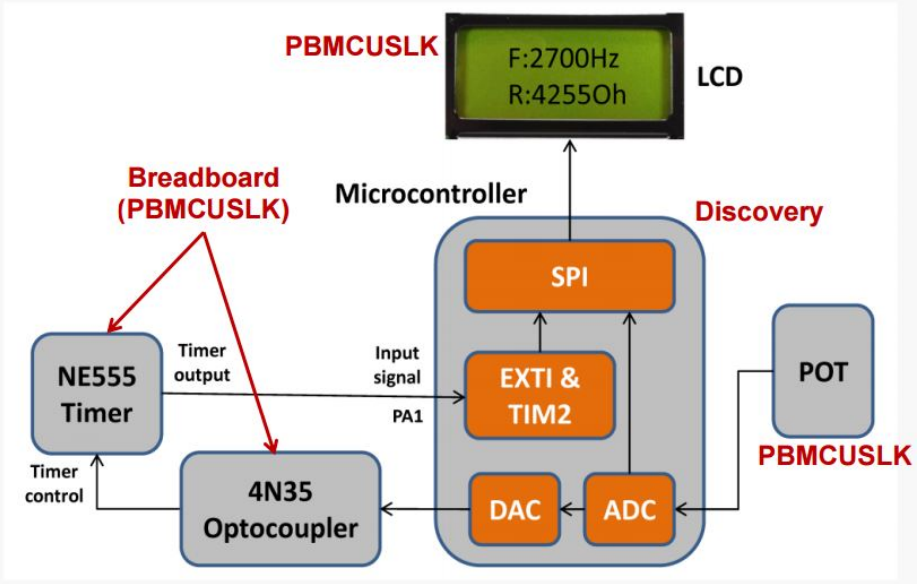


Figure 1: System Interfacing Diagram [1]

1 Problem description

The purpose of this lab is to design an embedded system to create an open-loop control system, where the position of a potentiometer is measured and a frequency dependent on the measured resistance, with the frequency produced through a 555 timer-based circuit. Systems and components in this lab include embedded programming of an STM32F0DISCOVERY board, and a Freescale Semiconductor project board with electrical circuit design of the variable-frequency 555 timer-based astable circuit, digital-to-analog and analog-to-digital converters, and serial peripheral interface (SPI) for inter-integrated circuit (IC) communication between the microprocessor and the liquid crystal display (LCD) board; the system was built on an STM32F0DISCOVERY ARM platform.

2 Design Solution

The design solution involved dividing the project into parts, including planning and implementation divisions which were then separated further to allow even distribution of the work. Information and reference was primarily found through the reference manuals for both the STM32F0DISCOVERY and project board [3, 4]: Figure 1 provides and overview of the interaction between components.

2.1 Planning

Before beginning the implementation phase, planning was done to determine who would primarily focus on which parts of the project, and come up with some broad design ideas.

2.1.1 Work Partitioning

Based on experience from the first lab, and personal preference, lab work was partitioned accordingly. The project was split into the embedded programming and accessory circuit design/implementation, where the majority of the embedded programming was assigned to Tayler Mulligan and the accessory timer circuit to Raymond Bamford. The partitioning was not strict, with members collaborating where necessary or convenient.

2.1.2 Technique and Technologies

Git and GithHub were utilized for the project to provide team access and syncing between lab computers (see `https://github.com/tamul/ceng355-lab-project`). The source code was split into three files: `main.c` (see A.1), containing the main program; `analog.c` (see A.2), containing ADC, digital-to-analog converter (DAC), and frequency monitoring code; and `lcd.c` (see A.3), containing code related to the LCD; each with corresponding header files. Each file provided initialization functions for the components and abstracted functions to control the components, such as:

```
void spi_init(void),
void lcd_cmd(uint8_t data),
void lcd_char(char c),
```

etc. in `lcd.h`; and:

```
void dac_init(void),
void adc_init(void)
uint16_t adc_read(void),
void dac_write(uint16_t),
```

etc. in `analog.h`. See the attached listings in the appendices for complete definitions and declarations.

2.2 Software Implementation

The main program called functions provided by `analog.h` and `lcd.h` to sequentially initialize each component. Components were initialized in the order of: the ADC, the DAC, the LCD, and the frequency monitor. Details of registers and other technical notes are available in the reference manual published by STMicroelectronic's [3].

Listing 1: Initialization order (`src/main.c`)

```
trace_printf("%s", "Initializing ADC...");
adc_init();
```

```
    adc_enable_pot(1);
    trace_puts("Done");

    trace_printf("%s", "Initializing DAC...");
    dac_init();
    trace_puts("Done");

    trace_printf("%s", "Initializing LCD...");
    lcd_init();
    trace_puts("Done");

    trace_printf("%s", "Initializing frequency monitor...");
    freq_init();
    trace_puts("Done");
```

2.2.1 ADC Initialization

Initialization of the glsadc requires initialization of the general purpose input output (GPIO) port C interface (to control the POT_EN signal of the Project Board), GPIOC (to read the potentiometer value), and the glsadc. The C code in Listing 2 comprises the initialization of the GPIOC register for the glsadc.

Listing 2: GPIO configuration for ADC (`src/analog.c`)

```
void adc_init(void) {
    /* Enable clock for GPIOC */
    RCC->AHBENR |= RCC_AHBENR_GPIOCEN;

    /* Configure PC1 as push-pull output  */
    GPIOC->MODER |= GPIO_MODER_MODER1_0;
    GPIOC->OTYPER &= ~GPIO_OTYPER_OT_1;
    /* Ensure high-speed mode for PC1 */
    GPIOC->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR1;
    /* Disable any pull up/down resistors on PC1 */
    GPIOC->PUPDR &= ~GPIO_PUPDR_PUPDR1;

    /* Configure PA0 as an analog pin */
    GPIOA->MODER |= GPIO_MODER_MODER0;
```

Firstly, the GPIOC clock is ensured to be running, followed by configuration of the pins. The pins are put in a push-pull output configuration at the highest speed, without any pull-up or pull-down resistors.

Listing 3: ADC configuration (`src/analog.c`)

```
    /* Enable the HSI14 (ADC async) clock */
    RCC->CR |= RCC_CR_HSION;
    RCC->APB2ENR |= RCC_APB2ENR_ADCEN;

    /* Start up the ADC */
    ADC1->CR = ADC_CR_ADEN;

    /* ---- Configure the ADC ---- */
    /* Set the ADC clock to the dedicated clock */
    ADC1->CFGR2 &= ~(0x00);
    /* Select the input channel */
```

```
    ADC1->CHSELR = ADC_CHSELR_CHSEL0;
    /* Set continuous conversion mode */
    ADC1->CFGR1 |= ADC_CFGR1_CONT;
    /* Enable starting with software trigger */
    ADC1->CFGR1 &= ~ADC_CFGR1_EXTEN;
    /* Disable auto-off */
    ADC1->CFGR1 &= ~ADC_CFGR1_AUTOFF;
    /* ----------------------------*/

    /* Wait for the ADC to stabilize */
    while(!(ADC1->ISR & ADC_ISR_ADRDY));
    /* Start converting the analog input */
    ADC1->CR |= ADC_CR_ADSTART;
}
```

Next the ADC proper is initialized: the C code in Listing 3 accomplishes this. The HSI14 clock, which supplies the ADC's clock, is enabled and the ADC started in preparation for configuration. Lines 57-68 configure the glsadc: setting the clock as the dedicated (HSI14) clock, selecting input channel 0 (corresponding to parallel pin A0), continuous conversion mode is enabled to continuously provide the digitized value of the PA0 pin. Finally, the function triggers conversion to start after waiting until the glsadc reports that it has stabilized.

