# Ultrasonic Vein Detector Implementation for Medical Applications

**by**

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# Abstract

Nowadays, taking blood samples from a human forearm and using Cephalic, Basilic, and Median Cubital veins to perform various injections can be considered as one of the most routine medical procedures for diagnostic purposes. Most human patients don't need to waste a lot of time in clinics waiting for the nurses and/or doctors to locate an applicable venipuncture site. However, minority of individuals who suffer from obesity, cancer, and other similar medical complications have to go to excruciating pain in order to provide the nurses with desired venipuncture sites. The goal of this research project is to research and utilize an accurate, safe, and cost-effective instrument that is able to help doctors and nurses to locate an accurate and proper venipuncture site for injections and/or blood withdrawals. An intensive research for high frequency ultrasonic transducers is performed and the results are applied to present accurate measurements for a cost-effective vein detector/seeking prototype. This biomedical device utilizes a high frequency transducer to generate and transmit sound waves that travel through various tissue layers and generates echo waves, each of which corresponding to a different medium through human skin, fat, and the actual vein. Using a microcontroller/microprocessor, such echo waves can be translated into digital signals, which in turn can locate the position of the required vein.

**Keywords**: Forearm; Venipuncture Site; Obesity; Ultrasonic Transducer; Microcontroller; Echo Waves

# Dedication

This project is dedicated to my father, whose experience and expertise in medicine as a radiologist provided me with the knowledge, insight and motivation to invent a biomedical device. Also, I would like to dedicate my thesis to my mother, who has always been supportive of me unconditionally.

# Acknowledgements

The author would like to thank the senior supervisor, Dr. Andrew Rawicz, for his helpful suggestions, guidance, support and mentorship throughout the completion of the project. In addition, the author appreciates Mr. William Hue's assistance for his hardware design suggestions and PCB Layout implementation. Finally, the author sincerely thanks his parents and family for their unlimited support and encouragement.

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## List of Acronyms

| | |
|---|---|
| ADC | Analog-to-Digital Converter |
| BNC | Bayonet Neill Concelman (A connect/disconnect coaxial cable connector) |
| CPU | Control Processing Unit |
| CT | Computed Tomography |
| DAC | Digital-to-Analog Converter |
| DAQ | Data Acquisition Unit |
| DSP | Digital Signal Processor |
| GND | Ground Connection |
| GPIO | General Purpose Input/output |
| IDE | Integrated Development Environment |
| JTAG | Joint Test Action Group |
| LCD | Liquid Crystal Display |
| LED | Light-Emitting Diode |
| LPM | Low Power Mode |
| MCU | Microcontroller Unit |
| MRI | Magnetic Resonance Imaging |
| MSP | Mixed Signal Processor |
| NDT | Non-Destructive Testing |
| OS | Operating System |
| PCB | Printed Circuit Board |
| RG | Radio Guide |
| T/R | Transmit/Receive |
| TVG | Time-Varying Gain |
| USB | Universal Serial Bus |

# Glossary

| | |
|---|---|
| Microcontroller | Considered as a small computer that contains a processor core, memory and programmable input/output peripherals, a microcontroller is applied for embedded applications. |
| Piezoelectric Effect | This phenomenon, described in solids, explains a bidirectional relationship between a mechanical stress and an electrical voltage. Crystals such as tourmaline, topaz, quartz, Rochelle salt and cane sugar play an important role in this energy conversion. Basically, an applied electrical voltage to such crystals will generate a mechanical stress, which can change the shape of the solid by up to 4% in volume. Reversely, an applied mechanical stress will generate an electrical voltage across the crystal. |
| Transceiver | A module capable of both transmitting and receiving signals by combining a transmitter and a receiver and sharing a common circuitry. |
| Transducer | A hardware module, containing piezoelectric material that is able to convert electrical signals into sound waves and convert sound waves back into electrical pulses. |
| Ultrasound | As mentioned in Wikipedia, “Ultrasound is a cyclic sound pressure with a frequency greater than the upper limit of human hearing.” It should be noted that this limit is a variable factor, approximately 20 KHz in healthy and young adults. As a result, such frequency is considered as the lower limit in ultrasound explanation. Generally speaking, ultrasound waves are within the range of 20 KHz to 200 MHz |
| Venipuncture Site | In medicine, this site is referred to the target body part where blood injection and/or withdrawal are applied. |

# 1. Introduction

A medical diagnostic sonar device is being designed for detection of sub-dermal structures in humans and/or animals. In order to detect superficial veins, a commercially-available, high-frequency (12 to 15 MHz) transducer has been chosen for transmitting short but high-intensity acoustic pulses into the subject tissue. Furthermore, to receive echoes from the underlying structures and to operate the transducer, a low-cost, portable transceiver and a control electronics unit are required. The commercially-available electronics unit that controls the transducer is large, costly and contains far more functionalities than required by the medical diagnostic sonar. A simple but effective, battery-operated replacement for the transceiver, mate-able to a microprocessor, is developed and discussed in this report.

I propose to design an ultrasonic vein detector that will be utilized in a pen-like instrument. This medical device uses an ultrasonic transducer, along with a pulser/receiver unit connected to a microcontroller in order to detect three main veins in a human forearm. Upon detection of such proper venipuncture sites, the device provides the user with an alarm in order to leave an indication for injections/withdrawals.

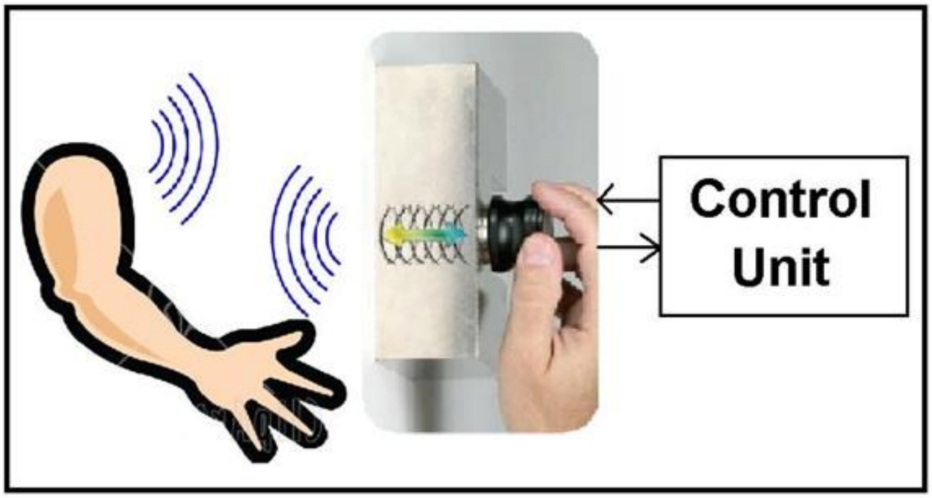
The integration and development of the project contains two different stages. The first stage of the project is dedicated to provide an intensive research for high frequency/ultrasonic transducers, as well as discovering the appropriate pulser/receiver, microcontroller, and various required mechanical systems needed to design a prototype product, which is capable of detecting three different human veins for venipuncture: Cephalic Vein, Basilic Vein, and Median Cubital Vein. Size constraint is not considered to be an issue in this stage, as the main objective is to provide an efficient research which can lead to design and production of a functional prototype.

In the second stage of the project, an actual prototype ultrasonic vein detector is planned to be developed. By the end of this stage, the utilized prototype should easily be used in clinics by nurses and/or doctors for the purpose of selecting an appropriate venipuncture site during injections and/or blood withdrawals.  Size constraints should be given attention in this phase.  In fact, the ultimate goal is to design a unit which can easily be fit inside a regular/small flashlight.

# 2. System Overview

Figure 2-1 below illustrates the overall high level design of the ultrasonic transducer vein detector. The operation begins when the pulser/transmitter generates an electrical pulse and sends it to the transducer. The high frequency transducer, composed of piezoelectric material, receives such pulse and starts to vibrate, which in turn creates sound waves with frequencies around 15 to 20 MHz based on the utilized transducer. These sound waves travel through various skin layers, fat, and vein in human forearm and generate echo waves, each of which corresponding to a specific medium. The transducer receives the echo signals and converts them back into electrical pulses, which will be sent to the receiver unit for A/D conversion. A calibrated control unit receives the digital signals and sends an alarm and/or turns on an LED as the indication of locating the proper vein for injection and or blood withdrawal. The methodology behind how well the multiple echo signals are separated is explained in detail throughout this report.

***Figure 2-1. Overall High Level Design of the Ultrasonic Vein Detector***[1]



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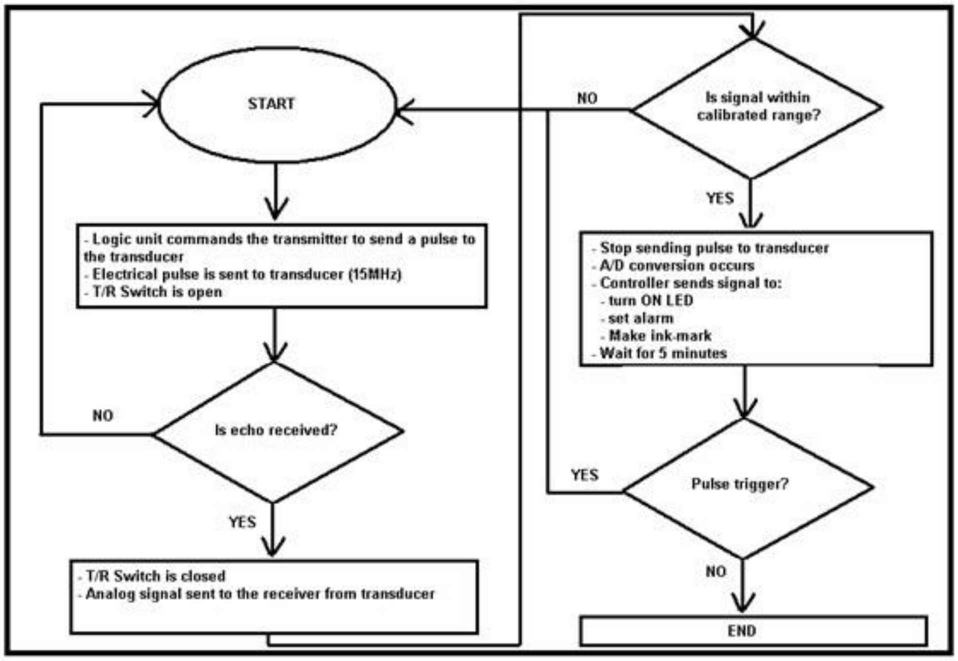
[1] Manually Controlled Pulser-Receivers, Olympus NDT

The uniqueness of the ultrasonic vein detector is that the entire circuitry should be sufficiently small in order to be situated inside a pen-like device or a small flashlight. The small size of the instrument bears the advantage of this system being easy to be used in clinics or hospitals by nurses and/or doctors. Having a size of a small flashlight makes this product to be easily handled and accessible when needed.

Figure 2-2 on the next page illustrates the overall flow chart of the design. As the figure represents, the ultrasonic transducer acts as the high frequency sound source by receiving electrical pulses from the pulser/transmitter and creating sound waves that penetrate to human forearm. The microcontroller connected to the receiver or the data acquisition unit, monitors the different intensities of the echo sound waves collected by the transducer. The receiver or DAQ unit is calibrated only to accept echo signals within a pre-defined voltage range. The microcontroller situated inside the DAQ unit monitors the different intensities of the received echoes, converted into electrical signals/pulses in units of Volts. When the intensities of the received echoes are within the calibrated range, the microcontroller turns ON the LED and fires up an alarm as the indication of a proper detected venipuncture site. In addition, another mechanical design is under investigation to be paired with the current system in order to automatically provide the nurses/doctors with an ink-like mark upon discovering a venipuncture site by the vein detector.

The biggest complication faced throughout design and development of the project is that the entire system, including the pulser/receiver, transducer, switch, microcontroller and circuit board, needs to be designed small enough to be situated inside a small flashlight for easy handling.

***Figure 2-2. Overall Flow Chart Design of the Project***



The following sections and subsections will outline the proposed design solution, as well as all required components with their detailed specifications.

# 3. Concepts

This section of the document provides a high-level introduction to various terminologies required for a user to have a better understanding of the project. Many factors are given attention to in order to provide a flawless prototype design as possible. Furthermore, in order to obtain a decent knowledge of various devices/components used in this design, a general perception of piezoelectric materials, as well as human skin should be provided.

## 3.1. Piezoelectric Materials

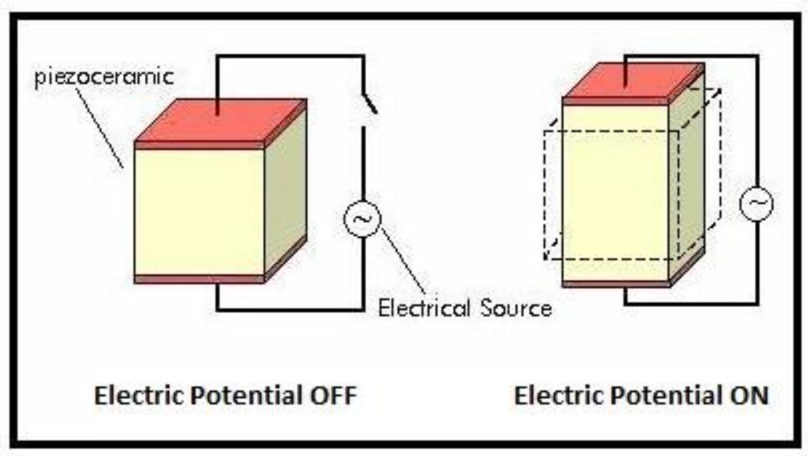
Piezoelectric materials have the ability to convert electrical pulses into sound waves with various frequencies. Frequency variation depends on the kind of material used, which has a direct relation to its piezoelectricity.

The Curie brothers, Jacques and Pierre, discovered a very important phenomenon back in 1880, called the "Piezoelectric Effect" [13]. The Piezoelectric Effect, described in solids, describes a bidirectional relationship between a mechanical stress and an electrical voltage. Crystals such as tourmaline, topaz, quartz, Rochelle salt and cane sugar play an important role in this energy conversion. Basically, an applied electrical pulse to such crystals will generate a mechanical stress, which can change the shape of the solid up to 4% in volume. Conversely, an applied mechanical stress will generate a voltage across the crystal. This description is depicted in Figure 3-1.

As Figure 3-1 illustrates, physics represents the piezoelectric effect as the link between mechanics and electrostatics: Applying a voltage across a piezoelectric material will generate vibrations, or mechanical stresses in the crystal. Such vibrations will result in creating sound waves with various frequencies. On the other side, applying mechanical stresses, such as exposing the crystal to sound waves, will generate electrical pulses across the material.

It is important to note that only non-conductive materials, grouped in crystals and ceramics, are able to take care of such energy conversion based on the Piezoelectric Effect. Piezoelectric ultrasonic transducers are considered to be piezoelectric effect's first application. The most important device used in this project, the ultrasonic transducer, is the result of applying piezoelectric effect. This transducer, which will be explained in great detail, is used to generate 15 MHz sound waves for human skin penetration.

***Figure 3-1. The Piezoelectric Effect***[2]



## 3.2. Ultrasound

In order to have a better understanding of ultrasonic transducers, a general knowledge of ultrasound must be provided. As mentioned in Wikipedia, "Ultrasound is a cyclic sound pressure with a frequency greater than the upper limit of human hearing." It should be noted that this limit is a variable factor, approximately 20 KHz in healthy and young adults. As a result, such frequency is considered as the lower limit of ultrasound.

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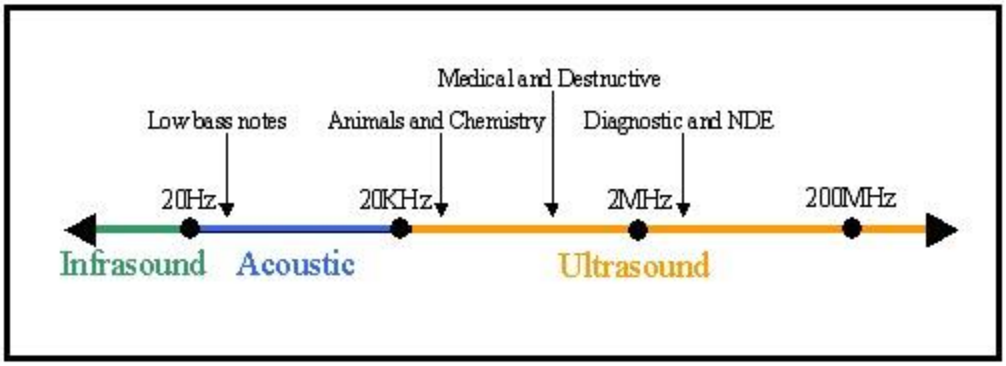
[2] Source: https://www.google.ca/search?q=The+Piezoelectric+effect&hl=en&tbm=isch&tbo=u&source=univ&sa=X&ei=5z5nUZ2xI43VigLf8oCIDQ&ved=0CEMQsAQ&biw=1366&bih=584

Generally speaking, ultrasound waves are within the range of 20 KHz to 200 MHz. One of the most important applications of ultrasound is the production of fetus pictures in human womb during pregnancy, using sonography. Figure 3-2 illustrates the approximate frequency ranges corresponding to ultrasound.

***Figure 3-2. Approximate Frequency Ranges Corresponding to Ultrasound***[3]



## 3.3. Medical Sonography

The ultrasonic vein detector used in this project uses the concept of medical ultrasound and sonography for human forearm veins detection. Ultrasonography is a diagnostic medical imaging technique with the ultimate goal of visualizing muscles, tendons, and various other internal organs in order to capture their structure and size. Furthermore, the technology used in ultrasonography is relatively less expensive when compared to techniques such as MRI (Magnetic Resonance Imaging) and CT (Computed Tomography). One of the most common applications of ultrasonography, called Obstetric Sonography, is to visualize fetuses during pregnancy and parental care. Moreover, sonography is referred to as a “safe test” due to the fact that no mutagenic ionizing radiation is used in the process. However, the only two minor risks involved in sonography are enhancing inflammatory response and heating soft tissue.

Another terminology for sonography is ultrasound imaging or ultrasound scanning. Unlike X-Ray, this medical diagnostic tool is a non-invasive medical

[3] Source: http://en.wikipedia.org/wiki/Ultrasound

examination procedure which provides a great deal of help to physicians in treatment of various medical conditions. In this process, human body is exposed to high-frequency/ultrasound waves in order to produce pictures of the desired organ(s). Since real-time capturing process is performed, the structure and movement of body's internal organs are clearly visible. Electrical waves go through the ultrasonic probe and hit the piezoelectric material. The electrical current is therefore converted into ultrasonic waves which will be sent to human body through a contact gel. Each tissue (skin, fat, bone, etc…) corresponds to a different and unique intensity. As a result, the ultrasound hits every tissue in human body and generates a unique echo signal sent to the probe with different speeds. These returned sound waves hit the piezoelectric material on the head of the probe and get converted into electrical current, which will be displayed on the monitor for analysis. The higher the image is on top of the monitor, the less dense the contacted material is. For example, skin image is shown on the top of the screen, whereas the image corresponding to human bone is depicted on the bottom of the display.

Ultrasound waves with frequencies between 3 MHz to 12 MHz are the most common waves used for clinical purposes. Frequency and wavelength have an inversely proportional relationship with each other. As a result, the lower the frequency of the sound, the higher its corresponding wavelength is. Therefore, low frequency signals are used to display high density organs. Similarly, as the frequency increases, decrease in wavelength is observed. As a result, high frequency sound waves, such as 3 MHz to 12 MHz are used to display low density tissues/organs. For the purpose of this project, the area of interest is human forearm, where three main veins are situated for injections/withdrawals. Since such veins are very close to the surface of the skin, high frequency sound waves, around 15 MHz, are used for signal detection. Higher frequency transducers may be utilized at a higher cost. The following table outlines the speed of sound in various mediums of interest.

***Table 3-1. Illustration of Speed of Sound in Important Mediums***[4]

| **Medium** | **Speed of Sound (m/s)** |
|---|---|
| Dry Air @ 20°C | 343 |
| Fresh Water | 1497 |
| Fat | 1450 |
| Average Human Soft Tissue | 1540 |
| Blood | 1570 |
| Muscle | 1580 |
| Bone | 3400 |

To design this project, several approaches can be considered. Since the speed of sound in various human skin layers and mediums are known, the time that it takes for a sound wave to penetrate into human forearm, generate an echo, and travel back to the transducer can easily be determined. As a result, calibrating a microcontroller for specific travel durations can result in locating the desired vein. However, due to the fact that the distance between the veins to skin layer is variable among different individuals, it will be significantly difficult to come up with a uniquely calibrated microprocessor that recognizes known echoes. Therefore, a more realistic approach needs to be considered, which will be introduced later in the report.

## 3.4. Human Skin

In this section of the document, various human skin layers are outlined and explained. Such description should be provided in order to understand the various layers that generated sound waves cross in order to have contact with three major veins located in human forearm.

