Signal Analyzer Design Evaluation

Project Report

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Abstract:

This project report is intended to serve as a high level design and analysis document, pursuant to request for services issued by Keithley Corporation, for the design evaluation of a Signal Analyzer. Based on the design and performance requirements desired by the client, simulations and tests were carried out using an evaluation board with the aid of external hardware and software components. Using these test results, which are listed as project deliverables, the suitability of the STM32F401RE microcontroller for the Signal Analyzer application was evaluated, along with providing recommendations pertaining to full system design and performance.

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Executive Summary

Pursuant to the Request for Services (RFS) issued by Keithley Corporation, the suitability of the STM32F401RE microcontroller (MCU) was evaluated for the design of their Signal Analyzer product. The NUCLEO-F401RE evaluation board was used in conjunction with analog and digital peripherals to test hardware performance aspects of this MCU. Software performance was qualitatively and quantitatively tested based upon the ability of the MCU to execute interrupt-driven, concurrent, and processing intensive tasks.

The most critical test results and findings pertaining to the design evaluation of the STM32F401RE MCU for the Signal Analyzer application are listed below.

- The MCU was able to be successfully interfaced with a serial terminal, which can serve as a natural, and easy-to-use debugging tool. Further, the STM32F401RE MCU was found to run at ca. 98 DMIPS, which agrees with the specified requirements for the Signal Analyzer application.
- Synthesis of audio waves (20 Hz — 20 kHz) was accomplished using the MCU, such that the frequency and amplitude could be adjusted by the use of potentiometers. Further, SPDT button switches could be used to control the blinking of LEDs based on wave parameters. These are essential functionalities for a signal generator/ harmonic analyzer, and the STM32F401RE MCU facilitated their implementation with ease.
- Real time performance was qualitatively measured by observing the ability of the STM32F401RE MCU to respond to interrupt-driven events. RTOS functionality such as threads were implemented and concurrently executed in a cyclic executive to service peripheral interrupts. The MCU was found to execute these tasks without any visible latency or jitter issues.
- Floating point samples of an audio wave signal with a predetermined frequency of 1004 Hz were provided externally to the STM32F401RE MCU. An autocorrelation based peak-detection algorithm was implemented and executed on the MCU, which was able to estimate the input audio frequency with an accuracy of 0.4%.

Based on these test results, the design evaluation team concludes that the STM32F401RE possesses the requisite functionality, while being able to satisfactorily meet all of the critical performance criteria listed in the RFS, and hence we give it a strong GO for the Signal Analyzer application.

1. Problem Statement and Objectives

Evaluate the STM32 Dynamic Efficiency MCU with core ARM Cortex-M4 processor Nucleo family of Microcontrollers to meet the requirements for Keithley 2017 Signal Analyzer product. The evaluation work entails both software and hardware evaluation to perform a series of tests and by design calculations.

Objective:

The objective is to evaluate the performance of the MCU based on several important criteria, namely I/O interfaces both digital and analog, CPU speed, power consumption, input and output peripherals. More specifically, evaluate hardware suitability by suggesting possible Analog Signal conditioning, ADCs, DACs, speaker driver, Display, buttons, LED drivers and calculating required I/O current drive and voltage levels for the processor I/O.