2.2.2 DAC Initialization

Enabling the DAC requires configuration of the PA4 pin and initialization of the DAC clock. Listing 4 shows the C code initializing the DAC.

Listing 4: DAC configuration (`src/analog.c`)

```
void dac_init(void) {
    /* Set PA4 (DAC output) as analog output pin */
    GPIOA->MODER = GPIO_MODER_MODER4;
    /* Set PA4 to open drain */
    GPIOA->OTYPER = GPIO_OTYPER_OT_4;
    /* Disable pull up/down resistors on PA4 */
    GPIOA->PUPDR &= ~GPIO_PUPDR_PUPDR4;
    /* Set PA4 to high-speed mode */
    GPIOA->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR4;

    /* Enable the DAC clock */
    RCC->APB1ENR |= RCC_APB1ENR_DACEN;
    /* Enable the DAC (with output buffering and auto-triggering */
    DAC->CR = DAC_CR_EN1;
}
```

The mode of PA4 is set to an open-drain analog output, allowing a variable voltage to be placed on PA4, with pull-up and pull-down pins disabled, at the highest speed setting to ensure the pin updates quickly. Next, the DAC's clock is enabled and the DAC enabled by writing the DAC's control register (CR)'s enable bit.

2.2.3 LCD Initialization

To initialize the LCD, the SPI, GPIOB, and GPIOC clocks are all initialized (Listing 5).

Listing 5: SPI, GPIOB, GPIOC clock enable (`src/lcd.c`)

```
void lcd_init(void) {
    /* Enable SPI1 clock */
    RCC->APB2ENR |= RCC_APB2ENR_SPI1EN;
    /* Enable GPIOB clock */
    RCC->AHBENR |= RCC_AHBENR_GPIOBEN;
    /* Enable GPIOC clock */
    RCC->AHBENR |= RCC_AHBENR_GPIOCEN;
```

The lock (LCK) pin (PC2) of the SPI shift-register is set to output mode, and the master output, slave input (MOSI) (PB5) and serial clock (SCK) (PB3) SPI pins are set to alternate function mode (Listing 6).

Listing 6: SPI pin mode configuration (`src/lcd.c`)

```
    /* Set PC2 to output */
    GPIOC->MODER = (GPIOC->MODER & ~GPIO_MODER_MODER2) | (
    GPIO_MODER_MODER2 & GPIO_MODER_MODER2_0);
    /* Set PB3 to alternate function */
    GPIOB->MODER = (GPIOB->MODER & ~GPIO_MODER_MODER3) | (
    GPIO_MODER_MODER3 & GPIO_MODER_MODER3_1);
    GPIOB->AFR[0] &= ~GPIO_AFRL_AFR3;
    /* Set PB5 to alternate function */
    GPIOB->MODER = (GPIOB->MODER & ~GPIO_MODER_MODER5) | (
    GPIO_MODER_MODER5 & GPIO_MODER_MODER5_1);
    GPIOB->AFR[0] &= ~GPIO_AFRL_AFR5;
```

Each SPI related pin is set to push-pull mode with pull-up and pull-down resistors disabled and high-speed mode (Listing 7).

Listing 7: SPI pin output configuration (`src/lcd.c`)

```
    /* Set PC2, PB3, PB5 to push-pull mode */
    GPIOC->OTYPER &= ~GPIO_OTYPER_OT_2;
    GPIOB->OTYPER &= ~GPIO_OTYPER_OT_3;
    GPIOB->OTYPER &= ~GPIO_OTYPER_OT_5;

    /* Disable pull up/down resistors on SPI pins */
    GPIOB->PUPDR &= ~GPIO_PUPDR_PUPDR3;
    GPIOB->PUPDR &= ~GPIO_PUPDR_PUPDR5;
    GPIOC->PUPDR &= ~GPIO_PUPDR_PUPDR2;

    /* Set SPI pins to high-speed */
    GPIOB->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR3;
    GPIOB->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR5;
    GPIOC->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR2;
```

After configuring the output pins, general purpose timer 3 (TIM3) is configured, allowing SPI writes to be delayed and the LCD time to complete the commands sent:

Listing 8: TIM3 configuration (`src/lcd.c`)

```
    /* Initialize TIM3 */
    /* Enable the TIM3 clock */
    RCC->APB1ENR |= RCC_APB1ENR_TIM3EN;
    /* Configure TIM3 with buffer auto-reload, count down,
     * stop on overflow, and only interrupt on overflow
     */
    TIM3->CR1 = 0xC6;
    /* Set clock prescaler value */
    TIM3->PSC = TIM3_PRESCALER;
    /* Set auto-reload delay */
    TIM3->ARR = TIM3_AUTORELOAD_DELAY;
    /* Set timer update configuration (rising edge, etc.) */
    TIM3->EGR = (TIM2->EGR & ~0x5F) | (0x1 & 0x5F);
    /* Load delay value */
    TIM3->CNT = MAX_DELAY;
    TIM3->CR1 |= 0x1;
```

The clock for TIM3 is enabled, then the clock is configured to use buffered auto-reload, count down from the set `CNT` register value, stop in the event of an overflow (which should never occur), and only interrupt in the event of an overflow not when the counter reaches 0. This configuration allows a value to be written to the timer which then counts down to 0, and the timer can be polled until the count is low enough (and enough time has passed), then allowing another command to be sent. This avoids the potential for an overflow if the counter was initialized to zero and counted up to or past the desired value.

The prescaler is set to 0, the auto-reload delay set to the lowest possible, writing to the `EGR` register is a carry-over from other timer initializations and is not necessary in this case; then, the `MAX_DELAY` value (the maximum time the LCD will take to execute a command) is loaded into the timer's `CNT` register, and the timer finally started. This timer is utilized by checking the `CNT` value rather than the updates generated for the purpose of allowing a potentially shorter delay. In the end this potential for a shorter delay was not utilized, however checking the `CNT` register rather than an update bit was retained.

Next, in Listing 9, SPI is configured and enabled with: unidirectional transmit, master mode, a data-size of 8 bits, clock polarity (CPOL) and clock phase (CPHA) are set for a falling edge clock pulse, software chip select, a 256 baud-rate prescaler, most significant bit (MSB) first output, and a 7 bit cyclic redundancy check (CRC) polynomial.