Skin can be described as an organ which constantly changes and contains several specialized cells. Human skin's main function is to act as a protective barrier

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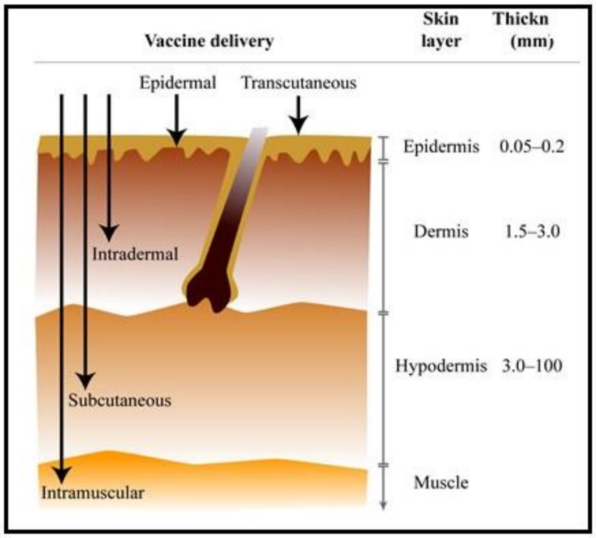
[4] George D. Ludwig, "The Velocity of Sound Through Tissues and the Acoustic Impedance of Tissues", J. Acoust. Soc. Am. Volume 22, Issue 6, pp. 862-866, Naval Medical Research Institute, Bethesda, Maryland

against external environment. Furthermore, skin is responsible for maintaining the proper temperature for the body to function. As illustrated in Figure 3-3, human skin contains three layers in the order of epidermis, dermis, and hypodermis (subcutaneous fat). Epidermis is considered to be the outer layer of skin with a variable thickness based on the skin type. In fact, epidermis contains the thinnest dimension on the eyelids, which is around 0.05 mm. On the other hand, it can be as thick as 1.5 mm on the palms and soles. Epidermis' main responsibility is to regulate skin rigidity.

The dermis, second human skin layer, also has a variable thickness which ranges between 0.3 mm on the eyelid and 3.0 mm on the back. Providing the skin with elasticity and producing collagen are considered to be two main functionalities of this layer. The third layer of skin, called both as the "Subcutaneous Fat" and "Hypodermis", protects body from mechanical trauma. In addition to acting as a protective barrier, regulating temperature, and providing the required space for fat metabolism are other two major functions of hypodermis. As the name implies, hypodermis contains a lot of fat. As a result, its thickness varies the most when compared to the other two layers. It can be as thin as 3.0 mm and as thick as 100 mm.

***Figure 3-3. Illustration of Human Skin Layers***[5]



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[5] Source: https://www.google.ca/search?q=Human+Skin+Layers&hl=en&tbm=isch&tbo=u&source=univ&sa=X&ei=Q1BnUbilEcmYiQKAoYG4Cg&ved=0CC0QsAQ&biw=1366&bih=584

Table 3-2 summarizes the variation of all three human skin layers. These numbers are taken from Figure 3-3.

***Table 3-2. Human Skin Layer Thickness***

| Skin Layer | Thickness (mm) |
|---|---|
| Epidermis | 0.05-0.20 |
| Dermis | 1.50-3.00 |
| Hypodermis (Subcutaneous Fat) | 3.00-100 |

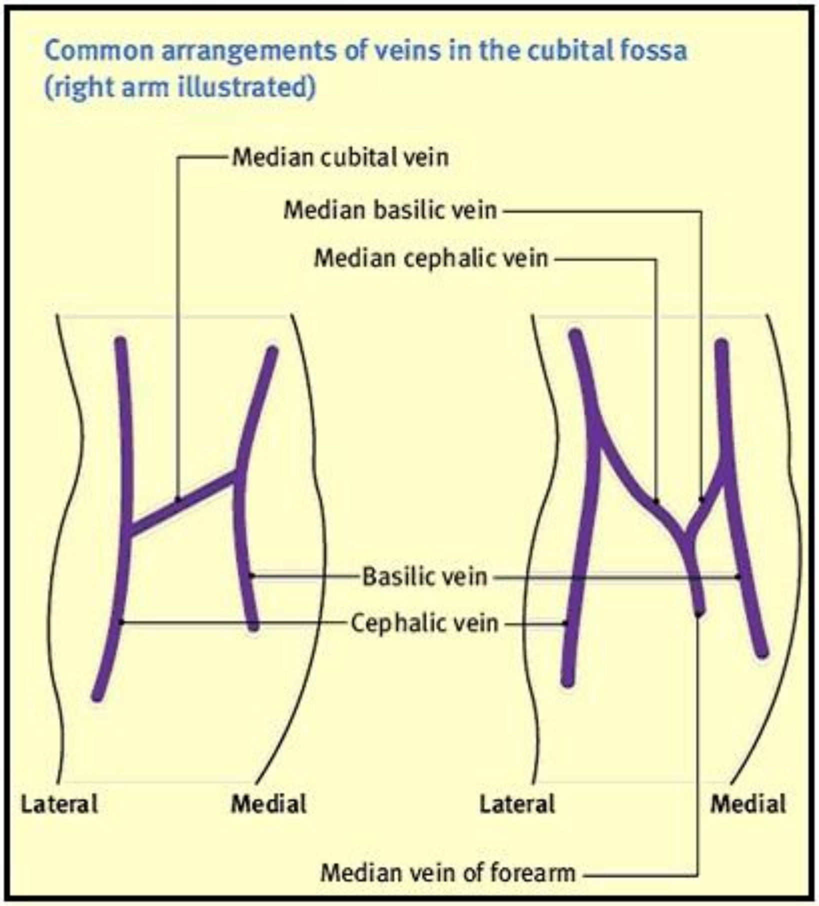
## 3.5. Forearm Veins

Superficial veins of the upper limb are considered to be the best venipuncture sites. Cephalic Vein, Basilic Vein, and Median Cubital Vein are the three major sites for injections and/or blood withdrawal in human forearm. Figure 3-4 illustrates the location of these three veins in a human forearm.

Median Cubital Vein, known as a superficial vein lying over the cubital fossa, is the most common location for venipuncture. This vein serves as an anastomosis between the cephalic and basilica veins. The second target site is the cephalic vein, which can be followed proximally where it empties into the axillary vein. The cephalic vein runs up the lateral side of the arm from the hand to the shoulder. The Basilic vein, joining the brachial vein is known as the third option for venipuncture.

As explained earlier in Introduction, the objective of this project is to design and implement a prototype device, which is capable of detecting any of the above three veins as quickly as possible. Since these superficial veins are located under the last skin layer, they are very close to the skin surface. The ultrasonic transducer generates sound waves with 15 MHz frequency and transmits them to human forearm using a contact gel. Sound wave travels through various mediums before hitting the target vein. In other words, these high frequency sound waves generate echo signals as they travel through epidermis, dermis, hypodermis, and the actual vein. Such signals are picked up by the transducer on the receiver end and accepted or ignored based on the calibration system provided to a microcontroller.  This algorithm will be explained in detail throughout the rest of the report.

***Figure 3-4. Best Venipuncture sites in Human Forearm***[6]



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[6] Source: https://www.google.ca/search?q=Human+Skin+Layers&hl=en&tbm=isch&tbo=u&source=univ&sa=X&ei=Q1BnUbilEcmYiQKAoYG4Cg&ved=0CC0QsAQ&biw=1366&bih=584

# 4. Design Decisions

This section of the document outlines the key decisions made in the ultrasonic vein detection system.

## 4.1. Physical Requirements

Since the overall system of our design should be able to fit inside a regular/small flashlight, one of the main difficulties faced throughout completion of this project is space constraints. As a result, the transmitter, T/R switch, transducer, receiver, and microcontroller should be chosen to be as small as possible in order to overcome this problem. Dimensions and physical properties of these five main parts will be discussed in detail in the hardware section of the document.

## 4.2. Device Communications

In order to have communication between the transducer, transmitter, receiver, and the alarm system, a small microcontroller named as “MSP430 Family” is used. This group of microcontroller has a very small size, which will be a perfect choice for this project, due to the required limited space. Communication between the ultrasonic transducer and the transceiver module is controlled via this family of microcontrollers. Furthermore, the calibration process for vein detection algorithm is designed through programming of MSP430 microcontroller.

# 5. System Hardware

This section of the document covers the hardware specifications for all the devices utilized throughout the completion of the project. Each part will be discussed in a section in detail.

## 5.1. Microcontroller

The Texas Instruments MSP430 family of ultra low power microcontrollers contains various tools providing several peripherals intended for different applications. The architecture, containing five low power modes, is designed to deliver extended battery life in portable measurement applications. A 16-bit RISC CPU, 16-bit registers, and constant generators are a few features of such MCUs with the main purpose of providing maximum code efficiency [14].

Furthermore, another advantage of utilizing this microcontroller in the design of the project is its small size. As mentioned previously, one of the main deliverables of this product is its small dimensions; hence, applying a small microcontroller which is capable of handling the required communications among all units is mandatory. The main responsibilities of the control unit can be summarized in the following:

- Providing the required excitation pulse to turn on the transducer, through the Transceiver Module
- Analyzing the received analog signals from the transducer to the receiver
- Detecting the required signals which represent the human vein
- Sending a signal to the alarm system (Siren, LED, Mechanical Marker) to provide the vein detection indication

- Shutting off the device after five minutes of inactivity using the low power mode feature

The microcontroller utilized in this project is the family of MSP430F6638. The most important features of this microcontroller are listed in the following figure.

***Figure 5-1. Important Features of MSP430F6638***

MIXED SIGNAL MICROCONTROLLER

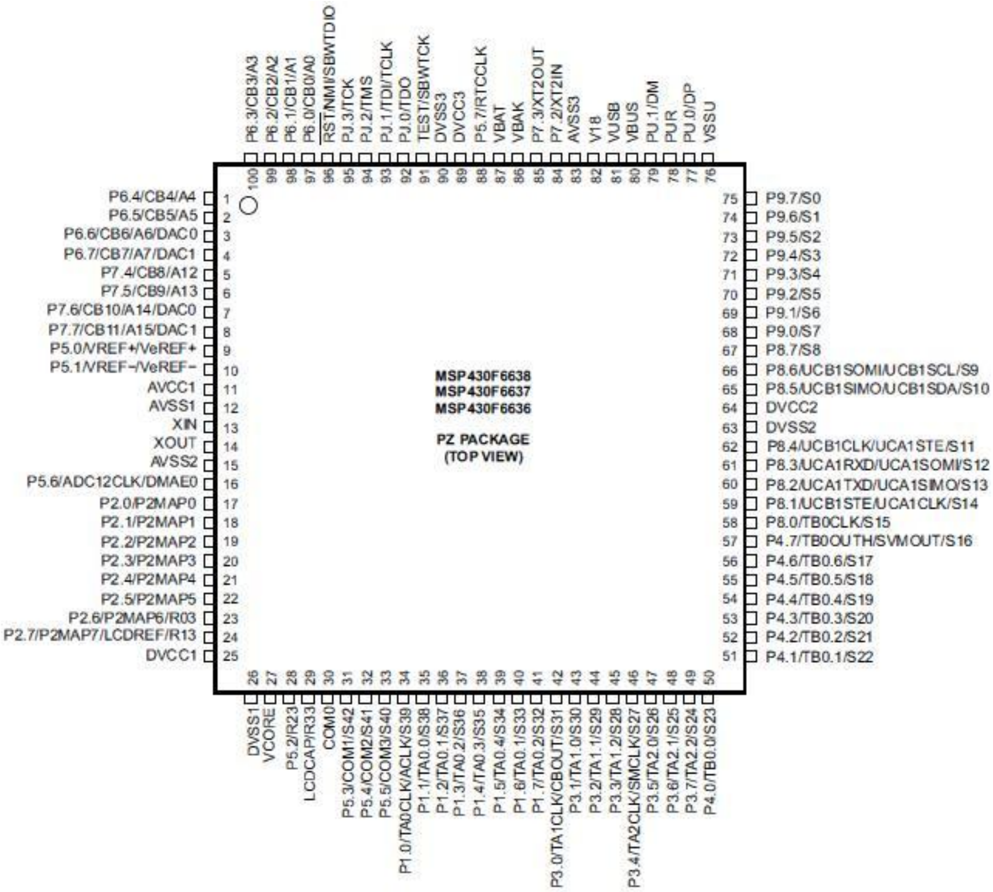
**FEATURES**

- Low Supply Voltage Range: 1.8 V to 3.6 V
- Ultralow Power Consumption
  - Active Mode (AM):
All System Clocks Active:
270 µA/MHz at 8 MHz, 3.0 V, Flash Program Execution (Typical)
  - Standby Mode (LPM3):
Watchdog With Crystal, and Supply Supervisor Operational, Full RAM Retention, Fast Wake-Up:
1.8 µA at 2.2 V, 2.1 µA at 3.0 V (Typical)
  - Shutdown RTC Mode (LPM3.5):
Shutdown Mode, Active Real-Time Clock With Crystal:
1.1 µA at 3.0 V (Typical)
  - Shutdown Mode (LPM4.5):
0.3 µA at 3.0 V (Typical)
- Wake-Up From Standby Mode in 3 µs (Typical)
- 16-Bit RISC Architecture, Extended Memory, up to 20-MHz System Clock
- Flexible Power Management System
  - Fully Integrated LDO With Programmable Regulated Core Supply Voltage
  - Supply Voltage Supervision, Monitoring, and Brownout
- Unified Clock System
  - FLL Control Loop for Frequency Stabilization
  - Low-Power Low-Frequency Internal Clock Source (VLO)
  - Low-Frequency Trimmed Internal Reference Source (REFO)
  - 32-kHz Crystals (XT1)
  - High-Frequency Crystals Up to 32 MHz (XT2)
- Four 16-Bit Timer With 3, 5, or 7 Capture/Compare Registers
- Two Universal Serial Communication Interfaces
  - USCI_A0 and USCI_A1 Each Support:
    - Enhanced UART Supports Auto-Baudrate Detection
    - IrDA Encoder and Decoder
    - Synchronous SPI
  - USCI_B0 and USCI_B1 Each Support:
    - $I^2C$™
    - Synchronous SPI
- Full-Speed Universal Serial Bus (USB)
  - Integrated USB-PHY
  - Integrated 3.3-V and 1.8-V USB Power System
  - Integrated USB-PLL
  - Eight Input and Eight Output Endpoints
- 12-Bit Analog-to-Digital (A/D) Converter With Internal Shared Reference, Sample-and-Hold, and Autoscan Feature
- Dual 12-Bit Digital-to-Analog (D/A) Converters With Synchronization
- Voltage Comparator
- Integrated LCD Driver With Contrast Control for up to 160 Segments
- Hardware Multiplier Supporting 32-Bit Operations
- Serial Onboard Programming, No External Programming Voltage Needed
- Six-Channel Internal DMA
- Real-Time Clock Module With Supply Voltage Backup Switch
- Family Members are Summarized in Table 1
- For Complete Module Descriptions, See the *MSP430x5xx and MSP430x6xx Family User's Guide* (SLAU208)

**(Source: TI Manual Book for MSP430 Series)**

Figure 5-2 illustrates the layout of the microcontroller used in this design.

***Figure 5-2. Pin Layout Representation of the MSP430F6638 Microcontroller***



This microcontroller is configured with a high performance 12-bit analog-to-digital converter and comparator, along with USB 2.0, four 16-bit timers, LCD driver, and up to 74 I/O pins. Analog and digital sensor systems, digital motor control, remote controls, thermostats, digital timers, and hand-held meters are typical applications for this family of microcontrollers.

Moreover, the microprocessor has sleep-and-wake up features. As a result, users are allowed to save power by putting the processor to sleep. Basically, the microcontroller is able to go to LPM (Low Power Mode) when the unit is not being used for vein detection. It is also able to switch back to regular mode as soon as the pulser/transmitter sends an electrical signal to the transducer. This function of the microcontroller will prevent the batteries from potential waste. More detail about this microcontroller will be provided in the software section of this research project.

## 5.2. Transducer

The conversion of electrical pulses to mechanical vibration and re-conversion of the echo sound waves back into electrical voltage is the basic fundamental for ultrasonic transducers. The piezoelectric material, known as the active element, is the heart of a transducer as it converts the electrical energy into acoustic/sound energy and vice versa. Applying an electrical pulse across a piezoelectric material, results in change of crystal dimensions. Such dimension change generates vibrating motions, leading to the transmission of sound waves. The frequency of the generated sound wave depends of the identity of the piezoelectric material and its dimension. Furthermore, the thickness of the active element is determined by knowing the desired frequency. In fact, piezoelectric crystals are cut to a thickness that is half the desired radiated wavelength.

As mentioned previously, the organ of interest for detection is the human forearm veins. These three superficial veins, the basilic, cephalic and median cubital, are very close to the surface of skin. As a result, penetration of signals into human forearm will not be significant. Therefore, selecting the appropriate transducer is very important for having an efficient design. Detection of echo sound waves and processing them through a receiver is the most important step in the procedure. In order to avoid receiving unwanted signals or noise, it is best to select a transducer with a frequency which penetrates slightly below the veins. Otherwise, echo signals from muscles and bones will be received which will have no function other than complicating the detection process. In conclusion, the ultrasonic transducer utilized in the design is chosen to operate at 15 MHz with different diameter tip sizes. The difference between these two utilized transducers will be explained in detail. Frequencies above 20 MHz and below 10 MHz were put in trial. However, at these frequencies, sound waves either penetrate too low (veins are never reached) or travel much below the veins (unwanted echoes are returned).

Delay line transducers are single element broadband contact transducers. These devices are manufactured to incorporate a short piece of plastic in front of the active element. This type of transducer provides an improved resolution and more accurate thickness measurements of target materials. Advantages of delay line transducers can be summarized in the following [10]:

- A delay line transducer combines a heavily damped transducer with a delay line to provide excellent resolution near the surface of the target material

- Increased resolution through utilizing a high frequency transducer

- High frequency of a delay line transducer increases the ability to detect very small materials and to measure their thickness by applying the direct contact method

- A delay line transducer is designed to fit curved surfaces

The main applications of delay line transducers are outlined below:

- Straight beam flaw detection

- precision thickness gaging

- Inspection of parts with limited contact areas

Based on the above specifications, the best, most practical and most accurate transducer applicable for this project are the “Sonopen Replaceable Delay Line Transducer” and “V205-RM” manufactured by Olympus NDT. Sonopen contains the following features:

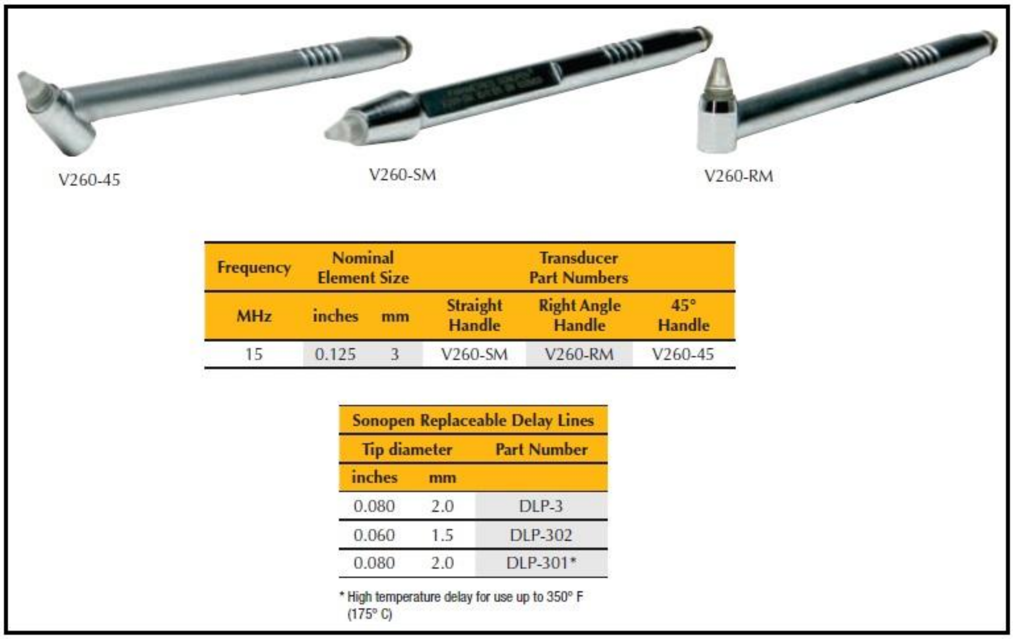
- Focused replaceable delay line

- Very small tip diameter, capable of improving performance on curved surfaces and small indentations

- Handle for easier positioning of transducer head

Figure 5-3 provides an illustration of the Sonopen along with its dimensions. Due to the ease of handling and the requirement that the transducer must be mounted perpendicular to the surface of the skin, “V260-SM Straight Handle” Sonopen is also chosen throughout the development of this project. As evident, this transducer operates at a frequency of 15 MHz, containing an very small tip diameter size of 3 mm.