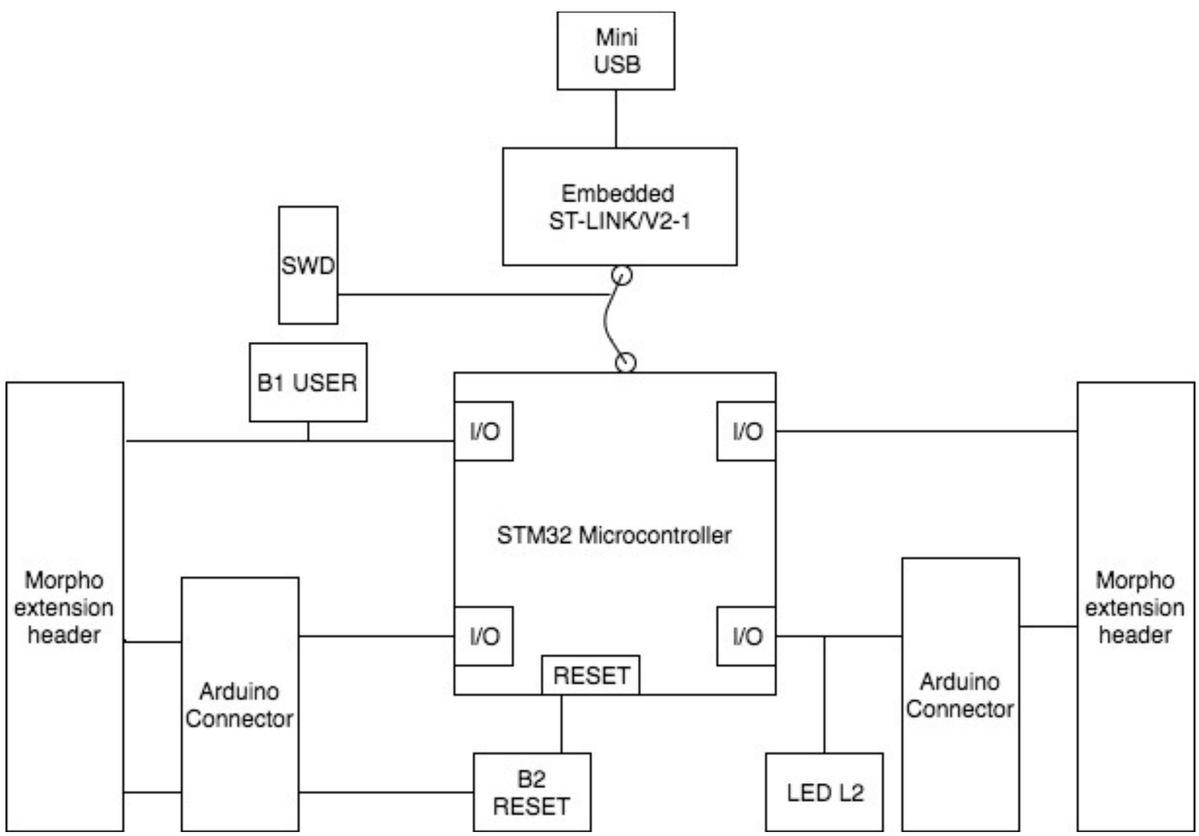

Figure 1: Block diagram of the NUCLEO-F401RE evaluation board, showing the MCU, software debugger (SWD), and I/O headers

2. Approach and Methodology for Evaluation

Tests and data analyses were performed using the NUCLEO-F401RE evaluation board, which provides Arduino Uno Revision 3 connectivity, as well as STMicroelectronics Morpho extension pin headers for full access to all STM32 I/O pins. Figure 1. illustrates the functional block diagram of the NUCLEO-F401RE board, wherein major components like the MCU, the ST-LINK/V2-1 software debugger (SWD) interface, and the I/O headers are shown. Connectivity to the platform was established via the Mini USB port and a Windows host machine.