Listing 9: SPI initialization (`src/lcd.c`)

```
    /* Initialize SPI */
    SPI_InitTypeDef SPI_InitStructInfo = {
            .SPI_Direction = SPI_Direction_1Line_Tx,
            .SPI_Mode = SPI_Mode_Master,
            .SPI_DataSize = SPI_DataSize_8b,
            .SPI_CPOL = SPI_CPOL_Low,
            .SPI_CPHA = SPI_CPHA_1Edge,
            .SPI_NSS = SPI_NSS_Soft,
            .SPI_BaudRatePrescaler = SPI_BaudRatePrescaler_256,
```

```
            .SPI_FirstBit = SPI_FirstBit_MSB,
            .SPI_CRCPolynomial = 7
    };
    SPI_Init(SPI1, &SPI_InitStructInfo);

    SPI_Cmd(SPI1, ENABLE);
```

Finally, in Listing 10, the command interface and the display of the LCD are initialized: the LCD is set to a 4-bit interface with 2 lines, followed by the LCD being cleared and homed with display shift disabled and cursor movement direction set to the right, cursor blinking being disabled. The persistent, unchanging characters of the user interface (UI) are then written to the LCD.

Listing 10: LCD initialization (`src/lcd.c`)

```
    /* Set the LCD to 4 bit interface */
    spi_write(0x02, MAX_DELAY);
    spi_write(0x82, MAX_DELAY);
    spi_write(0x02, MAX_DELAY);

    /* Set LCD to display 2 lines */
    lcd_cmd(0x28);

    /* Clear the LCD */
    lcd_cmd(0x01);
    /* Home the cursor */
    lcd_cmd(0x02);
    /* Set cursor move direction and disable display shift */
    lcd_cmd(0x06);
    /* Set the display on, don't show the cursor, don't blink */
    lcd_cmd(0x0C);
    /* Set the cursor to move right, no display shift */
    lcd_cmd(0x14);
    /* Write 'F:    Hz' to first line */
    lcd_cmd(0x80); // Start at very left

    lcd_char('F'); //F
    lcd_char(':'); //:
    lcd_cmd(0x86);
    lcd_char('H'); //H
    lcd_char('z'); //z

    /* Write 'R:    Oh' to second line*/
    lcd_cmd(0xC0); // set address to second line, first character
    lcd_char('R'); //R
    lcd_char(':'); //:
    lcd_cmd(0xC6);
    lcd_char('O');
    lcd_char('h');
}
```

2.2.4 Frequency Monitor Initialization

Initialization of the frequency monitor required the GPIOA and general purpose timer 2 (TIM2) clocks to be enabled, GPIOA pin 1 configured as an input, and

configuration of TIM2.

PA1 is first configured with the C code in Listing 11.

Listing 11: GPIOA pin 1 configuration (`src/analog.c`)

```
void freq_init(void) {
    /* Enable the GPIOA clock */
    RCC->AHBENR |= RCC_AHBENR_GPIOAEN;
    /* Configure PA1 as an input */
    GPIOA->MODER &= ~(GPIO_MODER_MODER1);
    /* Ensure no pull up/down for PA1 */
    GPIOA->PUPDR &= ~(GPIO_PUPDR_PUPDR1);
```

The GPIOA clock is first ensured to be enabled, followed by the setting pin PA1 to input mode with pull-up and pull-down resistors disabled. TIM2 is then initialized, seen in Listing 12.

Listing 12: TIM2 initialization (`src/analog.c`)

```
    /* Enable the TIM2 clock */
    RCC->APB1ENR |= RCC_APB1ENR_TIM2EN;
    /* Configure TIM2 with buffer auto-reload, count up,
     * stop on overflow, enable update events, and interrupt
     * on overflow only
     */
    TIM2->CR1 = 0x8C;

    /* Set clock prescaler value */
    TIM2->PSC = TIM2_PRESCALER;
    /* Set auto-reload delay */
    TIM2->ARR = TIM2_AUTORELOAD_DELAY;
    /* Set timer update configuration (rising edge, etc.) */
    TIM2->EGR = (TIM2->EGR & ~0x5F) | (0x1 & 0x5F);
```

TIM2 is configured with a buffered auto-reload in count up mode, with stop on overflow set and updates events enabled with interrupts only enabled for overflow. This allows the timer to notify in the event of an iInterrupt and avoid erroneous frequencies measurements when the frequency drops below a corresponding period of approximately 90 s.

Next, the interrupt routines are configured through the nested vector interrupt controller (NVIC) as seen in Listing 13.

Listing 13: NVIC configuration (`src/analog.c`)

```
    /* Assign TIM2 interrupt priority 0 in NVIC */
    NVIC_SetPriority(TIM2_IRQn, 0);
    /* Enable TIM2 interrupts in NVIC */
    NVIC_EnableIRQ(TIM2_IRQn);
    /* Enable update interrupt generation */
    TIM2->DIER |= 0x41;

    /* Map EXTI1 line to PA1 */
    SYSCFG->EXTICR[0] = (SYSCFG->EXTICR[0] & ~(0xF)) | (0 & 0xF);

    /* EXTI1 line interrupts: set rising-edge trigger */
```

```
    EXTI->RTSR |= 0x2;

    /* Unmask interrupts from EXTI1 line */
    EXTI->IMR |= 0x2;

    /* Assign EXTI1 interrupt priority 0 in NVIC */
    NVIC_SetPriority(EXTI0_1_IRQn, 0);
    /* Enable EXTI1 interrupts in the NVIC */
    NVIC_EnableIRQ(EXTI0_1_IRQn);
}
```

The priority of the interrupt is set to 0, as it is one of only two interrupts that should be firing in this system. TIM2 interrupts are enabled in the NVIC to allow notifiication of overflow, and interrupt generation is enabled in TIM2. The external interrupt line carrying the external waveform, external interrupt line 1 (EXTI1), is mapped to PA1. The external interrupt line has interrupts enabled with a rising-edge trigger and interrupts for EXTI1 unmasked in the NVIC so they are processed. Finally, EXTI1 is configured to have a priority of 0 in the NVIC, and enabled.

2.2.5 LCD Implementation

Utilization of the LCD was accomplished through the `void lcd_char(char c)` and `void lcd_cmd(uint8_t data)` functions. `lcd_char` provides an interface to specify a character which is then translated to the proper LCD command and displayed at the current cursor position. `lcd_cmd` does not translate it's input, instead implementing the transmission of 8 bits of data to the LCD over the 4 bit interface. Definitions of `lcd_char` and `lcd_cmd` can be seen in Listing 14