*Figure 5-3. Sonopen Dimensions*[7]



| Frequency | Nominal Element Size | | Transducer Part Numbers | | |
|---|---|---|---|---|---|
| MHz | inches | mm | Straight Handle | Right Angle Handle | 45° Handle |
| 15 | 0.125 | 3 | V260-SM | V260-RM | V260-45 |

| Sonopen Replaceable Delay Lines | | |
|---|---|---|
| Tip diameter | | Part Number |
| inches | mm | |
| 0.080 | 2.0 | DLP-3 |
| 0.060 | 1.5 | DLP-302 |
| 0.080 | 2.0 | DLP-301* |

* High temperature delay for use up to 350° F (175° C)

Having a very small size tip diameter has one main advantage and a main disadvantage when utilizing this transducer for vein detection. The advantage of having a small size tip diameter is the increase in resolution of the detection process. This means that the transducer is focused on the target site and the amount of unwanted signals received on the receiver end is minimized. For example, if the diameter size is larger than the vein thickness, echo signals from the neighbors of the vein will be detected, categorized as unwanted signals. On the other hand, it is very difficult to mount the Sonopen perpendicular to the skin surface in the forearm region. In addition, the amount of pressure applied when holding the Sonopen increases, as the tip diameter size decreases. It is strongly advised to mount the transducer to the target site with minimal amount of applied pressure, simply because pressing the tip against the skin surface deforms the shape of skin layers, which results in obtaining unwanted signals on the receiver end. For the purpose of testing, another transducer, V205-RM, with the same frequency of operation is utilized with a much wider tip diameter size. Figure 5-4

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[7] Olympus NDT, "Panametrics/Ultrasonic Transducers: Wedges, Cables, Test Blocks", http://www.olympus-ims.com/data/File/panametrics/panametrics-UT.en.pdf

provides a brief introduction to this transducer. Table 5-1 summarizes a list of transducers used in this project, along with their advantages and disadvantages.

*Figure 5-4. 6mm Diameter Delay Line Transducer*[8]

| Part Code | Frequency (MHz) | Nominal Element Size (mm) | Nominal Element Size (in) |
|---|---|---|---|
| V205-RM | 15 | 6 | 0.25 |

*Table 5-1. Summary of Transducers used in the Project*

| Transducer Type | Advantage | Disadvantage | Tip Diameter Size |
|---|---|---|---|
| Sonopen V260-SM | Smaller Tip Size ➔ Higher Resolution | Higher Overall Size and Harder Handling | 3 mm |
| V205-RM | Smaller Overall Size and Easier Handling | Wider Tip Size ➔ Lower Resolution | 9 mm |

Signal waveform and frequency spectrum of the Sonopen are illustrated in Figure 5-5. These graphs are obtained using the test conditions shown in Table 5-2. The left figure represents the echo signals generated using a back wall of one 1.00 mm steel as the target material.

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[8] Olympus NDT, "Panametrics/Ultrasonic Transducers: Wedges, Cables, Test Blocks", http://www.olympus-ims.com/data/File/panametrics/panametrics-UT.en.pdf

### *Table 5-2. Sonopen's Test Conditions*[9]

| **Damping Resistance** | **Receiver Attenuation** | **Gain** | **Target** |
|---|---|---|---|
| 30 Ω | 12 dB | 46 dB | 1.00 mm Thick Steel |

### *Figure 5-5. Sonopen's Signal Waveform and Frequency Spectrum*

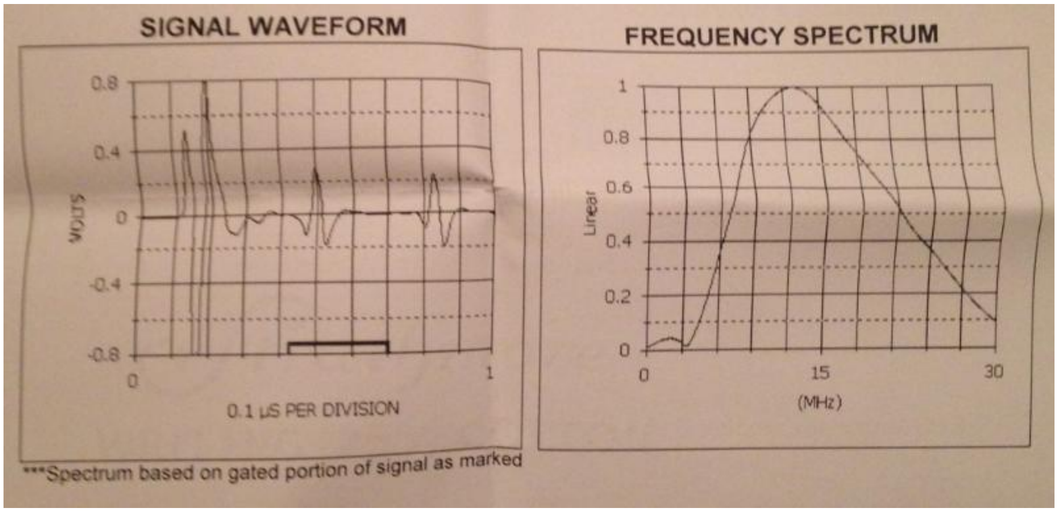

Figure 5-6 illustrates the small size of Sonopen and how practical it is for usage.

### *Figure 5-6. Sonopen's Dimension Illustration*

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[9] These results are provided by Olympus NDT. Manufacturer tests the transducer and provides the information listed on this table to the customers.

In order to generate echo signals, all ultrasonic transducers need to be mounted on the surface of the target material using an ultrasound scanning gel. Any standard industrial couplant, such as glycerine, propylene glycol, and formulate gels are applicable for this product. For the purpose of this project, “Clear Image Singles Ultrasound Scanning Gel” is utilized. The function of this acoustically optimized gel is to provide optimal sound velocity and acoustic impedance to couple diagnostic ultrasound between a transducer and the target/patient. Furthermore, such gel is capable of providing minimum amount of air bubbles in order to decrease the amount of reflection and refraction of sound waves passing through the gel. This feature delivers both increased acoustic transmission and reduced scattering from air bubbles [15].

### 5.2.1. Transducer Cable

In order to provide communication between the transducer and the Transceiver module, a transducer cable, manufactured by Olympus, is utilized. This “RG188 Heavy Duty Teflon Coated (HD) BNC Connector” is shown in Figure 5-7. Radio Guide, abbreviated as “RG”, is the designation for coaxial cables. It must be noted that most of the cables that are utilized in ultrasonic NDT (Non-Destructive Testing) are represented by military RG numbers that define the material, dimensions, and electrical characteristics of the cables. The characteristic impedance of this cable is around 50 Ω. This value can be obtained using either of the following two equations [9].

$$\mathrm{Im}\,pedance(Z_0) = \frac{138}{\sqrt{E}} Log(\frac{D}{d})\,\Omega \tag{5-1}$$

$$\mathrm{Im}\,pedance(Z_0) = \sqrt{\frac{L}{C}} \tag{5-2}$$

In the above equations, the following terminologies must be noted:

- $Z_0$: Characteristic Impedance of a coaxial cable
- D: Inner diameter of the outer conductor
- d: Outer diameter of the inner conductor

- E:  Dielectric constant of the insulating material between the conductors
- C:  Capacitance per unit length of the cable
- L:  Inductance per unit length of the cable

***Figure 5-7. Olympus BNC/Microdot Transducer Cable***[10]

| Type | Grade | Impedance | Nominal Diameter |
|---|---|---|---|
| | | | inches |
| 188 | RG188/U | 50 ohms | 0.11 |

## 5.3. Transceiver Module

The two transducers introduced in the previous section require a pulser/receiver module in order to transmit and receive echo signals and to transfer them to the microcontroller for data processing.  “Olympus NDT” provides such a unit for these two transducers; however, this commercial pulser/receiver module is very expensive for its various functionalities that are above and beyond the scope of this project.  A unit of this module costs around $10,000.  The following reasons provide the logic behind not utilizing this commercially available product:

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[10] Olympus NDT, “Panametrics/Ultrasonic Transducers:  Wedges, Cables, Test Blocks”, http://www.olympus-ims.com/data/File/panametrics/panametrics-UT.en.pdf

- The lack of having enough funding through my supervisor to purchase such an expensive product
- The purpose of moving forward with this project is its potential market sale price of $500 per unit. Hence, it is impossible to spend over $10,000 to manufacture one unit.

As a result, instead of spending lots of money for this commercially available and manually controlled ultrasonic pulser-receiver, I decided to design and implement a hardware unit that is capable of both exciting the transducer and receiving the echo signals.

### *5.3.1. Transceiver Module Design Requirements*

The requirements to design and develop this medical sonar module are summarized below:

- Work with the Olympus NDT transducer chosen for this project (Sonopen V260-SM and V205-RM);
- Provide a single connection to the transducer, i.e. have an integral transmit/receive (T/R) switch;
- Produce a negative excitation pulse appropriate for the transducer (The transducer manufactured by Olympus NDT is designed to get excited by applying a negative excitation pulse for a few hundreds of nanosecond);
- Detect and qualify the echoes received and provide an output signal appropriate for a low-cost, low-power microprocessor;
- Provide raw baseband representation of the echoes for more sophisticated signal-processing by a digital signal processor (DSP), if so desired;

- Run from a single supply voltage which can be reasonably generated from commercially-available 9-volt batteries, (or any battery from 7 to 10 volts);

- Be small and compact so that it can be integrated with a microprocessor board into a hand-held or desktop enclosure;

- Be low-cost and available for manufacturing by modern high-volume production techniques.

Based on the information provided by Olympus [9], the Sonopen requires a short (a few hundreds of nanoseconds) pulse of negative voltage to be excited and trigger a transmission pulse. Furthermore, the received echo signals need to be further amplified to be detectable in practice. Moreover, the acoustic couplants (i.e. glycerin or ultrasound gel) must be applied between the delay-line tip of the transducer and the medium being examined. (Sonopen V260-SM contains a very small delay-line tip.)

### *5.3.2. Transducer Testing*

In order to obtain a better understanding of the transducer needs, it was decided to test the transducer by exciting it with a programmable function generator, amplifying the echoes using a video amplifier circuit and viewing them on an oscilloscope. More circuit specifications are provided below:

- Diodes are utilized to act as the T/R switch (Transducer cable contains one line; therefore, transmit and receive traffics must be separated using a T/R switch.)

- An old monolithic amplifier from Motorola, the MC1590G, is configured as a wideband amplifier with gain of about 35 dB

- The circuit is based on Figures 20 and 21 of [2].

The next three figures illustrate the basic test setup for this experiment.

***Figure 5-8.   Amplifier Circuit***

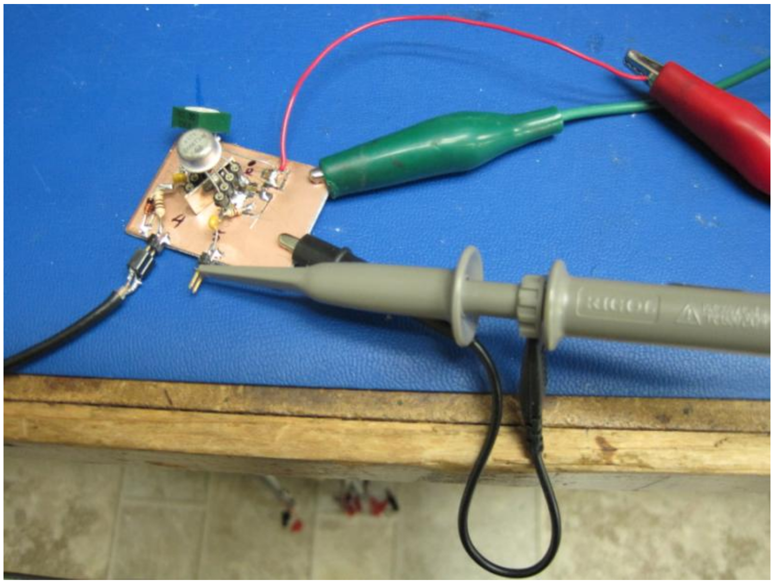


***Figure 5-9.   Test Connections***

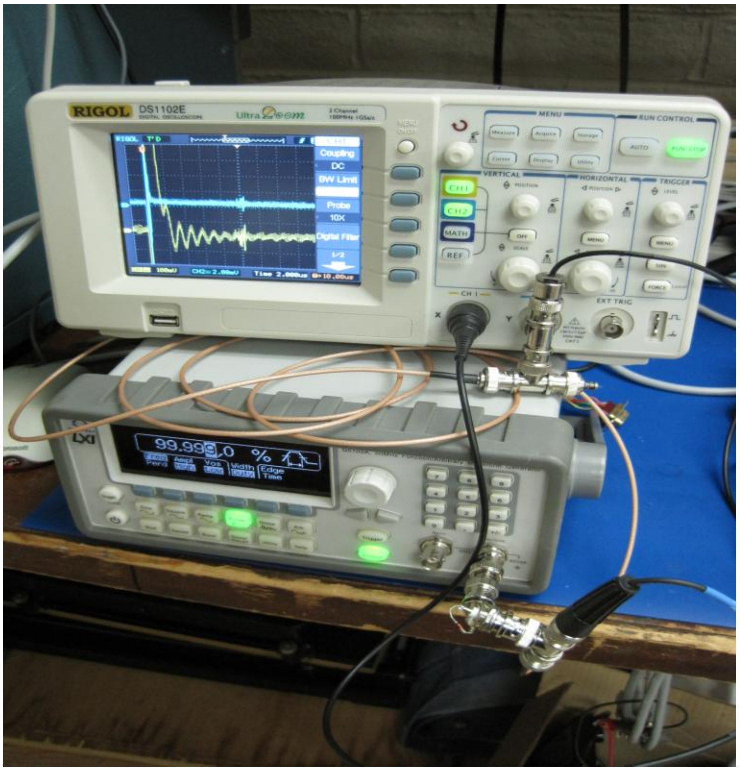


***Figure 5-10. Couplant on Target Material***

I was able to obtain echoes from a hard media such as a steel and aluminum plates shown above. The echoes coming from the back wall of the metal plate are shown in the following figures. As evident in Figure 5-11, Figure 5-12, and Figure 5-13, these echoes are very low in amplitude; hence, it was required to provide larger excitation pulses to the transducer in order to obtain louder transmissions and echoes.

Figure 5-11 illustrates the echo signal generated by the tip of the delay line and captured by the transceiver module. The blue signal represents the regular echo, while the yellow signal illustrates the amplified version of the blue signal using a MC1590G wide-band amplifier with approximately 35 dB gain. Figure 5-12 and Figure 5-13 represent the echo signals obtained using 1 mm thick steel and 3 mm thick aluminum blocks. As mentioned, the blue signals in these two figures depict the regular echo, while the yellow signals represent the amplified version.

***Figure 5-11. Transducer’s Echo Signal from Delay Line Tip***

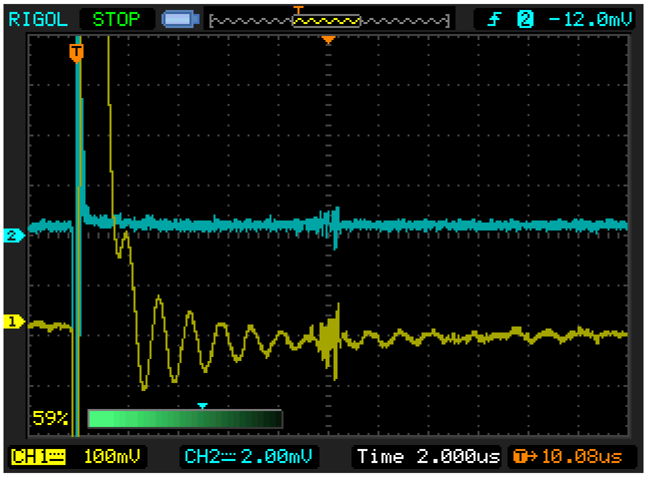


***Figure 5-12. Transducer’s Echo Signal from 1 mm thick Steel***

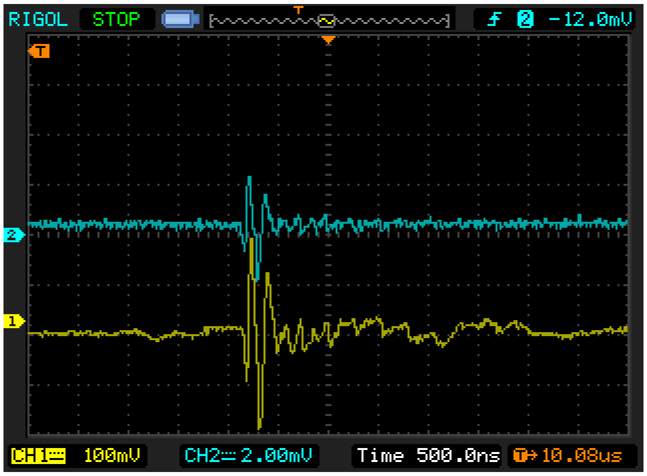
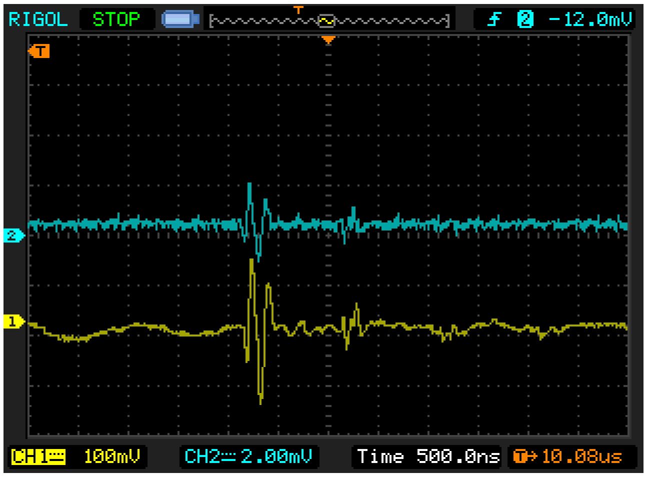


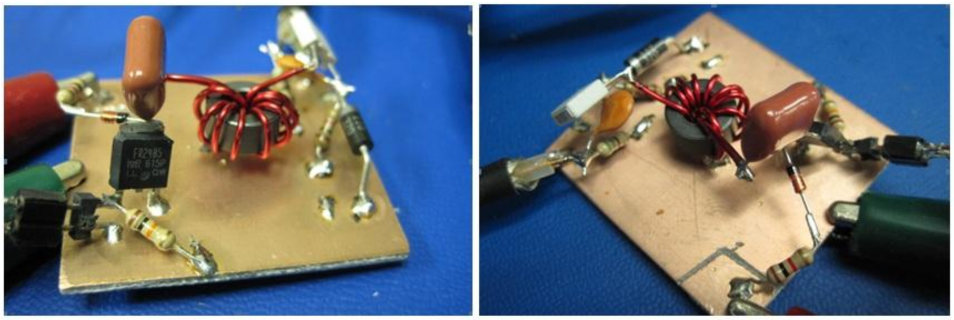
*Figure 5-13.   Transducer's Echo Signal from 3 mm thick Aluminum*



### 5.3.3. Pulser Development

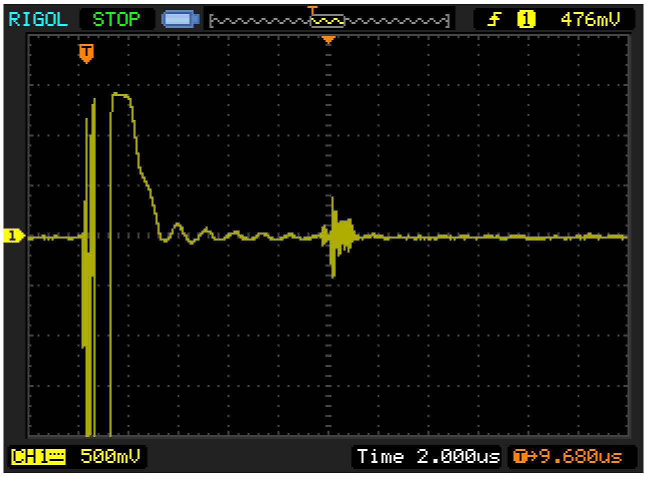
I was able to design and implement a prototype pulser based on [1]. For convenience, this prototype pulser is designed to produce pulses of positive voltage; therefore, the echo signals are inverted, having more negative voltage excursion than positive (Olympus transducers require negative excitation pulses to operate). At this stage, it is possible to detect multiple echo signals reverberating between the front and back walls of the metal test plates introduced in the previous section. Figure 5-14 illustrates the prototype pulser circuitry.

*Figure 5-14.   Prototype Pulser Circuit*



The first signal, shown to the left of Figure 5-15, represents the main bang signal (the signal that excites the transducer) produced by the pulser circuit. In fact, this inverted signal excites the ultrasonic transducer and enables it to start transmitting sound waves.  Furthermore, the second signal, shown in the middle of this figure, represents the echo signal generated by the tip of the delay line.