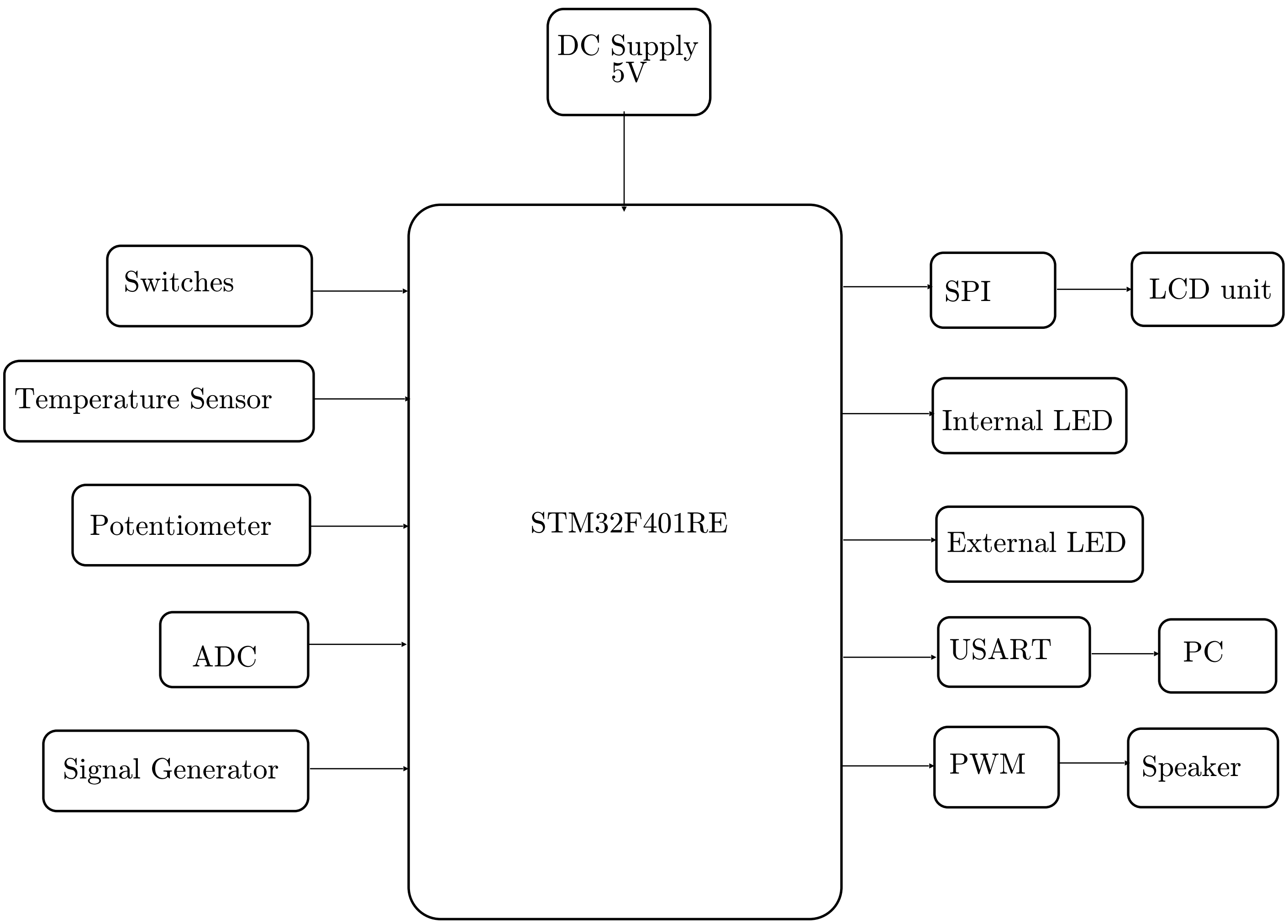

Figure 2: Block diagram of the STM32F401RE MCU, showing on-board components as well as peripherals that were used to conduct tests for design evaluation.

Integration and testing of peripherals such as SPDT button switches, speakers, potentiometers, and LEDs was accomplished using the Analog[In/Out], PWM, Digital[In/Out], and ADC interfaces. These peripherals were mounted on a bread-board and connected with the evaluation platform using the Arduino pin headers. Switch/button interfaces were tested using LED on/off and blinking functionalities. For testing audio wave synthesis and modulation, potentiometers were used in conjunction with a speaker module. A sawtooth waveform was generated by outputting software generated samples over one of the PWM pins. Two potentiometers were then used to modulate this wave by altering the pitch (frequency) and the duty-cycle (amplitude), and the corresponding results were qualitatively evaluated. These are illustrated in Figure 2.

Display peripherals such as the LCD, and the serial terminal of the host machine were tested using the SPI, and USART interfaces, respectively. A text string, an incrementing counter, and temperature values read by an external temperature sensor IC were displayed on the LCD with the help of a shift register and the SPI interface. The USART interface was configured to communicate with the host machine and display similar information. Multitasking capabilities of the STM32F401RE MCU were evaluated using RTOS threads. Specifically, threads were created for a subset of the tasks detailed above, and then spawned at regular intervals within a cyclical executive. To test harmonic analyzer functionality, the MCU was provided with floating-point samples of an audio wave at 1004 Hz, which were then analyzed using a autocorrelation based peak-detection algorithm to yield an estimate of the input frequency.