Listing 14: LCD interface function definitions (`src/lcd.c`)

```
void spi_write(uint8_t data, uint32_t delay) {
    /* Wait until SPI delay has passed */
    while (TIM3->CNT > ((MAX_DELAY+1) - delay));
    /* Force LCK low */
    GPIOC->BRR |= GPIO_BRR_BR_2;
    /* Wait until SPI1 is ready */
    while((SPI1->SR & SPI_SR_BSY) && ~(SPI1->SR & SPI_SR_TXE));
    /* Send the data */
    SPI_SendData8(SPI1, data);
    /* Wait until SPI1 is not busy */
    while(SPI1->SR & SPI_SR_BSY);
    /* Force LCK signal to 1 */
    GPIOC->BSRR |= GPIO_BSRR_BS_2;
    /* Reset LCD comm clock */
    TIM3->CNT = MAX_DELAY;
    TIM3->CR1 |= 0x1;
}

/*
 * Write to LCD using 4 bit interface. Send 4 high bits
 * by pulsing EN, then do the same for 4 low bits
 */
void lcd_cmd(uint8_t data) {
```

```
    /* Send HIGH bits */
    spi_write(0x00 | (data >> 4), MAX_DELAY);
    spi_write(0x80 | (data >> 4), MAX_DELAY);
    spi_write(0x00 | (data >> 4), MAX_DELAY);
    /* Send LOW bits */
    spi_write(0x00 | (data & 0x0F), MAX_DELAY);
    spi_write(0x80 | (data & 0x0F), MAX_DELAY);
    spi_write(0x00 | (data & 0x0F), MAX_DELAY);

}

/** Write a character to the LCD
 * Inputs:
 *  c: Character to write
 */
void lcd_char(char c) {
    /* Send HIGH bits */
    spi_write(0x40 | ((uint8_t)c >> 4), CHAR_DELAY);
    spi_write(0xC0 | ((uint8_t)c >> 4), CHAR_DELAY);
    spi_write(0x40 | ((uint8_t)c >> 4), CHAR_DELAY);
    /* Send LOW bits */
    spi_write(0x40 | ((uint8_t)c & 0x0F), CHAR_DELAY);
    spi_write(0xC0 | ((uint8_t)c & 0x0F), CHAR_DELAY);
    spi_write(0x40 | ((uint8_t)c & 0x0F), CHAR_DELAY);
}
```

Both commands split the 8 bits of data to be sent into 4 bit packets to be sent over the 4 bit interface: where 4 bits of the data sent are control bits and 4 bits are data. The difference between the two commands resides in the control bits, where `lcd_char` has the register select (RS) bit LOW whereas `lcd_cmd` send a HIGH RS bit.

Both functions utilize `void spi_write(uint8_t data)`, a function providing an abstracted interface to utilize the 74HC164 serial-in, parallel-out shift register which interfaces with the LCD. The command ensures suitable time has passed by polling TIM3, where it then sets the LCK signal LOW, loads the data into the shift register over SPI before finally setting the LCK pin HIGH again and resets the TIM3 delay counter.

Displaying frequency and resistance information on the LCD is accomplished by first setting up the UI by writing the persistent characters, where the underscores between represent spaces which are updated with the read values:

```
F:____Hz
R:____Oh
```

When the frequency monitor reads an updated value (see 2.2.6 for details) the LCD is updated with the new resistance and calculated frequency values. When these values are received, the code in Listing 15 updates the frequency of the UI.

Listing 15: LCD value update (`src/analog.c`)

```
char* freq_ascii = num_to_ascii(freq_value);
// Write the frequency value to the LCD
```

```
    lcd_cmd(0x82); // Set address to 02
    for (int i = MAX_DIGITS-1; i >= 0; i--){
        lcd_char(*(freq_ascii + i));
    }
```

The value of the frequency is converted to an array of ASCII characters by calling `char* num_to_ascii(uint16_t)` (Listing 16) , which are then written to the LCD. The loop decrements to read the array from end to start, as the way `num_to_ascii` operates stores the digits least significant digit first. The same method is used to update the resistance value, however the resistance value is rounded to the nearest 100 as the frequency does not change until the resistance varies by approximately this amount, and to improve readability by reducing flickering of the digits.

Listing 16: Convert a value to ASCII characters (`src/lcd.c`)

```
/** Convert a number to ASCII digits (max of 4)
 * Inputs:
 *  num: 32 bit unsigned integer to convert
 * Returns:
 *  ASCII encoded digits in LSD first order
 */
char* num_to_ascii(uint32_t num) {
    static char ascii[MAX_DIGITS] = {0, 0, 0, 0};
    uint8_t i = 0;
    // Get individual digits (in LSD order)
    do {
        ascii[i++] = ('0' + (char)(num % 10));
        num /= 10;
    } while (num && (i < MAX_DIGITS));
    // Fill remaining space with blanks
    for (; i < MAX_DIGITS; i++) {
        ascii[i] = ' ';
    }
    return ascii;
}
```

2.2.6 Frequency Monitor Implementation

The frequency monitor's main components consist of TIM2 and an interrupt routine triggered by EXTI1. Defined in Listing 17, `void EXTI0_1_IRQHandler()` is the routine called when the input PA1 sees a rising-edge.

Listing 17: Frequency monitor interrupt routines (`src/analog.c`)

```
void TIM2_IRQHandler() {
    /* Check if update interrupt flag is set */
    if (TIM2->SR & TIM_SR_UIF) {
        trace_printf("\n*** Overflow! ***\n");

        /* Clear update interrupt flag */
        TIM2->SR |= 0x1;
        /* Restart stopped timer */
        TIM2->CR1 |= 0x1;
    }
```

```
}

void EXTI0_1_IRQHandler() {
    /* Check if EXTI1 interrupt pending flag is set */
    // Disable interrupts while servicing
    NVIC_DisableIRQ(EXTI0_1_IRQn);
    if (EXTI->PR & EXTI_PR_PR1) {
        if (first_edge) {
            first_edge = 0;
            /* Reset current timer count */
            TIM2->CNT = 0;
            /* Start the timer */
            TIM2->CR1 |= 0x1;
        } else {
            /* Stop the timer */
            TIM2->CR1 &= ~0x1;
            /* Read the current timer count */
            uint32_t count = TIM2->CNT;

            uint32_t freq_value = period_to_freq(count);
            char* freq_ascii = num_to_ascii(freq_value);
            // Write the frequency value to the LCD
            lcd_cmd(0x82); // Set address to 02
            for (int i = MAX_DIGITS-1; i >= 0; i--){
                lcd_char(*(freq_ascii + i));
            }
            // Here we want to obtain the resistance, send the result
     to the DAC
            // and print it to the LCD. A short wait time will also
    be added so the display doesn't flicker too much
            adc_value = adc_read();
            // Get the string for resistance rounded to the 100th
            dac_write(adc_value); // Send value of ADC to DAC
            char* resistance_ascii = num_to_ascii((((uint32_t)(
    adc_value * ((float)5000/4095)) + 50)/ 100)*100);
            // Write the resistance value to the LCD
            lcd_cmd(0xC2); // Set address to h42
            for (int i = MAX_DIGITS-1; i >= 0; i--) {
                lcd_char(*(resistance_ascii + i));
            }

            TIM3->CNT = UPDATE_DELAY;
            TIM3->CR1 |= 0x1;
            while(TIM3->CNT > 1);
            first_edge = 1;
        }

        /* Clear the interrupt flag */
        EXTI->PR = EXTI_PR_PR1;
    }

    NVIC_EnableIRQ(EXTI0_1_IRQn);
}
```

Every $2n, n = 0, 1, \ldots$ executions (executions 0,2,... where `first_edge=1`) of this routine:

1. Interrupts are disabled.

2. The interrupt request flag is checked.
3. The count of TIM2 to 0 and the timer started
4. The interrupt flag is cleared and interrupts are re-enabled.
5. The service routine returns.