***Figure 5-15.   Illustration of the Main Bang Signal and the Delay Line Tip Echo***



The next two figures, in order, represent the echo signals generated using 3 mm aluminum and 1 mm steel blocks.  As evident, the first echo has the greatest amplitude; however, as the signal bounces back and forth between the front and back walls of each block, the echo signal becomes smaller and smaller in amplitude.

***Figure 5-16.   Illustration of the Echoes generated using a 3 mm Aluminum Block***

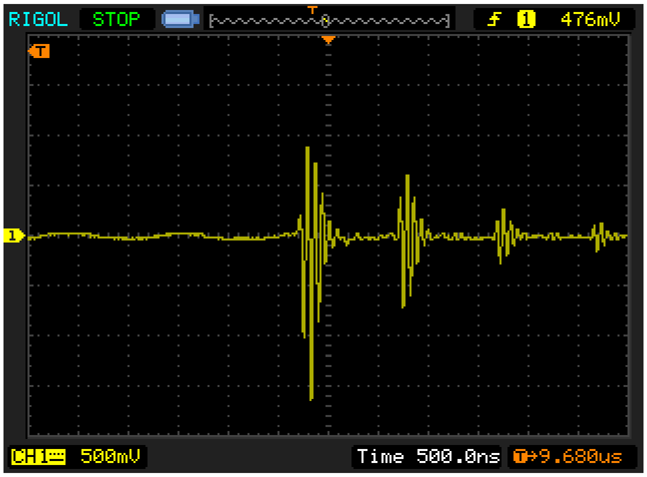
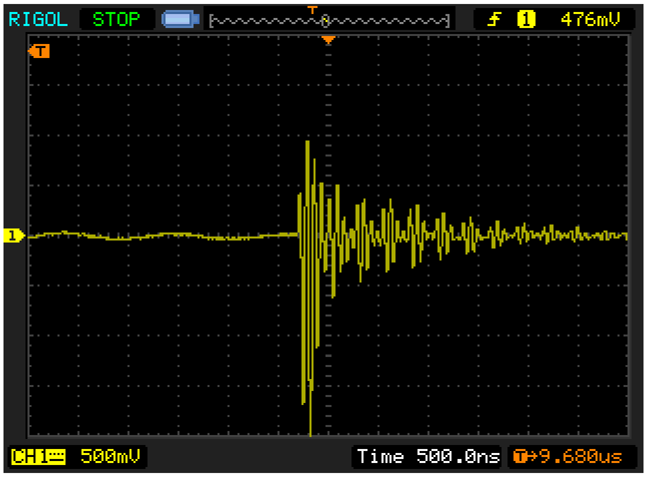


***Figure 5-17.   Illustration of the Echoes generated using a 1 mm Steel Block***



At this point, the basic techniques for transmitting a pulse and receiving the echo signals are understood correctly, because the designed pulser circuit can easily excite the transducer.  The next step is to design a transceiver circuit which can be used to interface the transducer to a microprocessor.  Based on my experiments, it is known that the echo signals are only a few cycles of the 12 to 15 MHz resonant frequency of the transducer.  In addition, it is suspected that more amplification and possibly band-pass filtering of the received signal will be required to detect clean signals.

### *5.3.4.     Amplifier Selection*

Development of the pulser prototype must be followed by researching for a higher-gain and lower-noise amplifier.  The MC1590G was obsolete, too.  After some parametric searching, it was decided to evaluate the Semiconductor NE592 and the Texas Instruments SN761666.  Both have differential inputs and outputs and can be tuned for band-pass behaviour.  The NE592 had the advantage of requiring only a single tuning network between its two gain pins to set its frequency-dependent behaviour; however, it requires dual supplies and higher overall power consumption.  The SN761666 featured a gain-control input and had similar cost, but lower power consumption.

I implemented test schematics and circuit-board layouts for the two candidate amplifiers using P-CAD software.  A photo-resist technique was used to transfer the circuit-board artwork to some copper-clad boards and etched them. The amplifiers were built and tested in simple wide-band configurations. The SN761666 is the clear winner, with its gain peaking at 50 dB around 11 MHz (The NE592's gain peaks at 2.5 MHz and drops off above 10 MHz). The SN761666 retains about 49.8 dB of gain at 15 MHz, which is the Sonopen's advertised resonant frequency. Figure 5-18 summarizes the development process of the "Amplifier Test Board".

***Figure 5-18. Amplifier Test Board Development Process***

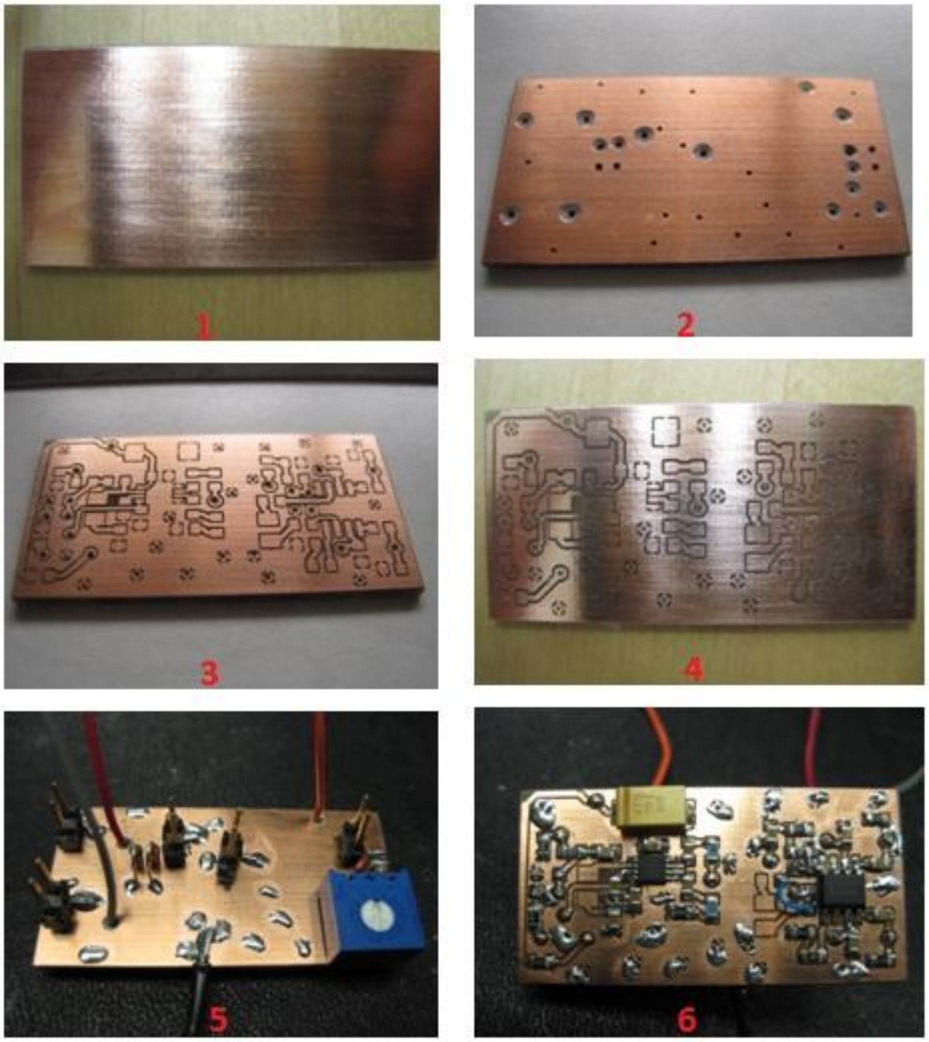
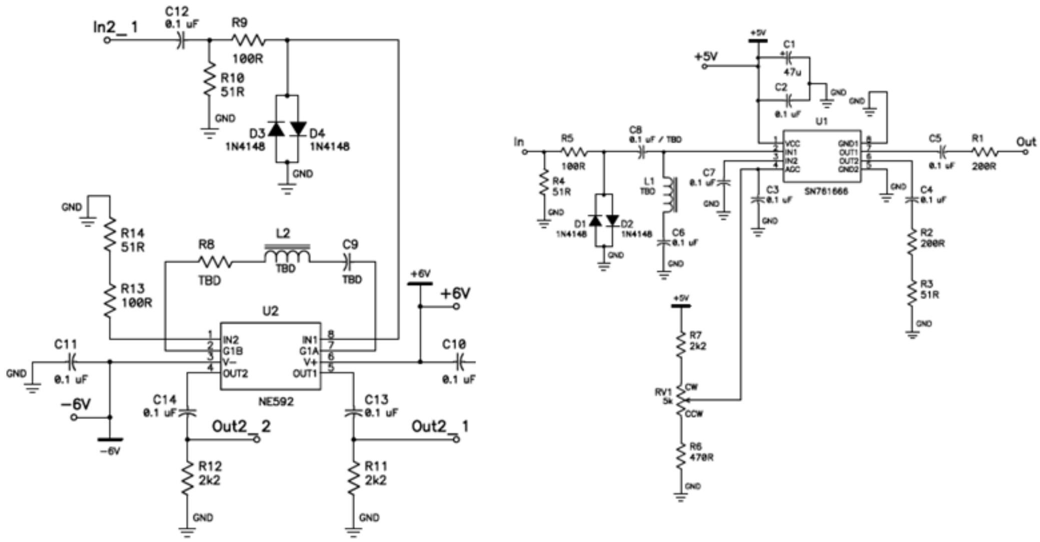


Figure 5-19 represents the amplifier test board designs using NE592 and SN761666 amplifiers.

***Figure 5-19. Amplifier Test Board Design using NE592 and SN761666[11]***



## *5.3.5. Pulser Optimization*

In order to optimize the pulser efficiency, a new version is developed that is able to generate negative-voltage pulses. In addition, this version of the pulser provides sharper drive edges to the transformer, resulting in stronger pulses. Furthermore, the input capacitance to the transformer is adjusted, and the output damping is reduced to obtain the largest possible pulse. As a result, the transducer is further tested with the new optimized pulser and the SN761666 amplifier. As evident in the following figures, the pulser optimization resulted in obtaining very strong and clean echo signals from metal plates, and detection of forearm veins became reasonably straightforward.

Figure 5-20 illustrates the connectivity between the optimized pulser and the amplifier circuit. In order to test this model, the pulser circuit is connected to the

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[11] B. Trout, “A High Gain Integrated Circuit RF-IF Amplifier With Wide Range AGC”, Motorola Semiconductor Products Inc. Application Note AN-513.

A. Kuthi, P. Gabrielsson, M. Behrend and M. Gundersen, “Nanosecond Pulse Generator Using a Fast Recovery Diode”, Department of Electrical Engineering - Electrophysics, University of Southern California, Los Angeles, CA 90089-0271 (no publication date provided by authors).

transducer and the echo signals generated by the walls of a metal plate are detected and viewed by an oscilloscope. The following figures illustrate this scenario.

***Figure 5-20. Optimized Pulser Connection with the Amplifier***

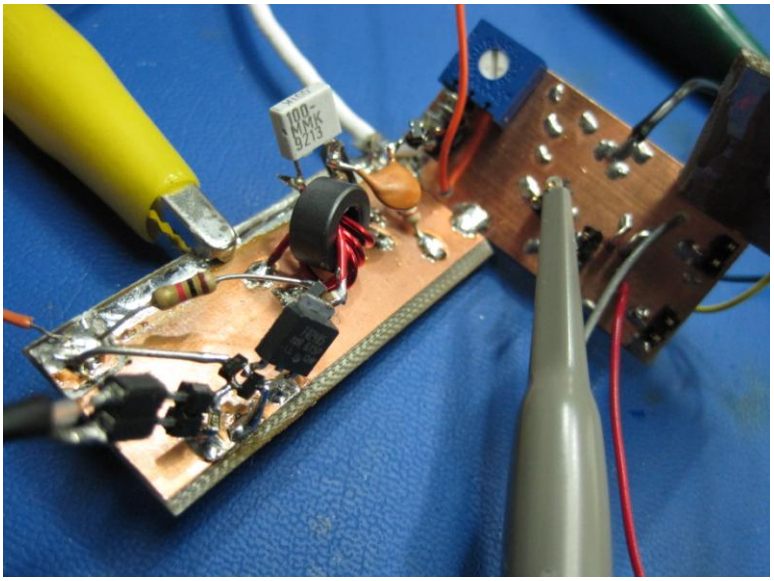
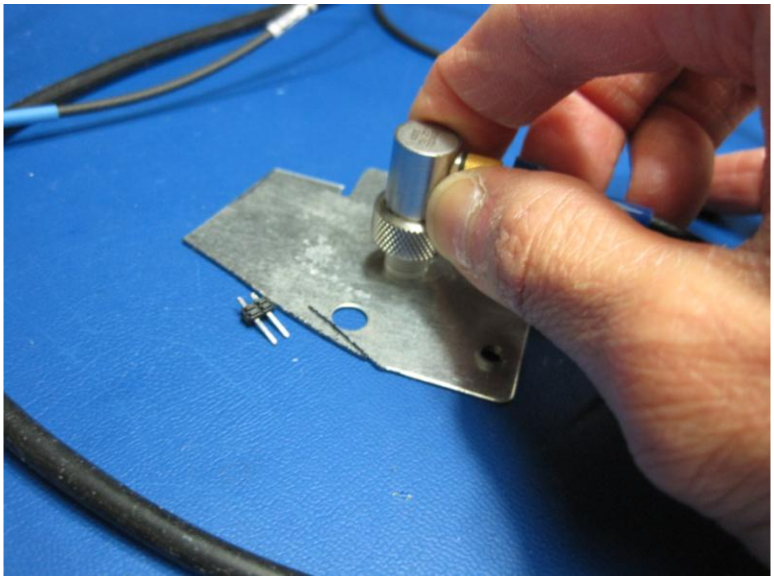
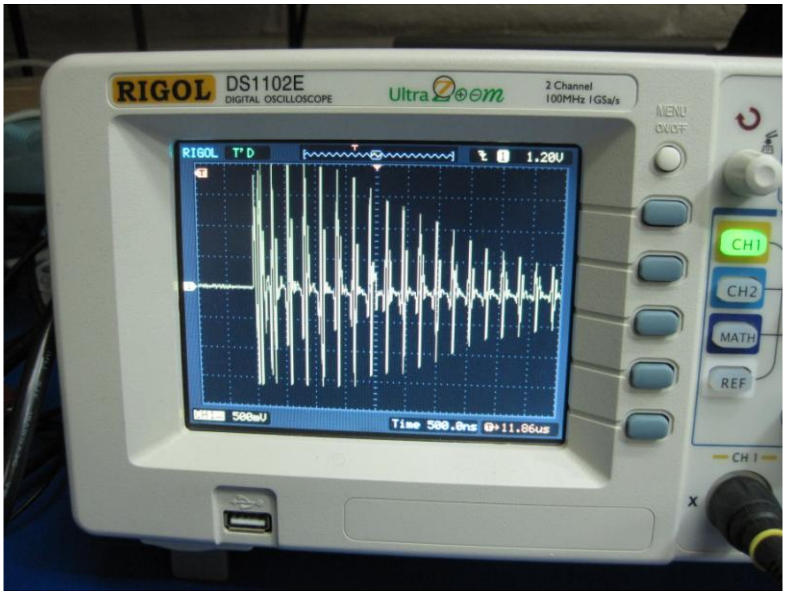


***Figure 5-21. Utilizing the V205-RM Transducer on a Metal Plate***



The transducer transmits sound waves at a frequency of about 15 MHz. These sound waves travel through the delay line tip generating the original echo signal. Furthermore, these sound waves keep hitting the front and back walls of the metal plate, each of which has its corresponding echo signal viewed by the oscilloscope.  As evident in Figure 5-22, the echo signals keep decreasing in amplitude, due to the loss of energy each time the sound waves hit the metal surfaces (Law of Conservation of Energy).

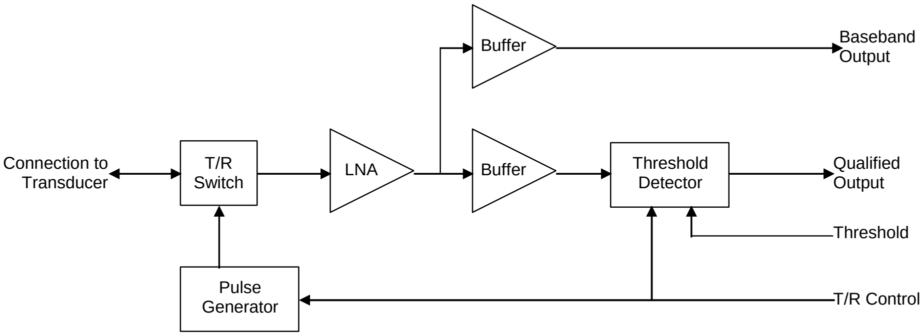
***Figure 5-22.   Illustration of Echo Signals using a Metal Plate***



## 5.3.6. *Transceiver Circuit Design*

At this stage, all the required analogue circuitry are tested and confirmed to be functional, and the next step is to add some circuitry to detect and qualify the echoes for use by a microprocessor.  Therefore, everything is prepared to design a transceiver circuit, which is settled on the topology shown in Figure 5-23.  This circuit would fulfill the design requirements quite nicely in a single, compact circuit board.

***Figure 5-23.   Transceiver Circuit Design Topology***



### *5.3.7. Prototype Module Testing and Revisions*

The first revision of the transceiver module schematic and circuit board layout were created. The prototype printed circuit boards (PCBs) were ordered from an online PCB manufacturer based in China. Upon arrival of the boards, I populated the components, starting with the power supply section and worked my way from the transmitter towards the transducer connector, then the receiver and digital interface, testing each section as I progressed.

The Transceiver's transmitter and receiver performed similarly to the prototype circuits that were built for the Optimized Pulser and SN761666 amplifier. The Threshold Detector, having never been tested before, required more attention but also worked well once the DC-balance circuit was corrected. Please refer to 5.3.8, Final Circuit Description, for more information.

Figure 5-24 and Figure 5-25 represent the Transceiver module's schematic diagram. As some other errors in the schematic were detected, the required components and connections were patched, as necessary, to correct the errors. The modified and final version of the schematic diagram for the Transceiver module is illustrated in Figure 5-26 and Figure 5-27. These four figures are generated using P-CAD software.