Dhrystone benchmarking (VAX DMIPS) was used to quantify the processing performance of the MCU. The mBed online compiler was used to develop and compile test code, and the Keil MDK5 IDE was the debugging environment employed.

Hardware Evaluation:

Hardware evaluation is done based on whether the required peripherals can be implemented on the given MCU for Keithley 2017 Signal Analyzer product.

Input Requirements:

1. Temperature Sensor: As there is no temperature sensor provided on the board, we use an external temperature DS1631. DS1631 is a high precision temperature sensor which provides 9 to 12-bit temperature readings over -55℃ to +125℃. To implement DS1631 with the MCU we use SDA and SCL serial communication ports.
2. Potentiometer: Two P103 high precision potentiometers are used as input to the MCU. These potentiometers are of 10K ohms specification with ffi10% tolerance.

The potentiometers are used to adjust the volume and pitch of the audio signal at PWM output.

3. Switches: Four SPDT type button switches were used to toggle LED states.
4. ADC: An ADC is provided on the board. It is a 12-bit 16 channel ADC. The output of the signal generator is given as input to ADC to perform further analysis. The output of temperature sensor is given to the ADC which then using SPI is displayed on the LCD.
5. DAC: There is no DAC provided on the board. But MCU has analog input pins to connect to an external DAC. Microchip MCP4921 is used in this system. This is a 12-bit low cost DAC appropriate for this system. DAC is used to create a 1004 Hz tone to perform further analysis. In this analysis, we used a software DAC to generate the 1004 Hz tone.

<u>Output Requirements:</u>

1. LCD: STM32F401RE has no on-board LCD. We use NewhavenNHD-0216HZ character LCD module instead. This LCD is 2 lines x 16 characters with a required power supply of 3.3V. LCD is interfaced with the processor using a shift register and SPI module.
2. LED: The board has an internal LED LD1 which is a red LED. We also use an external 5mm red LED. The external LED is connected to digital output port on STM32F401RE. The brightness of the LED is controlled using the potentiometer.
3. PWM: In STM32F401RE, one 16-bit timer can be used as PWM time for motor control. The PWM output port is used to drive the speaker module. By adjusting the period and pulse width of the PWM output, volume and pitch of the speaker can be adjusted. The brightness of LED is also controlled using a potentiometer and PWM.
4. Speaker: An analog speaker having that can be driven directly by the MCU AnalogOut pin was used to sense changes made to the pitch and volume of an audio signal.

Result: The STM32F401RE MCU can be used to implement all the input and output subsystems given in the requirements in the RFS. The features required are Digital I/O, Analog I/O, ADC, DAC, SPI, UART and PWM output.

3. Module Test Results

This section describes test results of the evaluation and insights inferred for each module. Results in the form of screenshots can be found in the project submission files.

3.1 Module 1

The purpose of Module 1 was to get familiar with the STM32F401RE MCU by executing basic tasks, and interfacing it to a serial terminal. This was accomplished by setting the current date on the MCU, and printing it to the terminal window. The date was computed in UNIX time format, i.e. number of seconds since 00:00:00 UTC on January 1, 1970. Using the Keil MDK debugger, the memory map of the MCU was studied, specifically with regards to the location of the reset handler. Dhrystone benchmarking was performed on the STM32F401RE using a standard program, and the MCU performance was quantified in terms of VAX DMIPS, i.e. DMIPS/second divided by 1757 (corresponding to a VAX 11/780 machine). Module specific questions and test results are listed below.