Every $2n+1, n = 0, 1, \ldots$ executions (executions 1,3,... where `first_edge=0`) of this routine:

1. Interrupts are disabled.
2. The interrupt request flag is checked.
3. The TIM2 clock is stopped.
4. The current count is stored in `uint32_t count`.
5. The frequency and resistance displayed on the LCD is updated (see 2.2.5).
6. TIM3 is utilized to delay updates to a reasonable period (to reduce flickering of the numbers on the LCD).
7. The interrupt flag is cleared and interrupts are re-enabled.
8. The service routine returns.

The end result is measurement of the time between 2 successive rising-edges, giving the frequency of the input waveform.

The `void TIM2_IRQHandler()` interrupt routine, also visible in Listing 17, is the routine called in the event of an interrupt generated by the TIM2, which only occurs in the event of an overflow.

2.3 Hardware Implementation

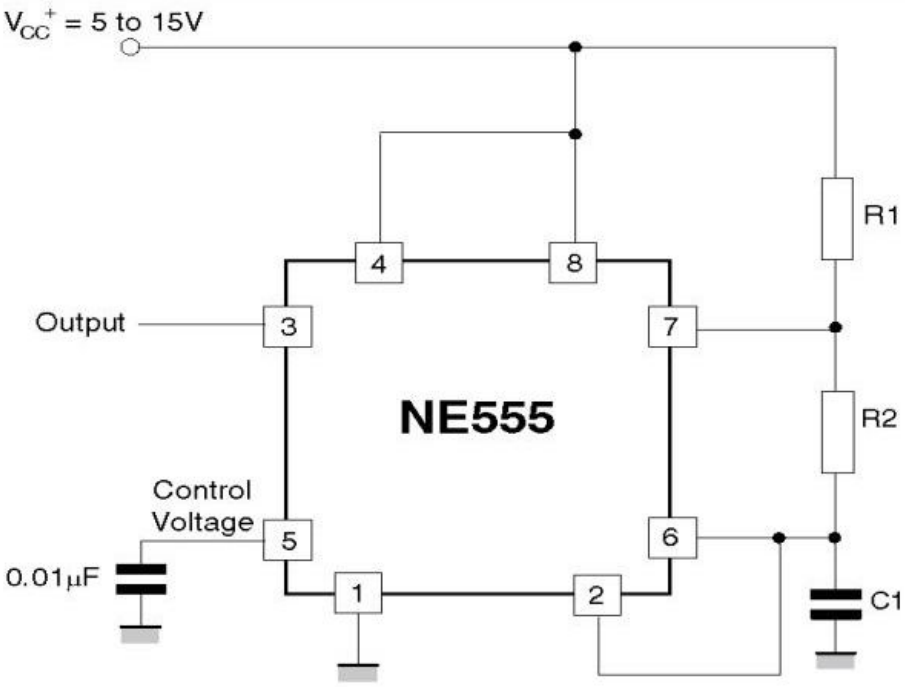
2.4 Test Procedures

Tests of the system were conducted in a unit manner: each individual component was tested before testing components together.

2.4.1 External PWM Signal Generator

The pulse-width modulation (PWM) generator was tested by building up the circuit and providing a variable voltage through a signal generator's DC supply function, and the output measured with the oscilloscope to ensure varying the voltage resulted in a changing frequency.

Figure 2: 555 Timer Configuration [2]



2.4.2 Potentiometer and ADC System

The ADC and potentiometer was tested by supplying the potentiometer to the analog input pin PA1 and printing the digitized analog value to the trace of the STM32F0DISCOVERY.

2.4.3 DAC System

The DAC system was tested using the ADC by writing the value measured by the ADC to the DAC's output register and measuring the outputted voltage and ensuring it varied with varying the resistance of the potentiometer.

2.4.4 LCD System

Testing the LCD was conducted with the other components working, where the test was simply getting the desired message to print. Initially that desired message was any symbol appearing on the display; and after debugging, the frequency and resistance value display.

2.4.5 Complete System

To test the complete system, the external 555 timer-based PWM signal generator output was connected to both the STM32F0DISCOVERY board and oscilloscope such that the frequencies could be compared. The potentiometer was varied and the generated PWM signal's frequency was measured on both the oscilloscope and the STM32F0DISCOVERY board as displayed on the LCD: they were found to coincide. Resistance measurement was confirmed by linearly varying the potentiometer between either extreme and ensuring the resistance displayed on the LCD linearly varies between $0\,\Omega$ and $5\,\mathrm{k}\Omega$.

2.5 Test Results

The results of testing with the above specified procedures including range, resolution, and measurement error were recorded.

2.5.1 Resistance Measurement

The measured resistance range was the full range provided by the potentiometer ($0\,\Omega$). As the range of values available from the DAC was that provided by a 12-bit integer (0 to 4095) and the resistance of the potentiometer varied between 0 and 5000, the measurement resolution of the potentiometer was slightly over $1\,\Omega$, $\frac{5000}{4095} \approx 1.221\Omega$. The error in measurement was less than could be measured with the test setup.

2.5.2 Frequency Production and Measurement

The frequency of the resulting PWM signal varied between 281-535Hz in increments of around $20\,\mathrm{Hz}$, or steps of approximately $400\,\Omega$ of change in the

potentiometer. The coarse resolution was caused The measurement error of the frequency in the available range was less than 1 Hz.

2.5.3 Limitations

The largest limitation of the system was the range of frequency the design external PWM circuit was capable of producing with the available voltage range from the STM32F0DISCOVERY board's analog output pin. Additional limitations came from the LCD display. With the LCD's size of 8x2 only 4 digit values could be displayed. The severe of ghosting of the LCD also limited the viable update speed: when the display was updated too quickly the two least significant digits, which changed the most, tended to blend together and become undecipherable; this was solved by eliminating the two least significant digits as there value did not tend to influence the produced frequency, which relied more on the two most significant digits.

3 Discussion

3.1 Limiting Factors

The largest factors in the design was that of simplicity and clearness over optimization and performance. As the time constraint was the dominant factor in this lab, decisions tended to be in favour of that which complimented the limited amount of time available.

3.1.1 Software Factors

Software factors in the design include the use of SPI to greatly simplify the LCD interface and an abstracted hardware interface to allow faster development. Using SPI reduced wiring and GPIO port setup and avoided potential "bit banging", or sending a series of hard-coded bits reducing flexibility of development and coordination of parallelizing serialized data.

3.1.2 Hardware Factors

Hardware design factors consisted of ensuring the measured frequency from the PWM signal generator was within the range of 0 to 9999, so that all decimal figures can fit on the LCD display. To do this, R1, R2, and C1 from Figure 2 were selected as 1 kΩ, 4.7 kΩ, and 470 nF respectively. The supply voltage was 5 V. Using the equation $f = \frac{1.443}{(R1+2R2)C1}$, the frequency when the optocoupler is off is $\sim$ 295Hz.