*Figure 5-24. Initial Transceiver Module Schematic Diagram*

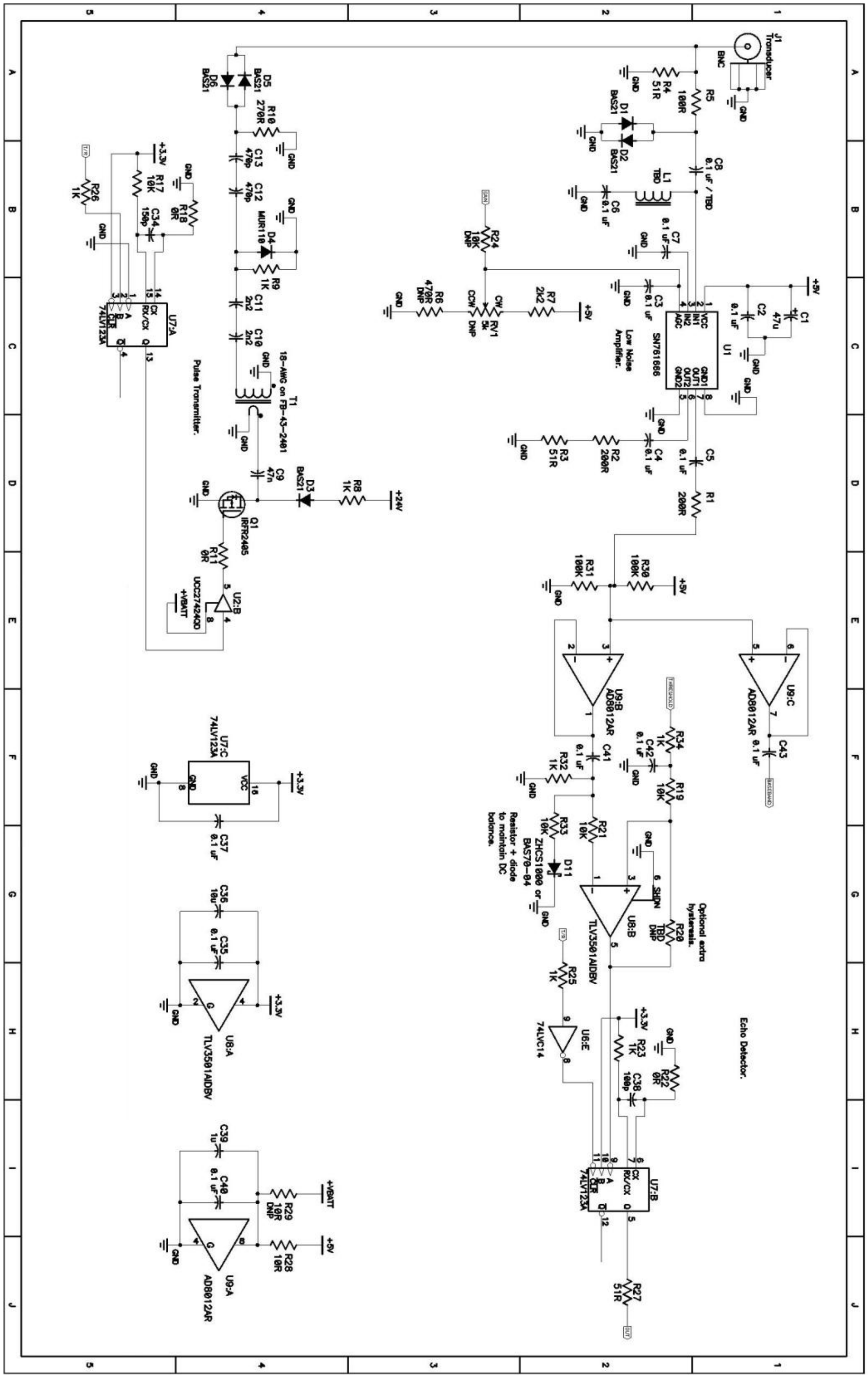
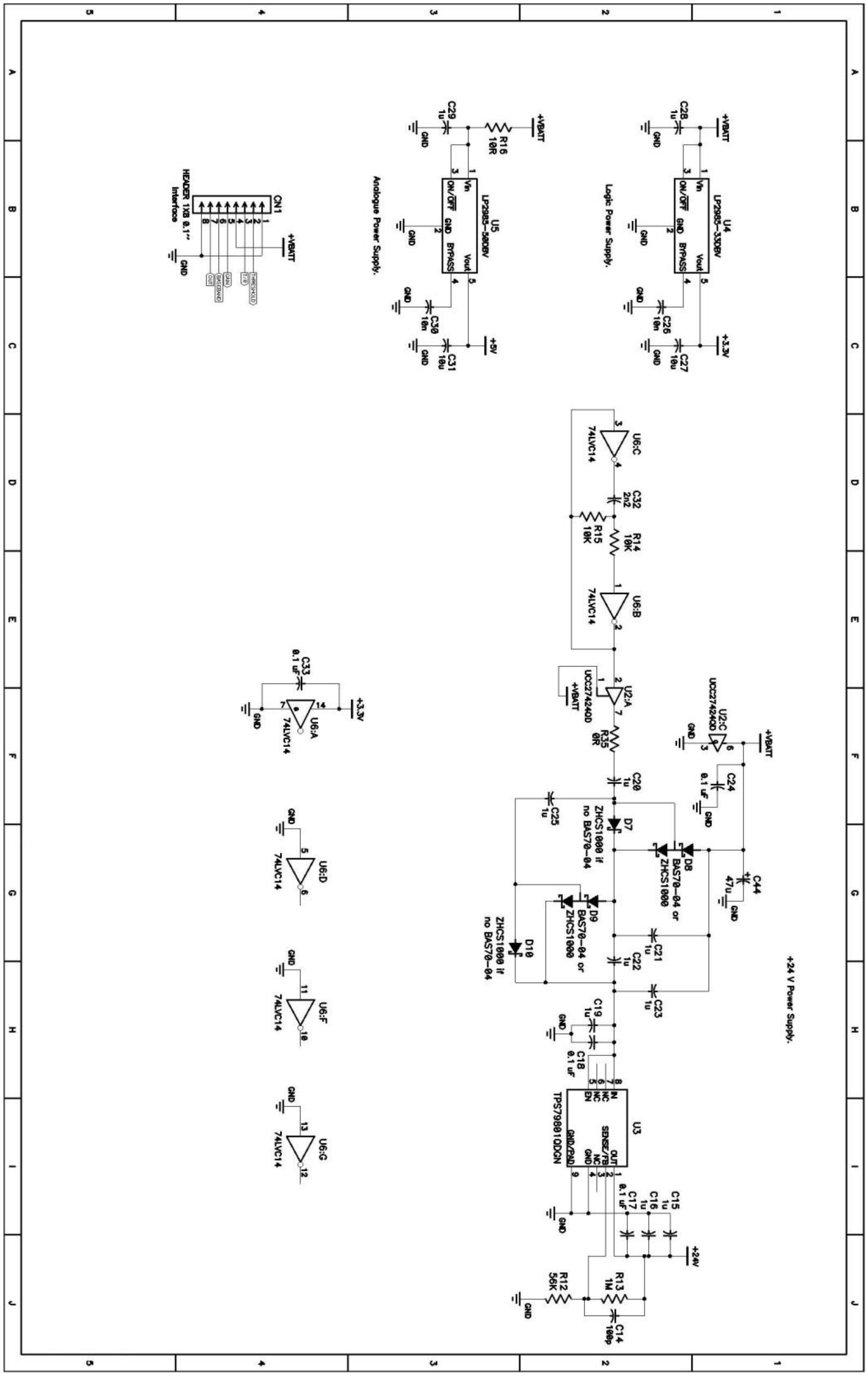


*Figure 5-25. Initial Transceiver Module Schematic Diagram-Improved*



## Figure 5-26. Final Schematic Diagram for the Transceiver Module

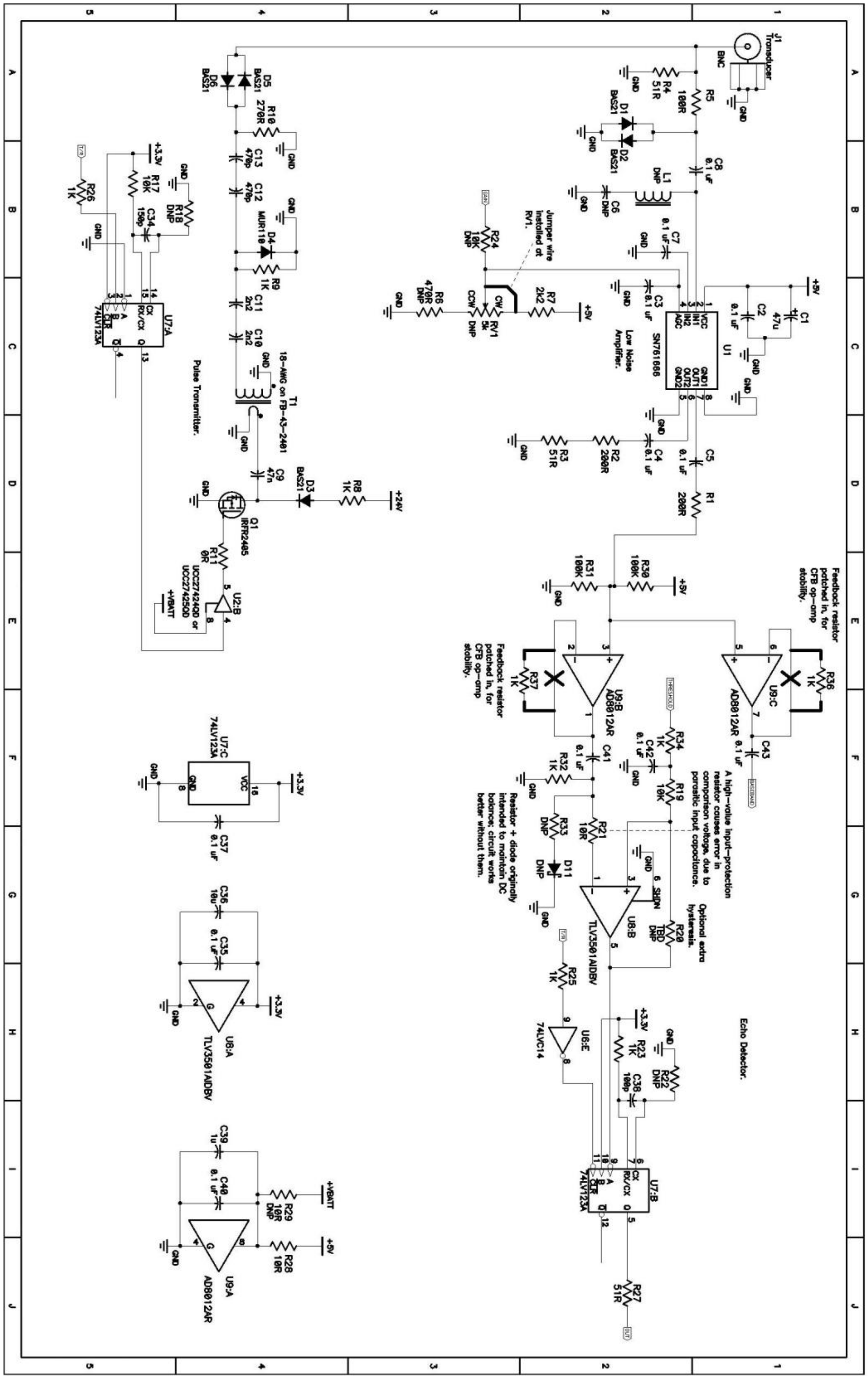
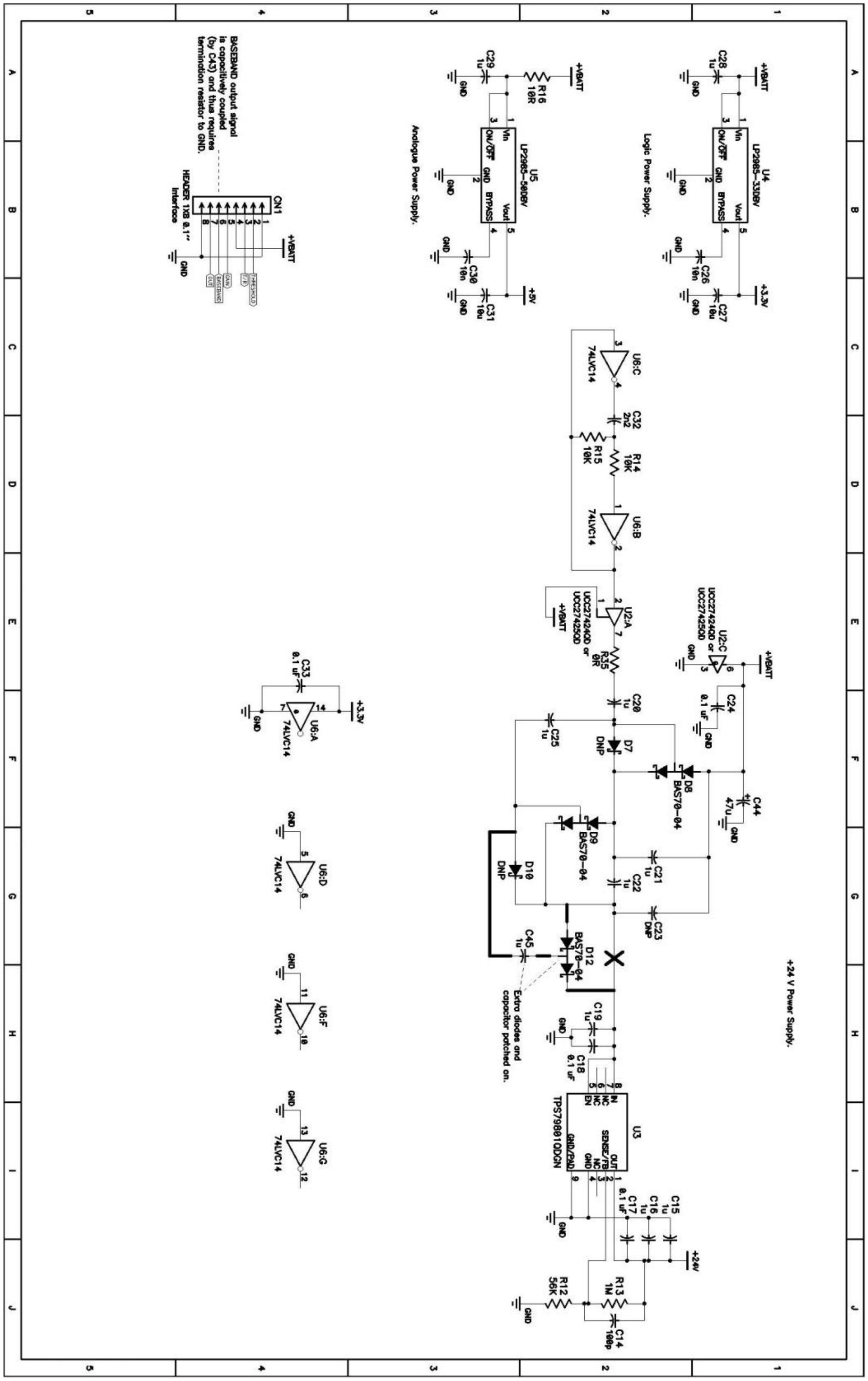
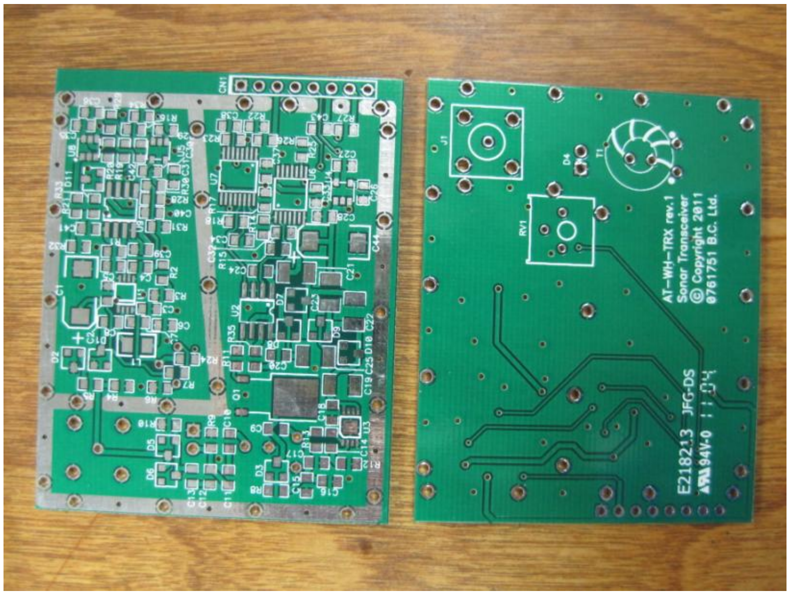


Figure 5-27. Final Schematic Diagram for the Transceiver Module-Improved



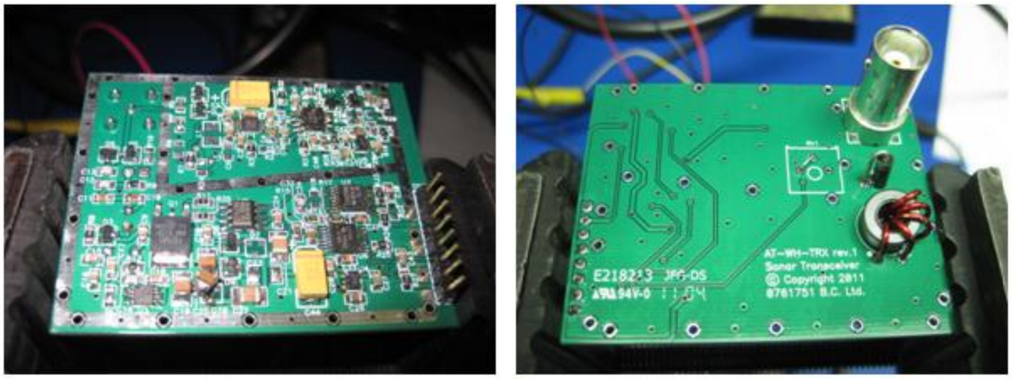
Both sides of the manufactured printed circuit board (PCB) for the Transceiver module are depicted in Figure 5-28.

***Figure 5-28. Incomplete Surfaces of the Transceiver PCB***



As evident, the above two figures do not show the parts, as the assembled PCB does in Figure 5-29 below. The following represents the pictures of the two surfaces of the completed prototype Transceiver Module.

***Figure 5-29. Completed Prototype Transceiver Module PCB***



The Transceiver module draws about 50 mA from a nominal 9 VDC supply. At this point, the prototype Transceiver is ready to be mated with the microprocessor board.

### *5.3.8. Final Circuit Description*

Figure 5-26 and Figure 5-27 illustrate the schematic for the final circuit as delivered for PCB manufacturing. The patches shown in the schematic are patched onto the Figure 5-24 and Figure 5-25 circuit board. To provide a great understanding of how the circuit works, including any non-obvious design decisions, the following subsections are delivered. Please refer to the block diagram in Figure 5-23. Transceiver Circuit Design Topology and the Transceiver schematic drawings in Figure 5-26 and Figure 5-27 for the following discussions.

#### **Front End**

J1 is the connection to the transducer, with R4 providing proper termination and damping. D1, D2, D5 and D6 implement a "passive" T/R switch; being low-cost and requiring no control signal. High voltages from the Transmitter are conducted easily through D5 and D6, while being limited in amplitude by R5, D1 and D2 before reaching the receiver circuitry. Echoes received by the transducer are much smaller in amplitude, being in the milli-volts to hundreds of milli-volts, and are not affected by D1 and D2.

#### **Transmitter**

The T/R signal from an external microprocessor triggers excitation of the transducer as follows: A one-shot monostable U7A is triggered by the rising edge of the T/R signal, delivering a high pulse of length predetermined for optimal charging and firing of saturable-core transformer T1 via Q1 and C9. A negative pulse is generated when ultra-fast rectifier D4 abruptly turns off. R9 provides proper core reset by discharging C10 and C11 after each pulse, while R10 in conjunction with C12 and C13 helps determine pulse duration. This design is adapted from the design described in [1]; please refer to this paper for more details.

#### **Receiver**

U1 and associated components form the LNA, with C8, L1and C6 allowing for input impedance matching. In the implementation, a broadband match is used (C8 being 0.1 µF, L1 and C6 being "Do Not Populate"). RV1 and associated components allow for gain adjustment, while R24 (if populated) allow for external voltage control of the gain.

The output of U1 is capacitively coupled to two buffer amplifiers U9B and U9C; these are current-feedback amplifiers, requiring resistance (R36 and R37) in the feedback path for stability. Resistors R36 and R37 were initially omitted from the schematic, and are patched onto the prototype rev.1 circuit board. One buffer provides the Baseband output for DSP processing, while the other drives the Threshold comparator U8:B; a TLV3501 was chosen for its high speed, since received echoes may be as short as a couple cycles of the transducer's resonant frequency of 12 to 15 MHz. Any signal excursion (e.g. an echo) which exceeds the Threshold results in U8:B's output going high. R21 was originally set at 10 kilo-ohms to limit the current flowing out of pin 1 of U8 during large negative excursions of the baseband signal; it was also thought that the internal diode clamp from pin 1 of U8 to ground would create a bias charge on C41, hence R33 and D11 were included to provide a balancing charge from the positive signal excursions. However, the large value for R21 resulted in a phase delay and low-pass filter effect due to the input capacitance at pin 1 of U8, and R21 was reduced to 10 ohms without harm to U8. It was also found that R33 and D11 could be omitted without C41 accumulating a bias charge; this is due to the very high frequencies (and thus short durations of the excursions) involved, as compared to the speed of the diodes.

The output of comparator U8:B triggers monostable U7:B, which acts as a pulse stretcher; U7:B's output is inhibited (blanked) by the T/R signal, so that an external microprocessor can choose for transmission transients and early echoes to be ignored until the T/R signal is brought low. Thus, the output of U7:B is qualified for both size and occurrence-time of echoes, freeing an external microprocessor from having to perform amplitude and time comparisons in real time.

### Power Supplies

The Transceiver module is designed to operate nominally from a 9-volt battery. In order to generate a negative excitation pulse sufficient for the transducer to produce an appropriately loud transmission, a ring oscillator (U6:B, U6:C and associated components) and high-current driver U2:A drives a voltage quadruple, producing between 26 and 36 volts (over varying battery voltages) at the input of regulator U3. An extra diode+capacitor stage had to be patched onto the circuit board, as they were missing from the application note [3] from which this circuit was derived. U3 provides a consistent 24-volt supply to the transmitter circuitry, so that transmission power is stable over the expected supply voltage range.

U4 is a linear voltage regulator which provides 3.3 volts for the comparators, monostables and ring-oscillator. U5 is a linear voltage regulator which provides 5.0 volts for the LNA and buffer amplifiers.

### Interface

CN1 is a single-row 0.1” header providing connections for power and signals to and from the external microprocessor. CN1 may also be populated with a 0.1” pitch board-to-board connector, if desired. The pin-out was chosen to minimize interference from digital to analogue signals, and also to prevent circuit damage in the event of mirror-image mating.