- The reset handler for the STM32F401RE MCU was found to reside at the address location 0x08000234
- The LED blinking code was found to occupy 29 kB in Flash memory, and 3 kB in Data memory
- The date code was found to occupy 24.4 kB in Flash memory, and 2.2 kB in Data memory

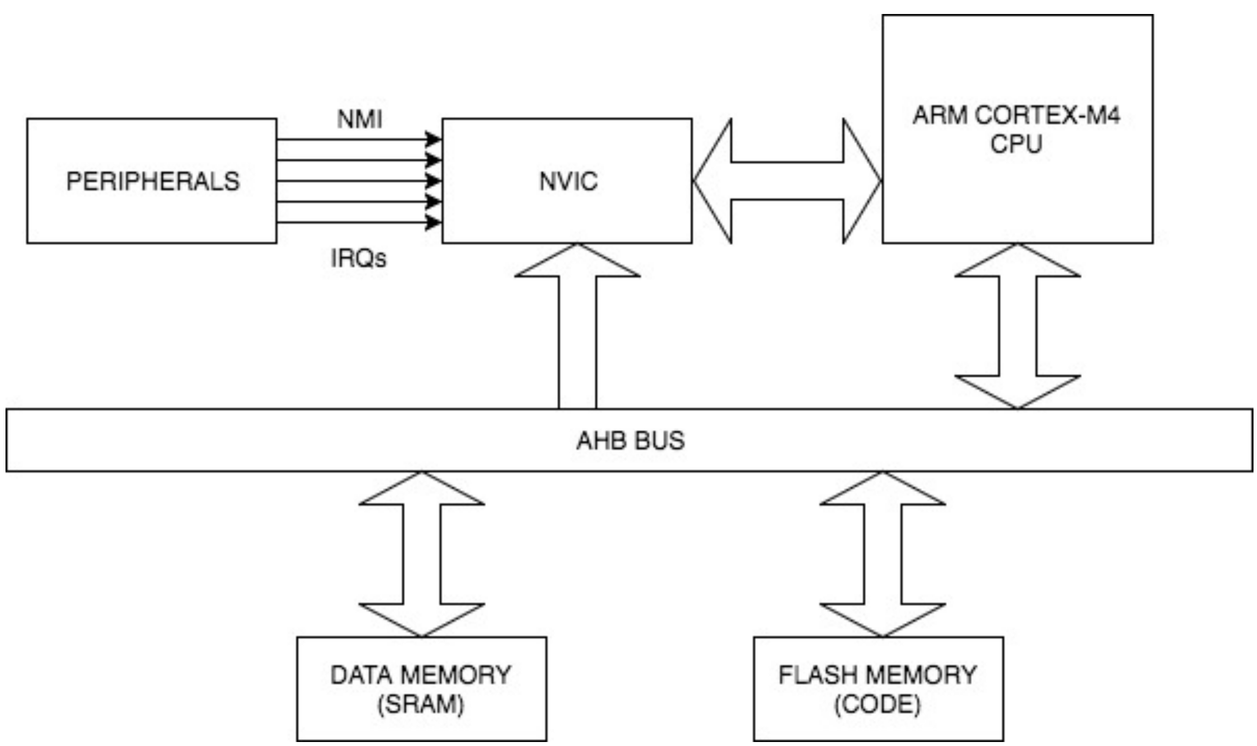

Figure 3: Memory model of the ARM CORTEX-M4 showing code and data regions, as well as peripherals and IRQs

- The diagram above (Figure 3) illustrates the memory map of the ARM CORTEX-M4. The CODE region extends from 0x00000000 to 0x1FFFFFFF. The SRAM region extends from 0x20000000 to 0x3FFFFFFF. The PERIPHERAL region extends from 0x40000000 to 0x5FFFFFFF.
- The current time was set for the STM32F401RE MCU, and was also displayed on the terminal window using the on-board USART.
- The Dhrystone benchmarking program was run on the STM32F401RE MCU, and it was found to operate at 98 VAX DMIPS.

3.2 Module 2

The purpose of tests carried out in this module was to evaluate the response of the STM32F401RE MCU to peripheral inputs, and concurrently display them to display devices. An audio frequency wave was synthesized using the onboard PWM channel, and the pitch and volume were successfully modulated using interrupts generated by potentiometer operation. The STM32F401RE MCU was also found to be compatible with reading data from a I2C based temperature sensor, and indicated a value of ca. 25 deg C inside the laboratory. The initialization sequence from the ST7066U LCD driver data sheet was programmed into the initlcd() function to establish the SPI interface to the LCD. The LCD contrast was adjusted using a potentiometer. Subsequently, text and numeric output was displayed on the LCD, as well as the host machine using the UART interface. Listed below are results and conclusions pertaining to this module.