By measuring the resistance between the collector and emitter of the optocoupler transistor when the DAC is supplying 3.3 V, this

3.1.3 Effects

The simple design of the PWM signal generator lead to a small range of producible frequencies with a relatively low resolution. A more complicated design may have been able to produce a wider range with more coverage. The trade-off for simplicity over optimization also resulted in a slower response time than could be achieved with a more complex design. Placing the LCD update code in the frequency monitor interrupt lead to simplicity with the LCD only changing when there was an update and avoided interrupts being serviced while writing to the LCD, however this also decreased the maximum update rate of the frequency monitor. This was deemed to be an acceptable trade-off as the measured frequency wasn't being supplied to another component other than the LCD for human observation and thus the maximum speed observable was deemed the maximum necessary speed of measurement.

References

[1] A. Jooya, K. Jones, D. Rakhmatov, and B. Sirna, *Electrical and Computer Engineering CENG 355: Microprocessor-Based Systems Laboratory Manual*. University of Victoria, 2016.

[2] D. Rakhmatov, "Interface examples," 2016.

[3] STMicroelectronics, *RM0091 Reference manual*, 2014.

[4] Freescale Semiconductor, *MCU project board student learning kit (PBM-CUSLK)*, 2007.

Appendices

A Source Code

A.1 Main

src/main.c

```
//
// This file is part of the GNU ARM Eclipse distribution.
// Copyright (c) 2014 Liviu Ionescu.
//

// ----------------------------------------------------------------------


#include <stdio.h>
#include <stdlib.h>
#include "diag/Trace.h"

#include "stm32f0xx_conf.h"

#include "analog.h"
#include "lcd.h"


// Sample pragmas to cope with warnings. Please note the related line at
// the end of this function, used to pop the compiler diagnostics status.
#pragma GCC diagnostic push
#pragma GCC diagnostic ignored "-Wunused-parameter"
#pragma GCC diagnostic ignored "-Wmissing-declarations"
#pragma GCC diagnostic ignored "-Wreturn-type"

int main(int argc, char* argv[]) {
  // By customizing __initialize_args() it is possible to pass arguments,
  // for example when running tests with semihosting you can pass various
  // options to the test.
  // trace_dump_args(argc, argv);

  // Send a greeting to the trace device (skipped on Release).
  trace_puts("Hello ARM World!");

  // The standard output and the standard error should be forwarded to
  // the trace device. For this to work, a redirection in _write.c is
  // required.

  // At this stage the system clock should have already been configured
  // at high speed.
```

```
  trace_printf("System clock: %u Hz\n", SystemCoreClock);

  trace_printf("%s", "Initializing ADC...");
  adc_init();
  adc_enable_pot(1);
  trace_puts("Done");

  trace_printf("%s", "Initializing DAC...");
  dac_init();
  trace_puts("Done");

  trace_printf("%s", "Initializing LCD...");
  lcd_init();
  trace_puts("Done");

  trace_printf("%s", "Initializing frequency monitor...");
  freq_init();
  trace_puts("Done");

  // Infinite loop, wait for interrupts to do anything
  while (1) {

  }
  // Infinite loop, never return.
  return 0;
}

#pragma GCC diagnostic pop

//
    ----------------------------------------------------------------------------
```

A.2 Analog

include/analog.h

```
#ifndef __ANALOG_H__
#define __ANALOG_H__

#include <stdio.h>
#include <stdlib.h>

#include "stm32f0xx_conf.h"

/* No prescaler on timer 2 */
#define TIM2_PRESCALER ((uint16_t)0x0000)
/* Maximum possible setting for auto-reload */
#define TIM2_AUTORELOAD_DELAY ((uint32_t)0xFFFFFFFF)
/* 48MHz clock speed */
#define TIMER_CLOCK_FREQ ((uint32_t)48000000)

/* Wiring:
 *  Potentiometer/ADC:
 *      - ADC input POT M20 -> PA0
 *      - POT_EN M32 -> PC1
 *  DAC:
 *      - DAC output is PA4
 *  Freq. Measurement:
 *      - Input is PA1
 */

void adc_init(void);
void dac_init(void);
void freq_init(void);

/* Enable or disable the potentiometer value line
 * Inputs:
 *  state: 1 for enable 0 for disable
 */
void adc_enable_pot(uint8_t state);

/* Read the current value for the potentiometer
 * If POT ENABLE is not high this will return garbage results
 * Outputs:
 *  uint16_t: right-aligned 12-bit ADC value
 */
uint16_t adc_read(void);

/* Write the output value of the DAC
 * Inputs:
 *  uint16_t value: 12-bit right-aligned value to set
 */
void dac_write(uint16_t value);

/* Returns the current input frequency
 * Outputs:
 *  float: current frequency in Hz
 */
uint32_t period_to_freq(uint32_t count);
```

```
#endif // __ANALOG_H__
```