# 6. System Algorithm

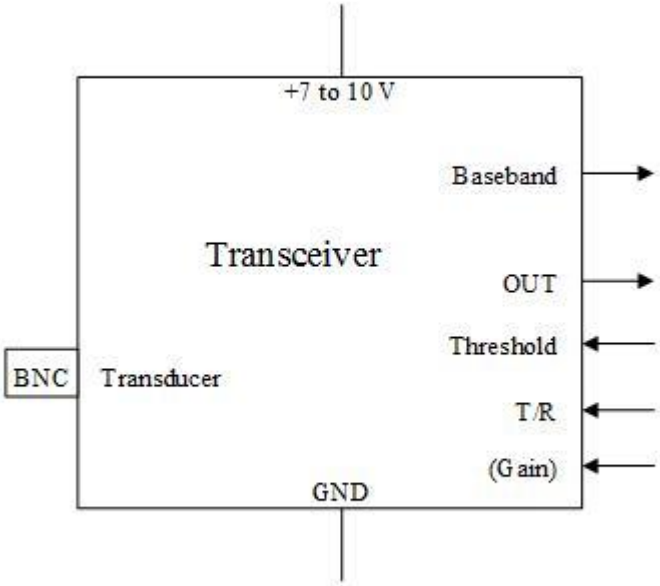
Two ultrasonic delay-line transducers with nominal resonance of 15 MHz were selected as candidates for a medical diagnostic sonar device. The major system design and implementation of the transceiver module associated with this product are explained in the previous sections. This transmitter/receiver module is utilized to excite the transducers; amplify, detect and qualify the acoustic echoes received from media in contact with the tips of the transducers. A working prototype is designed and delivered to prove this product concept. Further work is required to create the microprocessor circuit, user interface and software to turn this work into a marketable product.

The following sub-sections introduce the different algorithms involved throughout the process that starts by exciting the ultrasonic transducers and terminates by processing the received echo signals.

## 6.1. Transceiver Specification and Algorithm

The Transceiver shall be a module containing all the electronics required to pulse the Olympus NDT transducer and detect the signals there from. The Transceiver requires approximately 50 mA from a 7 to 10 VDC power source, making it suitable for operation from a single “9 volt” battery. The Transceiver module designed, implemented and introduced in section 5.3.8 contains the connections connection depicted in Figure 6-1.

*Figure 6-1. Transceiver Module Input/output Connections*



Descriptions of all the connections shown in the above figure are provided in the following sub-sections.

### *6.1.1. GND (The Main Ground)*

This is the main circuit ground for the Transceiver module. All other signals are referenced to GND.

### *6.1.2. Power Supply (+7 to 10 V)*

A clean source of DC power must be supplied to the Transceiver through this connection. Approximately 50 mA (at 9 V) is required. Hence, a “9 volt” battery is suitable for providing the required power to the Transceiver module. (Although a 9-V battery is preferred, the unit functions within the range of 7 to 10 volts)

### *6.1.3. Transducer*

The transducer cable should be connected directly to this BNC jack. Through this single connection, the Transceiver excites the transducer with negative pulses and receives the echo signals from the transducer.

### *6.1.4. T/R (Transmit/Receive) Switch*

This is a 3.3 V logic input signal which triggers transducer excitation (transmission), controls the blanking interval, and enables reception. The rising edge of this signal triggers an internally-timed excitation pulse to the transducer. When this signal is high, during the “blanking interval”, any signals returning from the transducer are ignored by the Transceiver’s receiver circuitry and the OUT signal is held low. When the T/R signal is brought low, the Transceiver begins detecting echoes and will pulse the OUT signal whenever an echo of sufficient amplitude is detected. The controlling microprocessor should make the blanking interval suitable for the transducer and application. See the theory of operation in 6.2 for more details.

### *6.1.5. Baseband*

This is a buffered version of the output of the receive amplifier (which is the transducer signal amplified by 45 to 50 dB). It may be sampled with a fast (50 Msps or faster) ADC in order to perform software detection of the echo signals.

### *6.1.6. Threshold*

This is a 0 to 2.0 V analogue input signal which sets the detection threshold for echoes. When the T/R signal is low, the amplified transducer echo signals will be compared to the Threshold voltage, and the OUT signal will be pulsed high when an echo exceeds the Threshold voltage. The chosen microprocessor should make the Threshold suitable for the transducer and application, and may also vary the Threshold dynamically, if desired, to implement time-varying gain.

### *6.1.7. OUT*

This is a 3.3 V logic output signal which pulses high for approximately 200 ns whenever an echo signal exceeds the Threshold voltage. This signal will only provide output pulses when the T/R control signal is low (during the receive mode).

### *6.1.8. Gain*

Normally, the Transceiver circuit board is built such that the receiver circuitry is fixed at maximum gain. However, if the Transceiver circuit board is built with R24 installed and RV1 omitted, this input pin may be used to control the gain of the receiver circuitry—the voltage applied to this input pin is fed, via a low-pass R/C filter (R24 and C3), to the AGC pin of the SN761666 low-noise amplifier; please see the SN761666 datasheet for more information.

## 6.2. Theory of Operation

The Transceiver generates all the internal supply voltages it needs from the +7 to 10 V input supply. Sections of the Transceiver may be shielded for optimal noise performance. The Transceiver delivers approximately 60 to 100 V (depending on the transducer) of negative pulse excitation, and provides approximately 45 to 50 dB of gain for the echo signals. Since the application is near-surface, under-the-skin structure detection, wherein the first strong echo is the desired detection target, time-varying gain (TVG) is neither required nor provided internally by the Transceiver; however, the Threshold voltage may be varied dynamically to create TVG effects.

A microprocessor should be used to control the Transceiver. The microprocessor is required to provide a Threshold voltage (e.g. from a DAC) to set the detection level, and a T/R signal to control transmission, blanking interval and reception timing. The microprocessor may also vary the Threshold voltage dynamically in order to implement TVG, if desired. A transmission/reception cycle may be initiated by the microprocessor as often as 100 times per second. The diagram depicted in Figure 6-2 (developed by Arash Taheri), illustrates a typical operating sequence; the Threshold voltage may be dynamically decreased (or the Gain voltage, if implemented, may be dynamically increased) during Reception to implement TVG:

*Figure 6-2.* ***Typical Operating Sequence of the Detection Process***

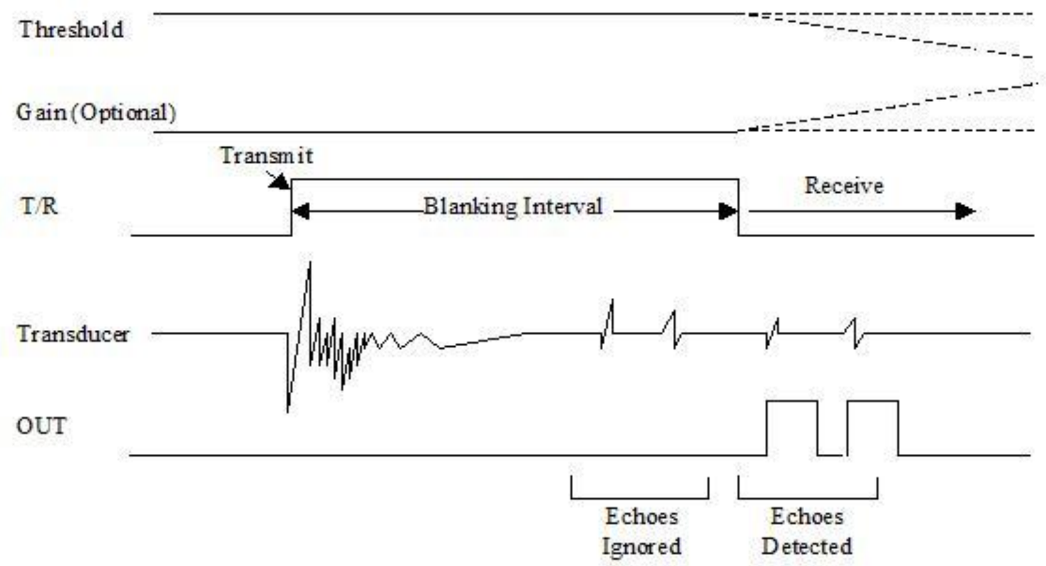
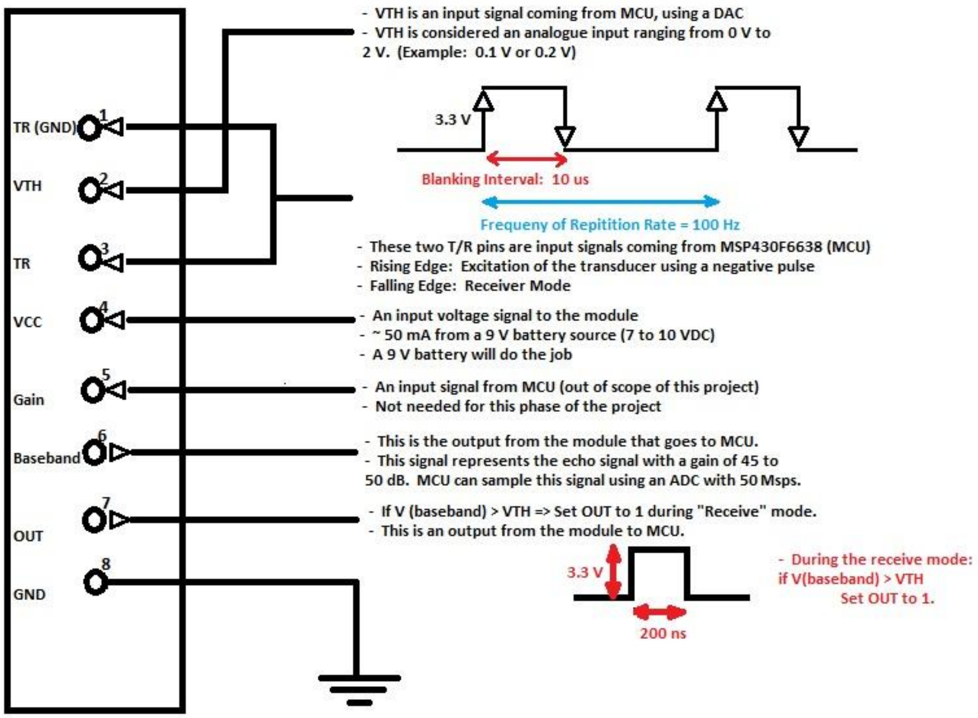


*Figure 6-3.* ***Illustration of Transceiver Module in Detail***



- VTH is an input signal coming from MCU, using a DAC
- VTH is considered an analogue input ranging from 0 V to 2 V. (Example: 0.1 V or 0.2 V)

- These two T/R pins are input signals coming from MSP430F6638 (MCU)
- Rising Edge: Excitation of the transducer using a negative pulse
- Falling Edge: Receiver Mode

- An input voltage signal to the module
- ~ 50 mA from a 9 V battery source (7 to 10 VDC)
- A 9 V battery will do the job

- An input signal from MCU (out of scope of this project)
- Not needed for this phase of the project

- This is the output from the module that goes to MCU.
- This signal represents the echo signal with a gain of 45 to 50 dB. MCU can sample this signal using an ADC with 50 Msps.

- If V (baseband) > VTH => Set OUT to 1 during "Receive" mode.
- This is an output from the module to MCU.

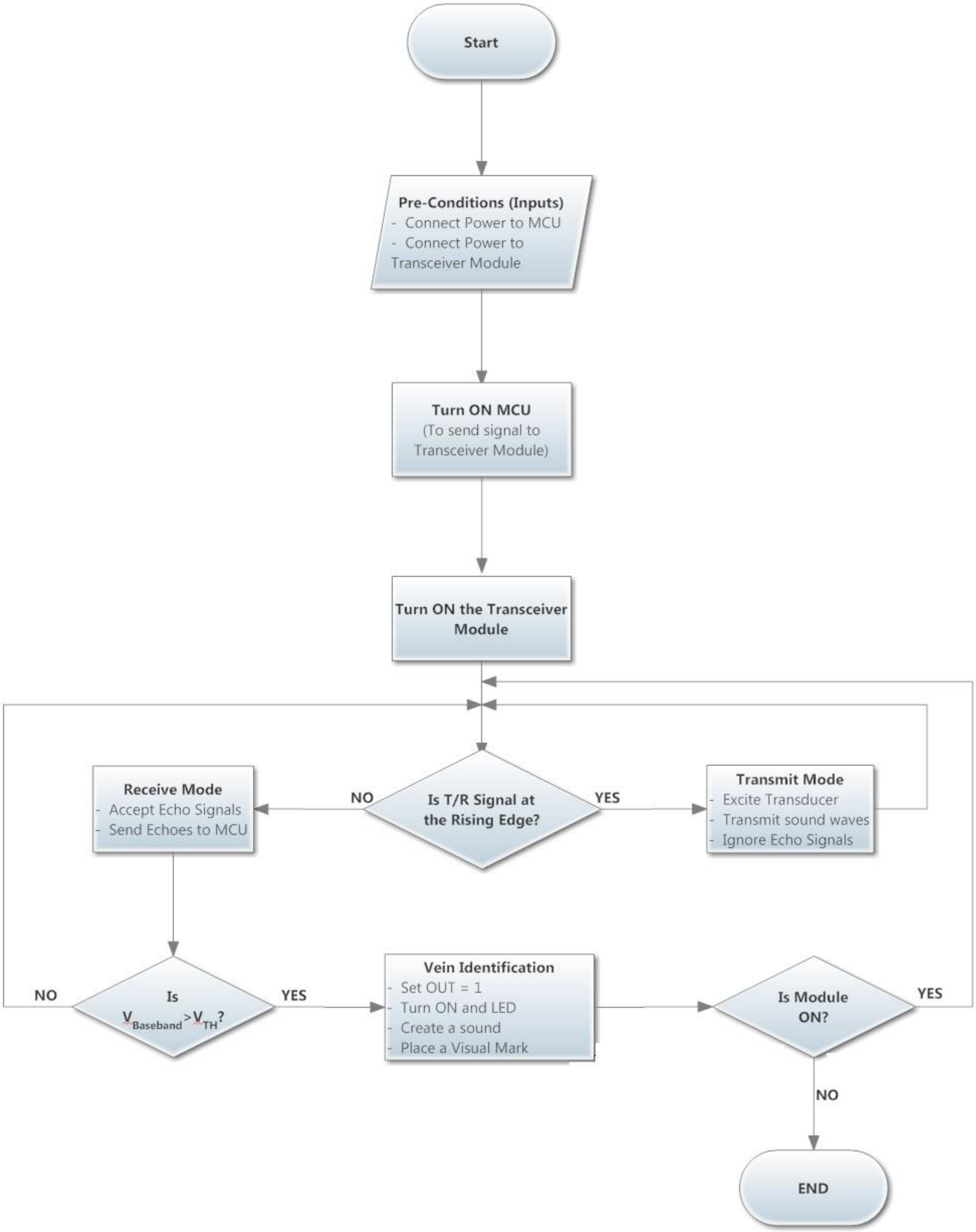
- During the receive mode:
if V(baseband) > VTH
Set OUT to 1.

Figure 6-3 (developed by Arash Taheri) represents the block diagram depicted in Figure 6-1 in detailed illustration. As evident, all eight pins of the Transceiver module, along with their names and a short description are provided in this figure.  As explained, this module contains five inputs, two outputs, and one common ground pin.

## 6.3. Flowchart Algorithm

Theory of operation throughout the process of vein detection is presented in section 6.2, with a brief explanation of the roles involved in every piece of the overall module.  Flowchart illustration of this theory is depicted in Figure 6-4.  In addition, detailed explanation of each block in this chart is provided.

*Figure 6-4. Flowchart Algorithm Illustration*



### 6.3.1. START

This is the beginning of the operation. At this stage, it is required that the overall module circuit is prepared as explained and all devices are operational.

### 6.3.2. Pre-conditions/Inputs

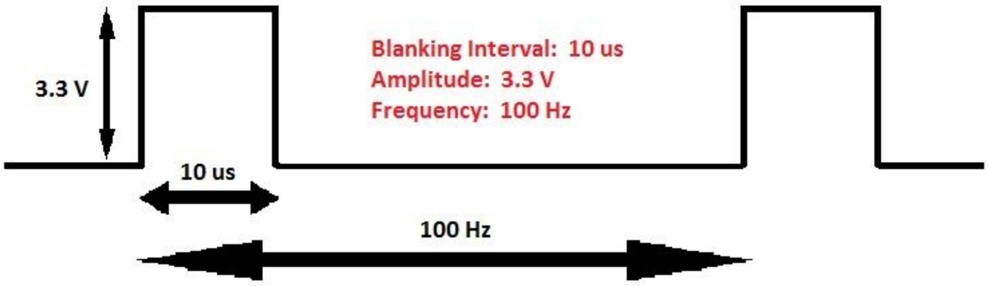
This block indicates that all input connections must be provided and all power supplies must be ready to use.

- Provide a power supply of 50 mA at 9 V (7 to 10 Volts) to the Transceiver module. (i.e. 9-Volt battery)
- Provide a power supply of between 1.8 V to 3.6 V to the microcontroller.

### 6.3.3. Turn ON MCU

The utilized microcontroller, MSP430F6638, is programmed to generate the following signal. Therefore, as the microcontroller starts operating by being turned on, the following signal is generated and fed to the T/R inputs of the Transceiver module. As illustrated in Figure 6-3, this signal is provided and fed to pins 1 and 3 of the module.

***Figure 6-5. Input T/R Signal to Pins 1 and 3 of the Transceiver Module***



- **Signal Amplitude:** As illustrated in the above figure, the T/R signal is programmed to have amplitude of around 3.3 Volts.

- **Blanking Interval**: Also defined as the “transmit period”, blanking interval is a duration where the Transceiver module ignores all received echo signals. Blanking interval is programmed to last about 10 µs.

- **Receive Mode**: The period that starts from falling edge of one period and continues until the rising edge of the next period is considered to be the receive mode. During this period, the Transceiver module accepts all incoming echo signals and passes them to the MCU for processing.

- **Frequency:** As illustrated in Figure 6-5, frequency, or repetition rate, of the T/R signal is programmed to be 100 Hz (10,000 µs).

### *6.3.4. Turn On the Transceiver Module*

By applying power to the Transceiver module, the unit is ready to accept the generated signal from the T/R inputs and act according to the programmed logic. As explained in section 6.3.3, the rising edge of the T/R signals force the Transceiver module to excite the transducer, ignoring the received echo signals. Furthermore, the falling edge of the T/R signals is the indication of entering the receive mode, where echo signals are accepted for signal processing.

### *6.3.5. T/R Signal at the Rising Edge*

This “decision making” block is considered to be one of the most import logic pieces of the algorithm. As depicted in Figure 6-4, the following two conditions exist:

- **T/R Signal at the Rising Edge:** If this condition exists, the module enters the “Transmit” mode.

- **T/R Signal at the Falling Edge:** If this condition exists, the module enters the “Receive” mode.

### *6.3.6. Transmit Mode*

Transmit mode state is activated upon rising edge of the T/R signal shown in Figure 6-5. The following operations take place in this state:

- The utilized transducer is excited through a short (a few hundred nanoseconds) pulse of negative voltage (60 to 100 Volts).
- The transducer transmits sound waves with frequency of around 15 MHz.
- The unit enters the “Blanking Interval” and all received echo signals are ignored.
- The unit enters the next T/R signal cycle

### *6.3.7. Receive Mode*

Receive mode state is activated upon falling edge of the T/R signal shown in Figure 6-5. The following operations take place in this stage:

- Echo signals received at the Transceiver module are accepted
- Received echo signals are sent to the MCU for signal processing.
- The logic unit enters the voltage comparison mode

### *6.3.8. Baseband Voltage VS Threshold Voltage*

The Threshold Voltage, $V_{TH}$, is set to a constant value of 0.1 V or 0.2 V through programming the MCU, utilizing a Digital-to-Analog Converter. Theoretically, $V_{TH}$ should be set to a constant value between 0 to 2 volts. This value should be decided and confirmed through the calibration process for the target material (vein). Baseband Voltage, $V_{BASEBAND}$, is the received echo signal amplified using a gain of 50 dB. This signal can be sampled using an ADC using a 50 Msps. This “decision making” block checks the following conditions and acts accordingly:

- **$V_{BASEBAND} \geq V_{TH}$:** If this condition is met, the unit enters the final processing block, where an indication of the vein will be provided using a visual mark or sound.

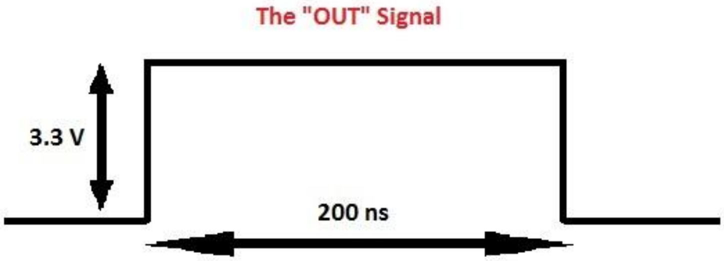
- **$V_{BASEBAND} < V_{TH}$:** If this condition is met, the echo signal will be ignored and the logic unit goes back to the next cycle of T/R signal.

### *6.3.9. Vein Identification*

This stage is reached if the baseband voltage is greater than or equal to the threshold voltage, $V_{BASEBAND} \geq V_{TH}$, as explained in the previous section. At this stage, the following operations occur:

- The “OUT” signal, represented in pin 7 of Figure 6-3, will be set to “High”. This signal is represented in Figure 6-6.