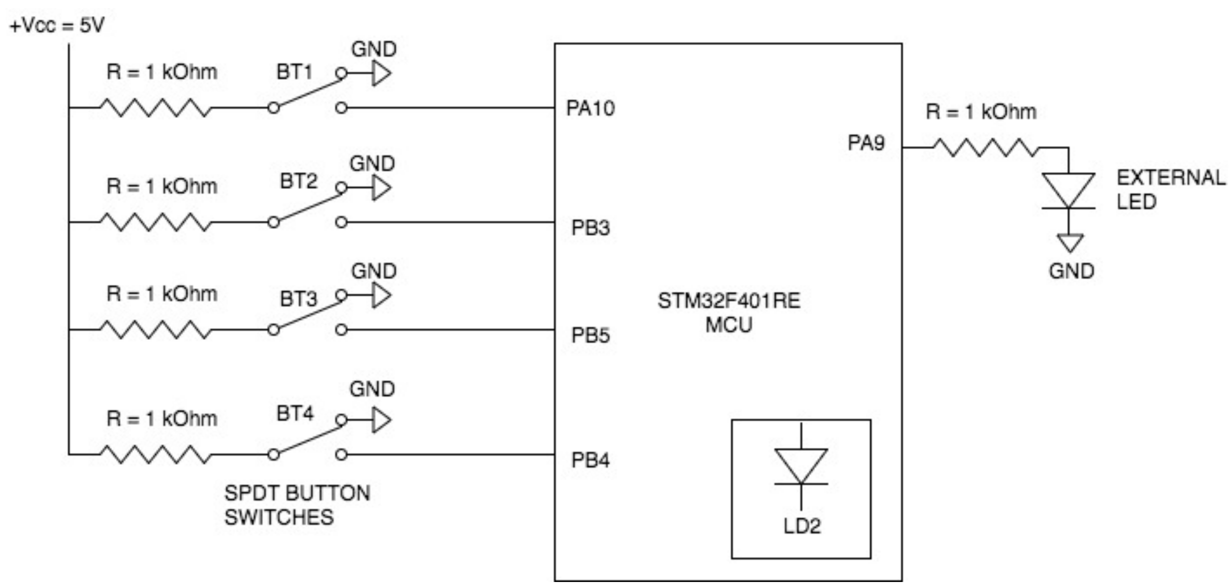

Figure 4: Schematic of external test circuit created using SPDT button switches and LEDs.

- The above circuit diagram (Figure 4) illustrates connections between the NUCLEO-F401RE evaluation board and peripherals including SPDT button switches and LEDs.
- When the interrupt is triggered on the rising edge, the LED is toggled once the button is released after it is pressed. On the other hand, when the interrupt is triggered on the falling edge, the LED is toggled as soon as the button is pressed.
- The LED blinking code was found to occupy 29 kB in Flash memory, and 3 kB in Data memory
- By changing the amount by which the variable 'i' is incremented, the period of the resulting waveform changes, thereby causing a difference in the frequency (pitch) of the audio signal.

3.3 Module 3

The purpose of Module 3 was to recreate the functionalities implemented in Modules 1 and 2, although with the aid of the mBed RTOS this time around. To accomplish this, individual threads were created for the following tasks:

- Display the temperature on the LCD
- Adjust the brightness of the external LED using a potentiometer
- Display an incrementing counter on the LCD
- Blink the internal LED LD2

Single-access to the LCD was ensured by assigning a mutex to the corresponding thread. Each thread contained an infinite loop with wait periods, such that the RTOS could facilitate cooperative scheduling for each of the four tasks. Concurrent execution of these tasks was qualitatively evaluated, and the STM32F401RE MCU was found to perform satisfactorily without any visible latency.