src/analog.c

```
#include "analog.h"

#include "diag/Trace.h"
#include "lcd.h"

#define UPDATE_DELAY (800000)

static uint16_t first_edge = 1;
static uint16_t adc_value;

uint16_t adc_read(void) {
    return ADC1->DR;
}

void adc_enable_pot(uint8_t state) {
    if (state) {
        GPIOC->BSRR = GPIO_BSRR_BS_1;
    }
    else {
        GPIOC->BRR = GPIO_BRR_BR_1;
    }
}

void dac_write(uint16_t value) {
    /* Write the provided value to the 12-bit right-aligned DAC input
     */
    DAC->DHR12R1 = (value & DAC_DHR12R1_DACC1DHR);
}

uint32_t period_to_freq(uint32_t count) {
    return (TIMER_CLOCK_FREQ)/count;
}

/* Initialize the ADC
 */
void adc_init(void) {
    /* Enable clock for GPIOC */
    RCC->AHBENR |= RCC_AHBENR_GPIOCEN;

    /* Configure PC1 as push-pull output  */
    GPIOC->MODER |= GPIO_MODER_MODER1_0;
    GPIOC->OTYPER &= ~GPIO_OTYPER_OT_1;
    /* Ensure high-speed mode for PC1 */
    GPIOC->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR1;
    /* Disable any pull up/down resistors on PC1 */
    GPIOC->PUPDR &= ~GPIO_PUPDR_PUPDR1;

    /* Configure PA0 as an analog pin */
    GPIOA->MODER |= GPIO_MODER_MODER0;

    /* Enable the HSI14 (ADC async) clock */
    RCC->CR |= RCC_CR_HSION;
    RCC->APB2ENR |= RCC_APB2ENR_ADCEN;
```

```
    /* Start up the ADC */
    ADC1->CR = ADC_CR_ADEN;

    /* ---- Configure the ADC ---- */
    /* Set the ADC clock to the dedicated clock */
    ADC1->CFGR2 &= ~(0x00);
    /* Select the input channel */
    ADC1->CHSELR = ADC_CHSELR_CHSEL0;
    /* Set continuous conversion mode */
    ADC1->CFGR1 |= ADC_CFGR1_CONT;
    /* Enable starting with software trigger */
    ADC1->CFGR1 &= ~ADC_CFGR1_EXTEN;
    /* Disable auto-off */
    ADC1->CFGR1 &= ~ADC_CFGR1_AUTOFF;
    /* ----------------------------*/

    /* Wait for the ADC to stabilize */
    while(!(ADC1->ISR & ADC_ISR_ADRDY));
    /* Start converting the analog input */
    ADC1->CR |= ADC_CR_ADSTART;
}

/* Initialize the DAC
 */
void dac_init(void) {
    /* Set PA4 (DAC output) as analog output pin */
    GPIOA->MODER = GPIO_MODER_MODER4;
    /* Set PA4 to open drain */
    GPIOA->OTYPER = GPIO_OTYPER_OT_4;
    /* Disable pull up/down resistors on PA4 */
    GPIOA->PUPDR &= ~GPIO_PUPDR_PUPDR4;
    /* Set PA4 to high-speed mode */
    GPIOA->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR4;

    /* Enable the DAC clock */
    RCC->APB1ENR |= RCC_APB1ENR_DACEN;
    /* Enable the DAC (with output buffering and auto-triggering */
    DAC->CR = DAC_CR_EN1;
}

void freq_init(void) {
    /* Enable the GPIOA clock */
    RCC->AHBENR |= RCC_AHBENR_GPIOAEN;
    /* Configure PA1 as an input */
    GPIOA->MODER &= ~(GPIO_MODER_MODER1);
    /* Ensure no pull up/down for PA1 */
    GPIOA->PUPDR &= ~(GPIO_PUPDR_PUPDR1);

    /* Enable the TIM2 clock */
    RCC->APB1ENR |= RCC_APB1ENR_TIM2EN;
    /* Configure TIM2 with buffer auto-reload, count up,
     * stop on overflow, enable update events, and interrupt
     * on overflow only
     */
    TIM2->CR1 = 0x8C;

    /* Set clock prescaler value */
```

```
    TIM2->PSC = TIM2_PRESCALER;
    /* Set auto-reload delay */
    TIM2->ARR = TIM2_AUTORELOAD_DELAY;
    /* Set timer update configuration (rising edge, etc.) */
    TIM2->EGR = (TIM2->EGR & ~0x5F) | (0x1 & 0x5F);

    /* Assign TIM2 interrupt priority 0 in NVIC */
    NVIC_SetPriority(TIM2_IRQn, 0);
    /* Enable TIM2 interrupts in NVIC */
    NVIC_EnableIRQ(TIM2_IRQn);
    /* Enable update interrupt generation */
    TIM2->DIER |= 0x41;

    /* Map EXTI1 line to PA1 */
    SYSCFG->EXTICR[0] = (SYSCFG->EXTICR[0] & ~(0xF)) | (0 & 0xF);

    /* EXTI1 line interrupts: set rising-edge trigger */
    EXTI->RTSR |= 0x2;

    /* Unmask interrupts from EXTI1 line */
    EXTI->IMR |= 0x2;

    /* Assign EXTI1 interrupt priority 0 in NVIC */
    NVIC_SetPriority(EXTI0_1_IRQn, 0);
    /* Enable EXTI1 interrupts in the NVIC */
    NVIC_EnableIRQ(EXTI0_1_IRQn);
}

void TIM2_IRQHandler() {
    /* Check if update interrupt flag is set */
    if (TIM2->SR & TIM_SR_UIF) {
        trace_printf("\n*** Overflow! ***\n");

        /* Clear update interrupt flag */
        TIM2->SR |= 0x1;
        /* Restart stopped timer */
        TIM2->CR1 |= 0x1;
    }
}

void EXTI0_1_IRQHandler() {
    /* Check if EXTI1 interrupt pending flag is set */
    // Disable interrupts while servicing
    NVIC_DisableIRQ(EXTI0_1_IRQn);
    if (EXTI->PR & EXTI_PR_PR1) {
        if (first_edge) {
            first_edge = 0;
            /* Reset current timer count */
            TIM2->CNT = 0;
            /* Start the timer */
            TIM2->CR1 |= 0x1;
        } else {
            /* Stop the timer */
            TIM2->CR1 &= ~0x1;
            /* Read the current timer count */
            uint32_t count = TIM2->CNT;
```

```
            uint32_t freq_value = period_to_freq(count);
            char* freq_ascii = num_to_ascii(freq_value);
            // Write the frequency value to the LCD
            lcd_cmd(0x82); // Set address to 02
            for (int i = MAX_DIGITS-1; i >= 0; i--){
                lcd_char(*(freq_ascii + i));
            }
            // Here we want to obtain the resistance, send the result to the DAC
            // and print it to the LCD. A short wait time will also be added so the display doesn't flicker too much
            adc_value = adc_read();
            // Get the string for resistance rounded to the 100th
            dac_write(adc_value); // Send value of ADC to DAC
            char* resistance_ascii = num_to_ascii((((uint32_t)(adc_value * ((float)5000/4095)) + 50)/ 100)*100);
            // Write the resistance value to the LCD
            lcd_cmd(0xC2); // Set address to h42
            for (int i = MAX_DIGITS-1; i >= 0; i--) {
                lcd_char(*(resistance_ascii + i));
            }

            TIM3->CNT = UPDATE_DELAY;
            TIM3->CR1 |= 0x1;
            while(TIM3->CNT > 1);
            first_edge = 1;
        }

        /* Clear the interrupt flag */
        EXTI->PR = EXTI_PR_PR1;
    }

    NVIC_EnableIRQ(EXTI0_1_IRQn);
}
```

A.3 LCD

include/lcd.h

```
#ifndef __LCD_H__
#define __LCD_H__

#include "stm32f0xx_conf.h"

#define MAX_DIGITS (4)

/* Maximum required delay between SPI writes */
#define MAX_DELAY ((uint32_t)96000)
/* Delay between characters */
#define CHAR_DELAY ((uint32_t)4800)

/** Wiring
 * PC2 - LCK -> M25
 * PB5 - MOSI -> M17
 * PB3 - SCK -> M21
 */

void lcd_init(void);

void lcd_clear(void);

void lcd_cmd(uint8_t data);

void lcd_char(char c);

char* num_to_ascii(uint32_t num);

#endif //__LCD_H__
```