***Figure 6-6. Representation of the OUT Signal***



- When the “OUT” signal is set to high, the MCU is programmed to provide an indication of the discovered vein through performing one or combination of the following actions: creating a sound signal, turning ON and LED, or injecting a visual mark.

### *6.3.10. Module in ON Mode*

This “decision making” state is reached shortly after the vein detection block. At this state, the logic unit checks the operational mode of the unit and takes on the following actions accordingly:

- **The Unit is ON:** This state means that the user has still not powered the unit off. Hence, the logic unit goes to the next cycle of the T/R input and repeats the detection process again.

- **The Unit is OFF:** This state means that the user has powered the unit off. Hence, the module is no longer operational.

### *6.3.11. END*

This state is reached if the unit is powered off and no longer in operation.

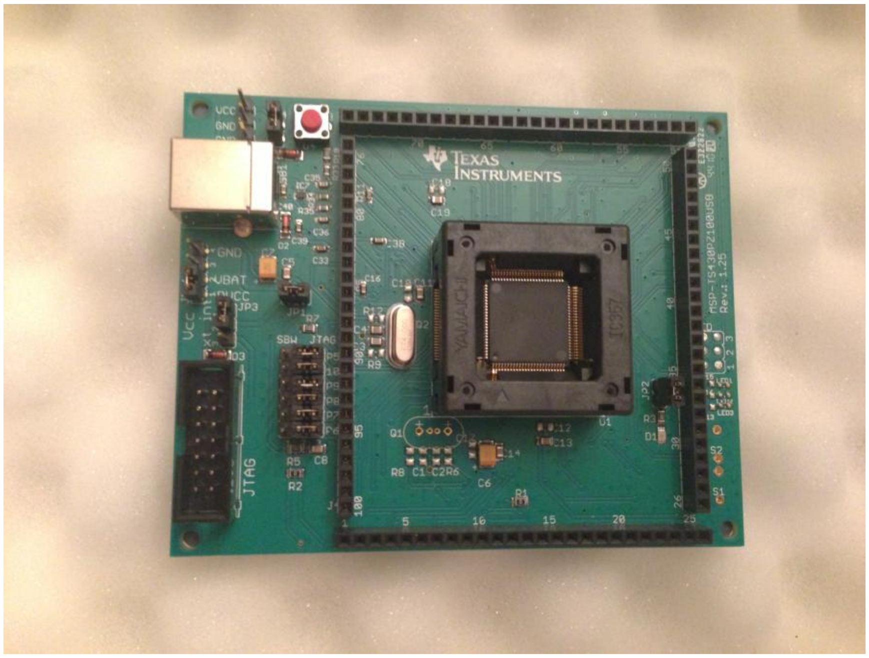
# 7. System Software

This section of the report outlines various utilized features and inputs/outputs of the MSP430F6638 microcontroller and introduces the concept of MCU programming. The utilized microcontroller from Texas Instruments, MSP430F6638, is introduced in section 5.1. This section provides the in-depth explanation of all the equipments that are required to program this microcontroller, along with their connections and communications.

## 7.1. MCU Socket

The following figure, taken by Arash Taheri, illustrates the microcontroller socket/debugger utilized in this project. This debugger is also known as the "USB Target Board".

***Figure 7-1. MCU Socket/Debugger Illustration***



In order to apply this debugger interface, it is required to install the MSP430F6638 MCU in the provided socket. As depicted in Figure 7-1, the microcontroller is gently situated inside the socket. Since this small MCU contains 100 pins, space-constraint makes it very difficult to utilize the pins. Therefore, this socket is used to provide a more clear connectivity along the pins, which makes the application more user-friendly. The following list outlines some quick introductions [12]:

- The 14-pin JTAG pin header/connector is required to connect this module to the USB-FET tool introduced in 7.2.
- The USB connector on this module can be utilized to provide USB connection (Type A or B) between computer and the target board.
- **USB-Powered Scenario**: This default setting requires connecting pin 3-2 of JP3 in order to inform the USB debugger of the external on-board power utilization. Pin header JP1 must be closed.
- **USB-FET Powered Scenario**: By placing jumper on pins 1-2 of JP3, the internal USB power is utilized; however, it is required to ensure that pin header JP4 is not closed. Pin header JP1 must be closed.

## 7.2. USB Debugger Interface

This powerful flash emulation module is required for application development of the project on MSP430F6638. This tool contains a USB debugging interface applied for programming and debugging the MCU through the JTAG interface. One of the great advantages of this tool is its ability to erase and program the flash memory in seconds, requiring only a few keystrokes. Furthermore, since the MCU flash is ultra-low powered, no external power supply is needed for utilization. This debugging interface provides connection between the microcontroller and the integrated software environment (i.e. a PC) to enable immediate designing and coding.

Figure 7-2 illustrates the USB Debugger Interface utilized in this project.

*Figure 7-2. USB Debugger Interface*[12]

The following list provides some quick introductions to the available features [12].

- The tool requires a software-configurable supply voltage between 1.8 and 3.6 volts at 100 mA.
- The interface contains a "JTAG Security Fuse blow" to provide code protection.
- All MSP430 boards with JTAG header can apply this interface.
- The module provides connection between a flash-based MSP430 MCU and a computer to enable real-time in-system programming and debugging.

## 7.3. Code Composer Studio

Known as an "Integrated Development Environment" (IDE), Code Composer Studio is a software tool that is utilized for application developments through Texas

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[12] Texas Instruments, "MSP430 Hardware Tools User's Guide", http://www.ti.com/lit/ug/slau278l/slau278l.pdf, 2009-2012.

Instruments (TI) embedded processors such as DSPs, ARM based devices, and processor such as MSP430. In this project, Code Composer is utilized to program the MSP430F6638 processor.

DSP/BIOS, or know as SYS/BIOS, is the real-time operating system included in Code Composer Studio software. Furthermore, this software provides support for both OS-level application debugging and low-level JTAG-based development. Moreover, Eclipse is an open-source software framework that Code Composer Studio is based on.

Code Composer Studio version 5, which provides support for both Linux and Microsoft Windows Operating Systems is chosen for programming the MSP430 MCU in this project. The next subsection illustrates how Code Composer is utilized in implementing an algorithm, written in C programming language, in order to generate the desired signal introduced in Figure 6-5.

### *7.3.1. Signal Generation and Experimental Results*

Revisiting Figure 6-5 provides the following information with regards to the signal required to excite the transducer and to receive and process the echo signals:

- Amplitude: 3.3 V (peak-to-peak)
- Frequency: 100 Hz (10,000 µs)
- Duty Cycle: 0.1% (10 µs)

As evident, the required signal contains a very low duty cycle value which is not possible to generate utilizing normal function generators. Most function generators used in universities and research laboratories can deliver as low as 10% duty cycle. However, for the purpose of this project, it is required to obtain a 0.1% duty cycle with high time of only 10 µs. The best tools for delivering such low duty cycle are microcontrollers. MSP430F6638 is utilized to deliver the Transceiver module with 0.1% duty cycle.

On the MSP430, each pin has a few potential functions; however, by default, most of the pins are considered to function as GPIOs (General-Purpose Input/output). In order to utilize a pin for a specific function, it is required to program the pin to configure it for the desired function. For example for Port 1, this is achieved by setting P1DIR and P1SEL to the second and third bits as shown in the code in “Appendix A”. The table at the bottom of the datasheet in [11] provides the settings required to follow for P1DIR and P1SEL to output TA0.1 and TA0.2 on pins. As illustrated in the comments of the code, presented in “Appendix A”, P1.x pins are being set as the timer output.

“User’s Guide” chapter in [11] provides excellent information about how to utilize timers in MSP430. Figure 17-12 in [11] is very useful in understanding how timers are generated. The “TA0CCR1” and “TA0CCR2” registers each set a high time for a signal on a particular pin. Therefore, only one of these registers is required to output a signal. As presented in the code comments listed in “Appendix A”, “TA0CCR0”, sets the period of the signal (the length of time for the entire high/low cycle). In addition, “TA0CCR1” sets the high time on the output pin “TA0.1”. Setting the high-time configures the low-time value automatically, as their addition delivers the period.

Furthermore, as mentioned in the “MSP430 User’s Guide” in [11], the values in each of the “TA0CCRx” registers correspond to a number of clock ticks. By default, the port runs at 1 MHz; hence, each clock tick is set to 1 µs. Moreover, the pins output $V_{CC}$ for their high level; therefore, whatever $V_{CC}$ is applied to the part is what is delivered at the output pins.

*Figure 7-3.* *Overall Project Setup*

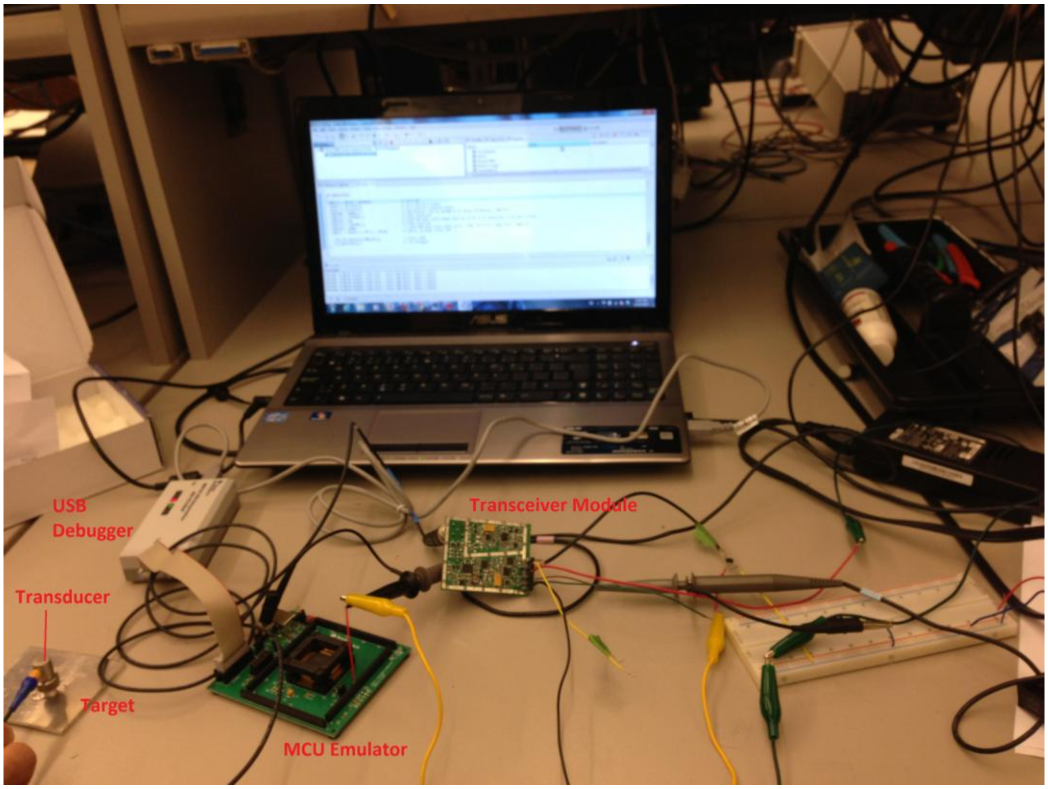
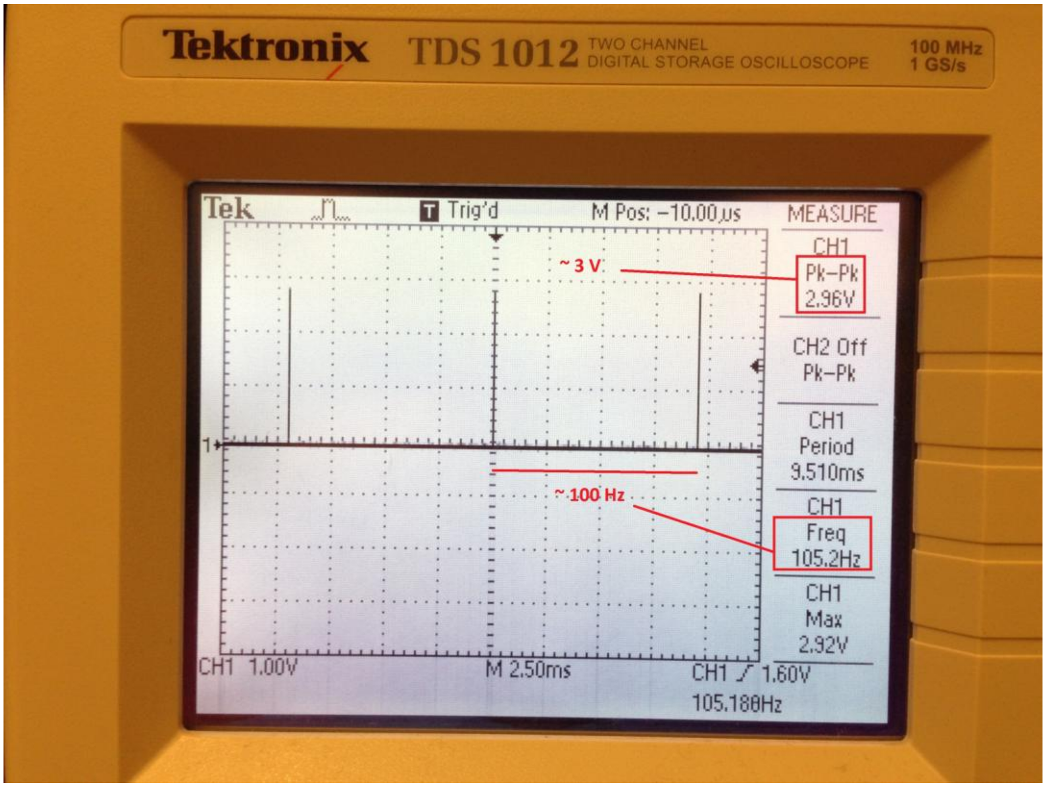


Figure 7-3 illustrates the overall setup of the project for a practical demo. As evident, MCU Emulator, USB Debugger, and the computer must work together to generate the required signal for the Transceiver Module. The code shown in “Appendix A”, written in C, and compiled using “Code Composer Studio”, is transferred to the MCU Emulator through the USB Debugger Interface. The generated signal is fed to the Transceiver Module, which is connected to the ultrasonic transducer. The transducer generates high frequency, 15 MHz, sound waves which will hit the target material, leading to generation of various echo signals. The echo signals are fed to the Transceiver Module through the transducer cable and ready for analysis.

As illustrated in Figure 6-5, the required signal to excite the transducer must have a frequency close to 100 Hz with a peak-to-peak voltage of around 3.3 V. Figure 7-4 proves that utilizing MSP430 MCU and programming it provides an extremely matching signal.

***Figure 7-4. MCU Generated Signal (Voltage and Period)***



Another characteristic of the required signal is its low high-time of 10 µs which leads to the duty cycle of 0.1%. As mentioned previously, this signal needs to have a period of 100 Hz (0.01 s or 10,000 µs). In order to achieve a duty cycle of 0.1%, the high-time of the signal must equal 10 µs, with the remaining of the period set to the low-time. (10,000 µs – 10 µs = 9990 µs) Figure 7-5 illustrates the generated signal through MSP430 programming as an output on the oscilloscope. As evident, the selected MCU is capable of delivering the required signal with 100% match to the duty cycle requirement.

***Figure 7-5.   MCU Generated Signal (High-Time)***

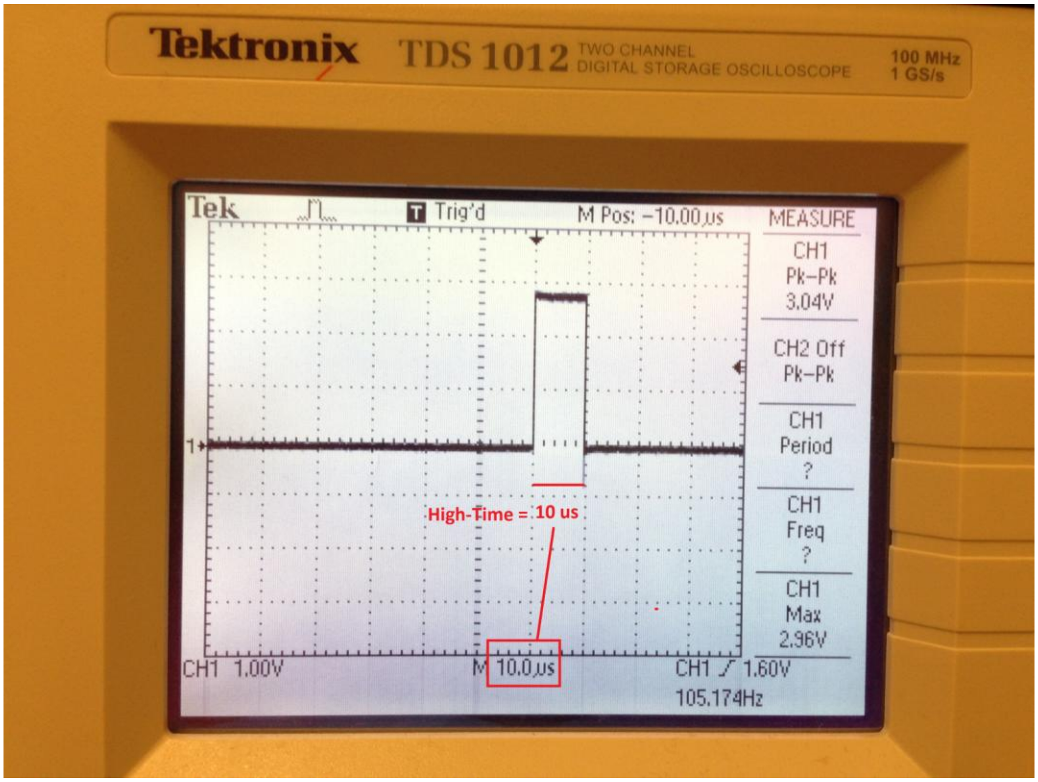
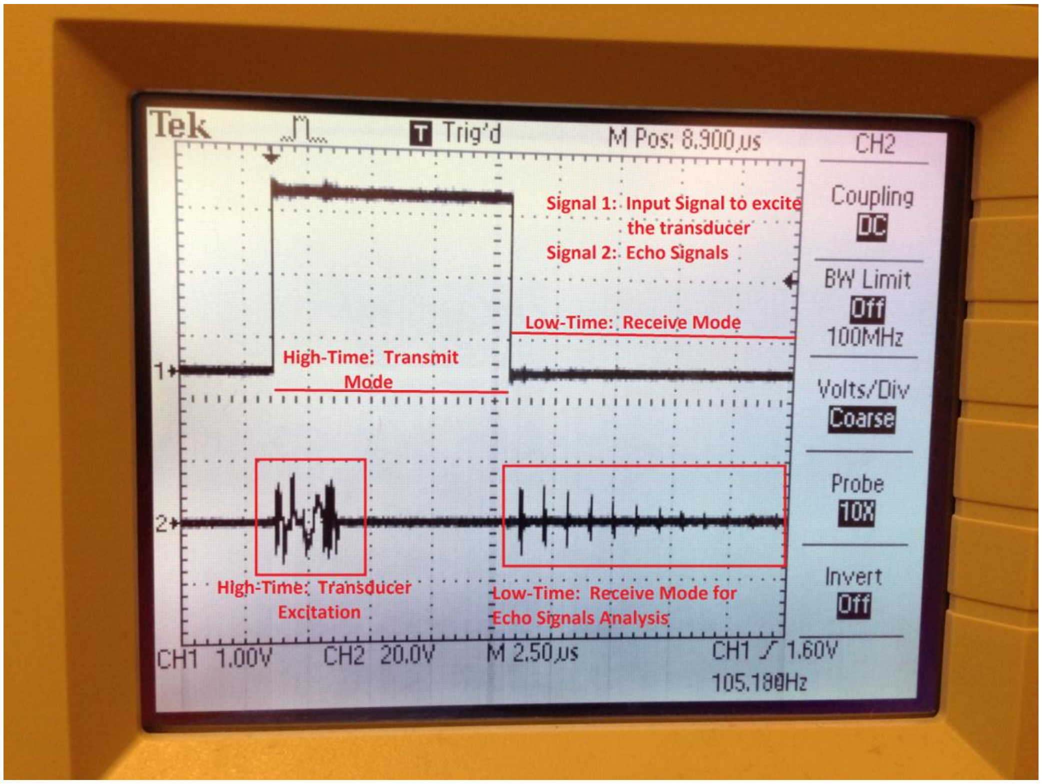


Figure 7-6 illustrates a screen capture taken by an oscilloscope which outputs both the signal generated by MCU (Signal 1) and the echo signals received by the ultrasonic transducer and transferred to the Transceiver Module (Signal 2). As evident, the high-time of “Signal 1” is set to 10 µs as required. During this transmit mode, the Transceiver Module excites the transducer which leads to sending high-frequency sound waves to the target material shown in Figure 7-3. It should be noted that the echo signal shown in “Signal 2” during the transmit mode correspond to the echo signals generated by the delay-line at the tip of the transducer. However, these echo signals are never processed by the Transceiver Module, since signal analysis only happens during the receive mode. After exactly 10 µs, “Signal 1” becomes low, which is the indication of entering the receive mode. As evident by looking at “Signal 2” in Figure 7-6, many echo signals are observed during the receive mode. These echo signals are generated as the high-frequency sound waves collide with walls of the target material shown in Figure 7-3. However, as the collisions continue, the amplitude of the echo signals reduces. This phenomenon is depicted in “Signal 2” echo signals in Figure 7-6.