3.4 Module 4

Module 4 dealt with evaluating the ability of the STM32F401RE MCU to function as a harmonic analyzer, i.e. to estimate the frequency of an analog input signal. This was tested by analyzing floating point numbers representing samples of a audio signal (frequency = 1004 Hz, sampled with a 10 us resolution). An autocorrelation based peak-detection algorithm, was used to estimate the input signal frequency, which was found to be 1000 Hz. This result agrees perfectly with that of the Simulink model illustrated below in Figure 5.

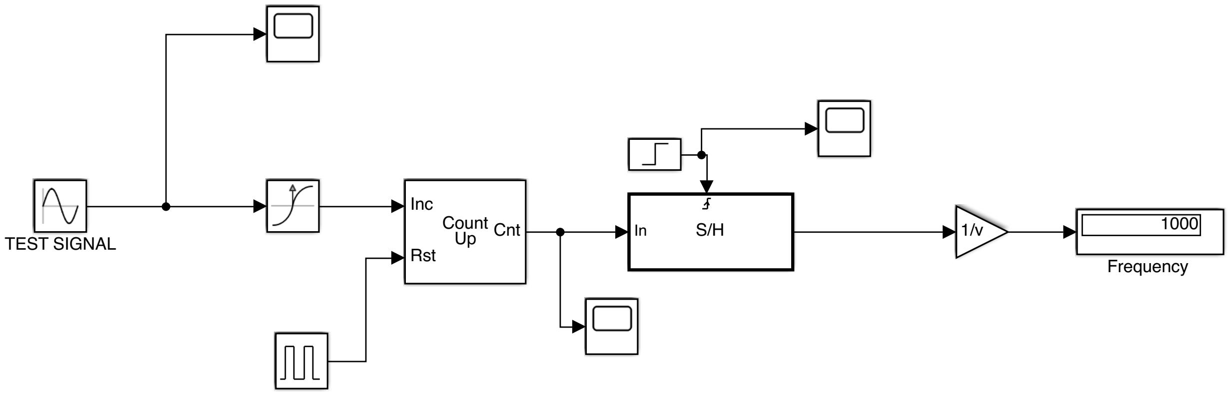

Figure 5: Simulink model depicting the frequency detection algorithm deployed on the STM32F401RE.

The relative error in frequency estimation (with respect to the sampled 1004 Hz signal) is only 0.4%. Although small in most contexts, this error is much larger than the 5 ppm requirement listed in the RFS. The error arises on account of the fact that the frequency is computed using the inverse of time difference between peaks in the autocorrelation function. Since the autocorrelation function, is limited in time resolution by the sampling period of 10 us, there is a lower limit on the achievable frequency resolution. A more complex algorithm which employs polynomial curve fitting to autocorrelation data will provide the capability to have a finer frequency resolution. To complete this test, a LED was made to blink at a rate proportional to the estimated frequency of 1000 Hz.

4. Recommendations

The STM32F401RE MCU was evaluated qualitatively and quantitatively keeping in mind the design and performance requirements listed by Keithley Corporation in their RFS for the Signal Analyzer product. Hardware interface capabilities were evaluated using the responsiveness of the MCU to interrupt-driven I/O. The ability to interface with output devices was evaluated using standard display indicators and components like LEDs, LCD, and a serial terminal. Harmonic analysis capabilities were evaluated by implementing a peak-detection algorithm that estimated frequency using software generated samples, and was able to achieve a 0.4% accuracy. Based on these evaluation and test results, we can affirm that STM32F401RE MCU is capable of handling the interfacing and processing requirements for the Signal Analyzer product.

From the perspective of software development, programming of components, peripheral buses, and debugging was easily facilitated by the use of standard IDEs like the mBed online compiler, and Keil MDK5. Further, from a system design standpoint, the cost for developing the entire system was $15.11, which is well within the budget limitation of

$20. Thus, development of the product is certainly feasible within the time and budget constraints specified in the RFS. Hence, the evaluation team has given the STM32F401RE MCU a straight GO for the Keithley Corporation 2017 Signal Analyzer product.

Appendix: References

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Appendix: Project Team Staffing

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