src/lcd.c

```
#include "lcd.h"

#define LCD_BAUD_RATE_PRESCALER (16)

/* No prescaler on timer 3 */
#define TIM3_PRESCALER ((uint16_t)0x0000)
/* Maximum possible setting for auto-reload */
#define TIM3_AUTORELOAD_DELAY ((uint32_t)0xFFFFFFFF)
/* 48MHz clock speed */
#define TIMER_CLOCK_FREQ ((uint32_t)48000000)

/* Output data to the shift register through SPI */
void spi_write(uint8_t, uint32_t delay);

void lcd_init(void) {
    /* Enable SPI1 clock */
    RCC->APB2ENR |= RCC_APB2ENR_SPI1EN;
    /* Enable GPIOB clock */
    RCC->AHBENR |= RCC_AHBENR_GPIOBEN;
    /* Enable GPIOC clock */
    RCC->AHBENR |= RCC_AHBENR_GPIOCEN;
```

```
    /* Set PC2 to output */
    GPIOC->MODER = (GPIOC->MODER & ~GPIO_MODER_MODER2) | (
    GPIO_MODER_MODER2 & GPIO_MODER_MODER2_0);
    /* Set PB3 to alternate function */
26  GPIOB->MODER = (GPIOB->MODER & ~GPIO_MODER_MODER3) | (
    GPIO_MODER_MODER3 & GPIO_MODER_MODER3_1);
    GPIOB->AFR[0] &= ~GPIO_AFRL_AFR3;
    /* Set PB5 to alternate function */
    GPIOB->MODER = (GPIOB->MODER & ~GPIO_MODER_MODER5) | (
    GPIO_MODER_MODER5 & GPIO_MODER_MODER5_1);
    GPIOB->AFR[0] &= ~GPIO_AFRL_AFR5;
31
    /* Set PC2, PB3, PB5 to push-pull mode */
    GPIOC->OTYPER &= ~GPIO_OTYPER_OT_2;
    GPIOB->OTYPER &= ~GPIO_OTYPER_OT_3;
    GPIOB->OTYPER &= ~GPIO_OTYPER_OT_5;
36
    /* Disable pull up/down resistors on SPI pins */
    GPIOB->PUPDR &= ~GPIO_PUPDR_PUPDR3;
    GPIOB->PUPDR &= ~GPIO_PUPDR_PUPDR5;
    GPIOC->PUPDR &= ~GPIO_PUPDR_PUPDR2;
41
    /* Set SPI pins to high-speed */
    GPIOB->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR3;
    GPIOB->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR5;
    GPIOC->OSPEEDR |= GPIO_OSPEEDR_OSPEEDR2;
46
    /* Initialize TIM3 */
    /* Enable the TIM3 clock */
    RCC->APB1ENR |= RCC_APB1ENR_TIM3EN;
    /* Configure TIM3 with buffer auto-reload, count down,
51   * stop on overflow, and only interrupt on overflow
     */
    TIM3->CR1 = 0xC6;
    /* Set clock prescaler value */
    TIM3->PSC = TIM3_PRESCALER;
56  /* Set auto-reload delay */
    TIM3->ARR = TIM3_AUTORELOAD_DELAY;
    /* Set timer update configuration (rising edge, etc.) */
    TIM3->EGR = (TIM2->EGR & ~0x5F) | (0x1 & 0x5F);
    /* Load delay value */
61  TIM3->CNT = MAX_DELAY;
    TIM3->CR1 |= 0x1;

    /* Initialize SPI */
    SPI_InitTypeDef SPI_InitStructInfo = {
66          .SPI_Direction = SPI_Direction_1Line_Tx,
            .SPI_Mode = SPI_Mode_Master,
            .SPI_DataSize = SPI_DataSize_8b,
            .SPI_CPOL = SPI_CPOL_Low,
            .SPI_CPHA = SPI_CPHA_1Edge,
71          .SPI_NSS = SPI_NSS_Soft,
            .SPI_BaudRatePrescaler = SPI_BaudRatePrescaler_256,
            .SPI_FirstBit = SPI_FirstBit_MSB,
            .SPI_CRCPolynomial = 7
    };
```

```
76      SPI_Init(SPI1, &SPI_InitStructInfo);

        SPI_Cmd(SPI1, ENABLE);

        /* Set the LCD to 4 bit interface */
81      spi_write(0x02, MAX_DELAY);
        spi_write(0x82, MAX_DELAY);
        spi_write(0x02, MAX_DELAY);

        /* Set LCD to display 2 lines */
86      lcd_cmd(0x28);

        /* Clear the LCD */
        lcd_cmd(0x01);
        /* Home the cursor */
91      lcd_cmd(0x02);
        /* Set cursor move direction and disable display shift */
        lcd_cmd(0x06);
        /* Set the display on, don't show the cursor, don't blink */
        lcd_cmd(0x0C);
96      /* Set the cursor to move right, no display shift */
        lcd_cmd(0x14);
        /* Write 'F:    Hz' to first line */
        lcd_cmd(0x80); // Start at very left

101     lcd_char('F'); //F
        lcd_char(':'); //:
        lcd_cmd(0x86);
        lcd_char('H'); //H
        lcd_char('z'); //z
106
        /* Write 'R:    Oh' to second line*/
        lcd_cmd(0xC0); // set address to second line, first character
        lcd_char('R'); //R
        lcd_char(':'); //:
111     lcd_cmd(0xC6);
        lcd_char('O');
        lcd_char('h');
    }

116 void spi_write(uint8_t data, uint32_t delay) {
        /* Wait until SPI delay has passed */
        while (TIM3->CNT > ((MAX_DELAY+1) - delay));
        /* Force LCK low */
        GPIOC->BRR |= GPIO_BRR_BR_2;
121     /* Wait until SPI1 is ready */
        while((SPI1->SR & SPI_SR_BSY) && ~(SPI1->SR & SPI_SR_TXE));
        /* Send the data */
        SPI_SendData8(SPI1, data);
        /* Wait until SPI1 is not busy */
126     while(SPI1->SR & SPI_SR_BSY);
        /* Force LCK signal to 1 */
        GPIOC->BSRR |= GPIO_BSRR_BS_2;
        /* Reset LCD comm clock */
        TIM3->CNT = MAX_DELAY;
131     TIM3->CR1 |= 0x1;
    }
```

```
/*
 * Write to LCD using 4 bit interface. Send 4 high bits
 * by pulsing EN, then do the same for 4 low bits
 */
void lcd_cmd(uint8_t data) {
    /* Send HIGH bits */
    spi_write(0x00 | (data >> 4), MAX_DELAY);
    spi_write(0x80 | (data >> 4), MAX_DELAY);
    spi_write(0x00 | (data >> 4), MAX_DELAY);
    /* Send LOW bits */
    spi_write(0x00 | (data & 0x0F), MAX_DELAY);
    spi_write(0x80 | (data & 0x0F), MAX_DELAY);
    spi_write(0x00 | (data & 0x0F), MAX_DELAY);

}

/** Write a character to the LCD
 * Inputs:
 *  c: Character to write
 */
void lcd_char(char c) {
    /* Send HIGH bits */
    spi_write(0x40 | ((uint8_t)c >> 4), CHAR_DELAY);
    spi_write(0xC0 | ((uint8_t)c >> 4), CHAR_DELAY);
    spi_write(0x40 | ((uint8_t)c >> 4), CHAR_DELAY);
    /* Send LOW bits */
    spi_write(0x40 | ((uint8_t)c & 0x0F), CHAR_DELAY);
    spi_write(0xC0 | ((uint8_t)c & 0x0F), CHAR_DELAY);
    spi_write(0x40 | ((uint8_t)c & 0x0F), CHAR_DELAY);
}

/** Convert a number to ASCII digits (max of 4)
 * Inputs:
 *  num: 32 bit unsigned integer to convert
 * Returns:
 *  ASCII encoded digits in LSD first order
 */
char* num_to_ascii(uint32_t num) {
    static char ascii[MAX_DIGITS] = {0, 0, 0, 0};
    uint8_t i = 0;
    // Get individual digits (in LSD order)
    do {
        ascii[i++] = ('0' + (char)(num % 10));
        num /= 10;
    } while (num && (i < MAX_DIGITS));
    // Fill remaining space with blanks
    for (; i < MAX_DIGITS; i++) {
        ascii[i] = ' ';
    }
    return ascii;
}
```