*Figure 7-6. MCU Generated Signal (Overall) Plus Echo Signals*



In conclusion, as illustrated in section 7.3.1, utilizing the MCU MSP430F6638 is the best practical method to generate the required signal with specifications shown in Figure 6-5. Programming this MCU enables us to feed the required signal to the Transceiver Module with a low duty cycle of 0.1%, which is not possible to deliver with most function generators out in the market.

Moreover, the target material introduced in Figure 7-3 is replaced with human forearm to repeat the same experiment on an actual vein. As illustrated in Figure 7-7 shown below, the ultrasonic vein detection system is successfully able to detect the echo signals generated by human veins in the forearm region. As evident in this figure, the echo signals that are generated by Cephalic, Basilic, and Median Cubital are very low in amplitude and hard to detect and illustrate on an oscilloscope. Regardless, the Transceiver Module is capable of generating and applying enough gain to amplify such low-amplitude signals for detection. In addition, Figure 7-8 illustrates the echo signal generated by Median Cubital vein.

*Figure 7-7. Echo Signal Generated by Cephalic Vein*

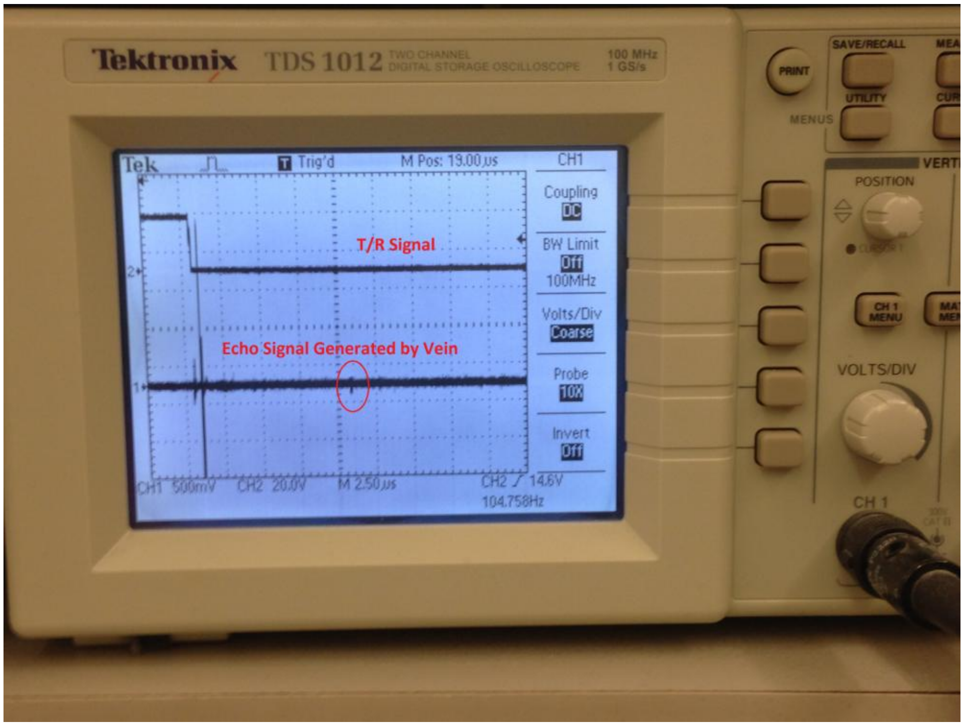
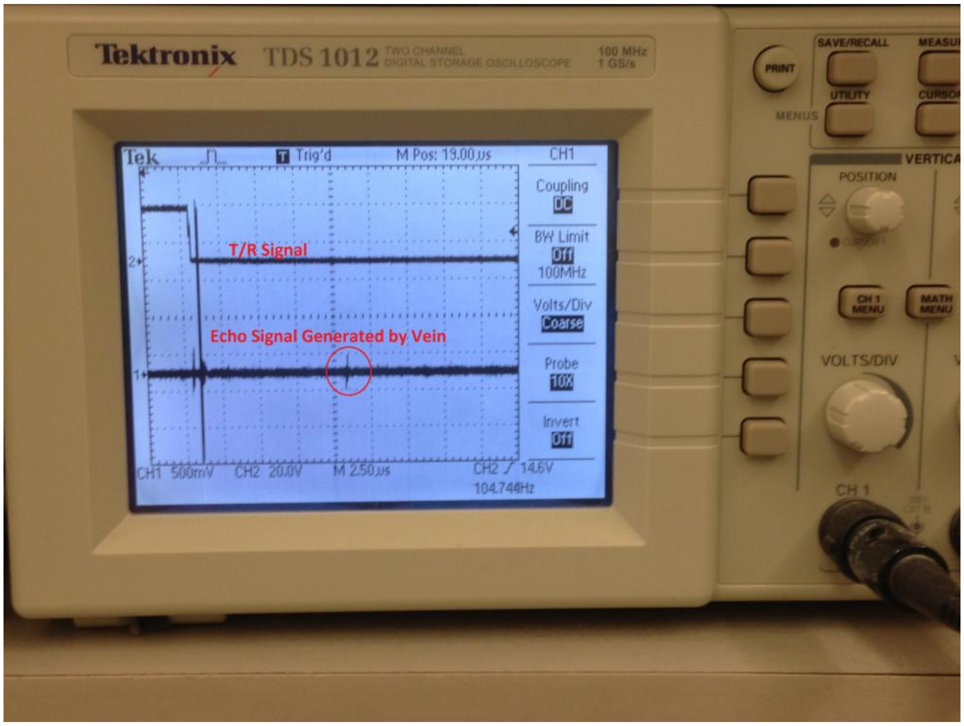


*Figure 7-8. Echo Signal Generated by Median Cubital Vein*



# 8. Conclusion

The objective of this biomedical research project is to provide an intensive research for ultrasonic transducers and utilize the investigation results in implementing a proof-of-concept and cost-effective vein seeking device.

To achieve the purpose, two high-frequency (15 MHz) ultrasonic transducers, provided by “Olympus NDT”, are utilized as illustrated in Figure 5-3 and Figure 5-4. To excite the transducer and process the echo signals, a cost-effective Transceiver Module is developed from scratch through gaining ideas from the paper sourced in [1]. This pulser/receiver circuit, illustrated in Figure 5-29, excites the transducer, receives the echo signals from the target material/vein and through the transducer, and passes the received signals to a microprocessor for data processing. MSP430F6638 microcontroller from Texas Instruments is utilized to generate the required signal, shown in Figure 6-5, and deliver it to the Transceiver Module. The pulser/receiver unit applies this signal to excite the transducer and receive the echo signals in a timely manner illustrated in the algorithm in Figure 6-4.

In order to provide a proof-of-concept methodology, the above components are utilized to investigate the echo signals generated by a metal piece as shown in Figure 7-3. The T/R signal and the generated echo signals are depicted in Figure 7-6. As evident in this figure, the entire ultrasonic vein detection module can successfully excite the transducer, receive the echo signals and display them on an oscilloscope. Therefore, Figure 7-6 verifies the functionality of this medical diagnostic sonar device.

Moreover, the ultrasonic vein detector module repeats the same experiment on an actual human vein in the forearm region. As illustrated in Figure 7-7 and Figure 7-8, the device is able to successfully detect the echo signals related to actual human veins and display them on an oscilloscope for demonstration purposes. Although these signals are very small in amplitude, the microcontroller utilized in this project, MSP430F6638, is able to detect them and perform further analysis based on the algorithm shown in Figure 6-4.

In conclusion, an ultrasonic vein detector device is designed in this project, which will be utilized in a pen-like instrument. This medical device utilizes an ultrasonic transducer, along with a Transceiver Module connected to an MCU to detect three main veins in human forearm, known as the venipuncture sites.

## 8.1. Future Work

As explained in Conclusion section, the medical diagnostic sonar device designed and developed in this project is able to detect echo signals produced by any target material and display them on an oscilloscope for demonstration purposes. However, in order to implement a prototype ultrasonic vein detection device for marketing purposes, it is required to provide various enhancements to the current state of the module.

As mentioned earlier in section 5.2, one of the major difficulties of working with the Sonopen transducer is its small tip size diameter. The generated echo signals are very dependent on the amount of pressure the transducer applies on the skin surface. In addition, any changes on the angle in which the transducer is mounted on the skin result in generating a different echo signal. Due to the above two complications, it is very difficult to obtain an identical echo signal from the superficial veins at all times. On the other hand, the microcontroller needs to identify the veins based on their recognized echo signals to be calibrated against them. Therefore, as an improvement feature, it is decided to situate the Sonopen inside a rectangular enclosure. This solution resolves the handling problem as the transducer will always be mounted perpendicular to the skin surface. Moreover, the amount of applied pressure will be kept somewhat unique.

As evident in Figure 7-7 and Figure 7-8, the echo signals related to the superficial veins of forearm are very small in amplitude and sometimes very difficult to locate. Although the utilized MCU is powerful enough to catch the signals, it is highly recommended to magnify the signals before sending them to the microcontroller. Hence, as another improvement feature to the current product, the Transceiver Module needs to be modified to provide more gain.  This will result in magnifying the received echo signals before passing them to the MCU for data processing.

Also, the current stage of the project requires the microcontroller to be placed inside the socket.  In addition, the program code is kept inside a PC and the communication between the two components is handled through the “USB Debugger Interface”.  To implement an actual prototype device, it is required to eliminate both the debugger interface and the PC to enable the MCU to run independently.  Hence, the MCU must be taken out of the socket and the C program must be hard-coded inside the microcontroller.

In addition, dedicated power supplies must be provided for all components. Currently, the MCU is obtaining the required power through a PC.  A 3.3 V power supply/battery can easily deliver enough power to the MCU and eliminate the need for a PC.  Moreover, to introduce an actual biomedical device with a market potential, it is essential to reduce the size of the apparatus.  As mentioned previously, the ultimate goal is to develop a prototype with dimensions similar to a small flashlight.  Hence, it is required to situate all components inside a small enclosure.

At last, one of the major advantages of this biomedical device is its ability to recognize superficial veins of forearm to provide indications for proper venipuncture sites.  Currently, the product is only able to obtain the echo signals generated by these veins to show them on an oscilloscope.  To provide improvements, it is required to process these signals by calibrating the microcontroller against recognized echo signals that represent superficial veins.  Furthermore, it is planned to implement an alarm system which will activate upon detecting the superficial veins.  The alarm system can greatly help the doctors/nurses in spotting the proper venipuncture site as the device is being mounted on the forearm.  Moreover, a mechanical drug injection system will be added to the apparatus to automatically activate the process of injection or withdrawal upon recognizing the venipuncture site.

# References

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# Appendices

# Appendix A.

## Code Example for Signal Generation

This section provides the code written in C, and compiled using “Code Composer Studio V5”, that generates the required signal introduced in Figure 6-5. The specific details of the code for each line are shown in the green comments within the body of the code in the next page.

This program generates two signal outputs on P1.2 and P1.3 ports using Timer1_A configured for up mode. The value in CCR0, 10000-1, defines the signal period and the values in CCR1 and CCR2 define the signal duty cycles. Using ~1.045 MHz SMCLK as TACLK, the timer period is ~10,000 µs with a 0.1% duty cycle on P1.2 (Physical Pin 36) and 50% on P1.3 (Physical pin 37). Pin 37 is not used in this project and is only shown for demonstration purposes. In addition ACLK is not applicable as SMCLK = MCLK = TACLK = default and DCO ~1.045 MHz.

Utilizing the code shown in the next page generates two different signals on pins 36 and 37 of the MCU part. The signal on pin 36 complies with the requirements show in Figure 6-5 and is used to feed the Transceiver Module in order to excite the ultrasonic transducer:

- Amplitude: 3.3 V (peak-to-peak)
- Frequency: 100 Hz (10,000 µs)
- Duty Cycle: 0.1% (High-Time: 10 µs)

The signal corresponding to the above specifications is produced at output pin 36 and is illustrated in Figure 7-5.

The signal generated on pin 37 of the MCU part has the same characteristics except for a different duty cycle. As illustrated in the code, the value of “TA0CCR2”, which corresponds to pin 37, is set to 5000, which sets the duty cycle of the signal to 50% and the high-time to 5,000 µs. This signal is not used in the project and is only included in the code for the purpose of demonstration.

```
//*******************************************************************************
//  MSP430F66x Demo - Timer0_A5, PWM TA1.1-2, Up Mode, DCO SMCLK
//
//  Description: This program generates two PWM outputs on P1.2,P1.3 using
//  Timer1_A configured for up mode. The value in CCR0, 10000-1, defines the PWM
//  period and the values in CCR1 and CCR2 the PWM duty cycles. Using ~1.045MHz
//  SMCLK as TACLK, the timer period is ~10,000 us with a 0.1% duty cycle on P1.2
//  (Physical Pin 36) and 50% on P1.3 (Physical pin 37).  Pin 37 is not used in
//  this project and is only shown for demonstration purposes.
//  ACLK = n/a, SMCLK = MCLK = TACLK = default DCO ~1.045MHz.
//
//              MSP430F66x (MSP430F6638)
//          -  -------------------
//        /|\|                   |
//         | |                   |
//         --|RST                |
//           |                   |
//           | (Pin 36)P1.2/TA0.1|--> CCR1 - 0.1% PWM (high-time=10 us; low-time=9990 us)
//           | (Pin 37)P1.3/TA0.2|--> CCR2 - 50% PWM (high-time = low-time = 5000 us)
//
//   Arash Taheri
//   Simon Fraser University
//   February 2013
//   Built with IAR Embedded Workbench Version: 4.20 & Code Composer Studio V5.0
//******************************************************************************

// importing the required library
#include <msp430.h>

// Summary of the code:
//
// main program starts
int main(void)
{
  WDTCTL = WDTPW + WDTHOLD;                 // Stop WDT
  P1DIR |= BIT2+BIT3;                       // P1.2 and P1.3 output
  P1SEL |= BIT2+BIT3;                       // Selecting desired pins:  P1.2
                                            // physical pin 36) and P1.3 (physical pin 37)
  TA0CCR0 = 10000-1;                        // PWM Period:
                                            // Set to 10,000 us or 10 ms (Frequency = 100 Hz)
  TA0CCTL1 = OUTMOD_7;                      // CCR1 reset/set
  TA0CCR1 = 10;                             // CCR1 PWM duty cycle
                                            // (high time set to 10 us by selecting a 0.1%
                                            // duty cycle.  This is fed to pin 36)
  TA0CCTL2 = OUTMOD_7;                      // CCR2 reset/set
  TA0CCR2 = 5000;                           // CCR2 PWM duty cycle (duty cycle = 50%;
                                            // therefore, high time = 5000 us.
                                            // This is fed to pin 37)
  TA0CTL = TASSEL_2 + MC_1 + TACLR;         // SMCLK, up mode, clear TAR

  __bis_SR_register(LPM0_bits);             // Enter LPM0 (Low Power Mode)
  __no_operation();                         // For debugger
}
// End of the main method
```

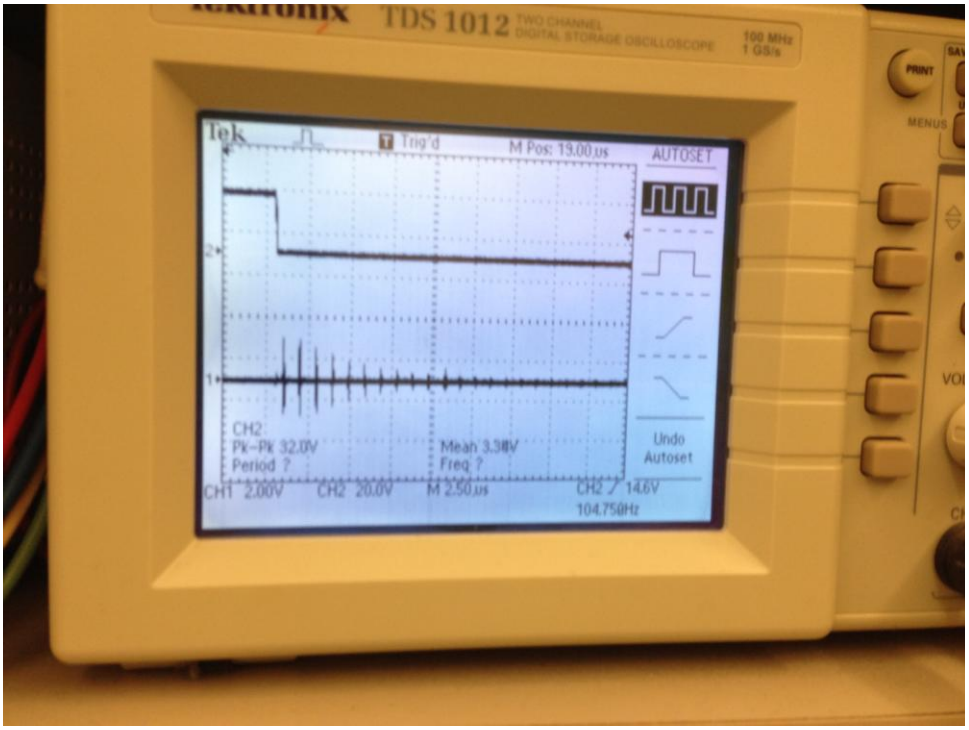
# Appendix B.

## Echo Signals Results and Analysis

This appendix provides more results and figures that correspond to various tests performed using the ultrasonic vein detection device.

Figure 8-1 illustrates the echo signals generated from a 3 mm thick aluminum block utilizing the V205-RM transducer. As evident, over time, the echo signals reduce in amplitude. This is due to the fact that the ultrasound waves keep colliding with the front and back walls of the aluminum block. During each collision, the amplitude reduces in voltage due to the loss in energy. This phenomenon is clearly illustrated in the following figure.

***Figure 8-1. V205-RM Echo Signal (3 mm thick Aluminum Block)***



In addition, Figure 8-2 represents a similar graph with the echo signals zoomed to improve the illustration. Again, as evident, the echo signals keep colliding with the walls of the target material until they disappear completely due to the loss in the signal amplitude.

*Figure 8-2.  V205-RM Echo Signals (3 mm thick Aluminum Block-Zoomed)*

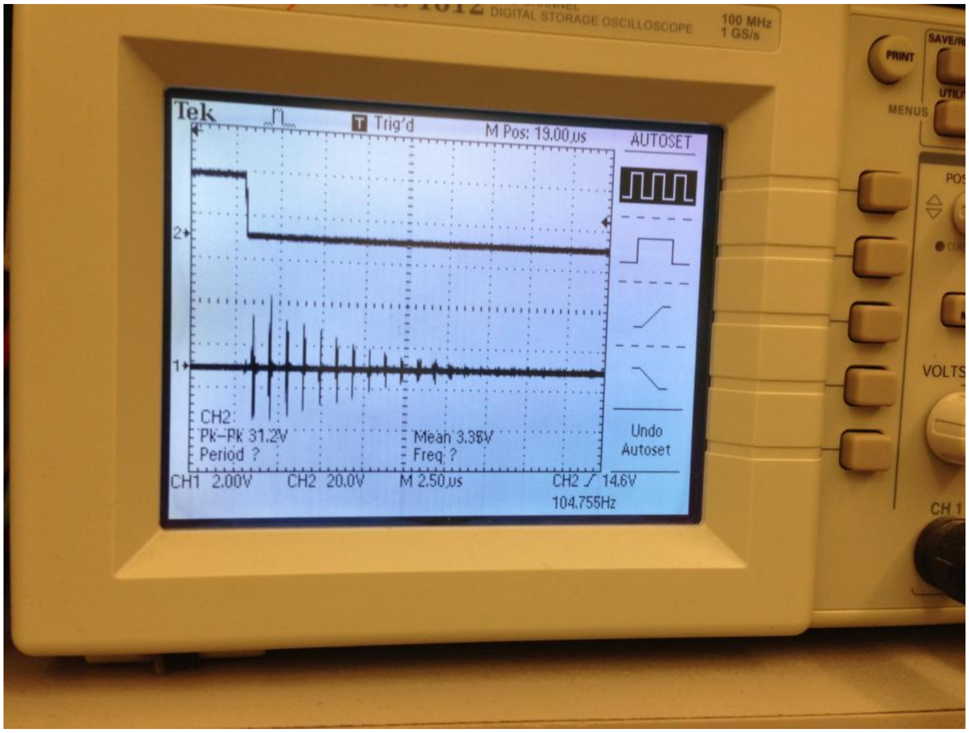


*Figure 8-3.  Sonopen V260-SM Echo Signals (3 mm thick Aluminum Block)*

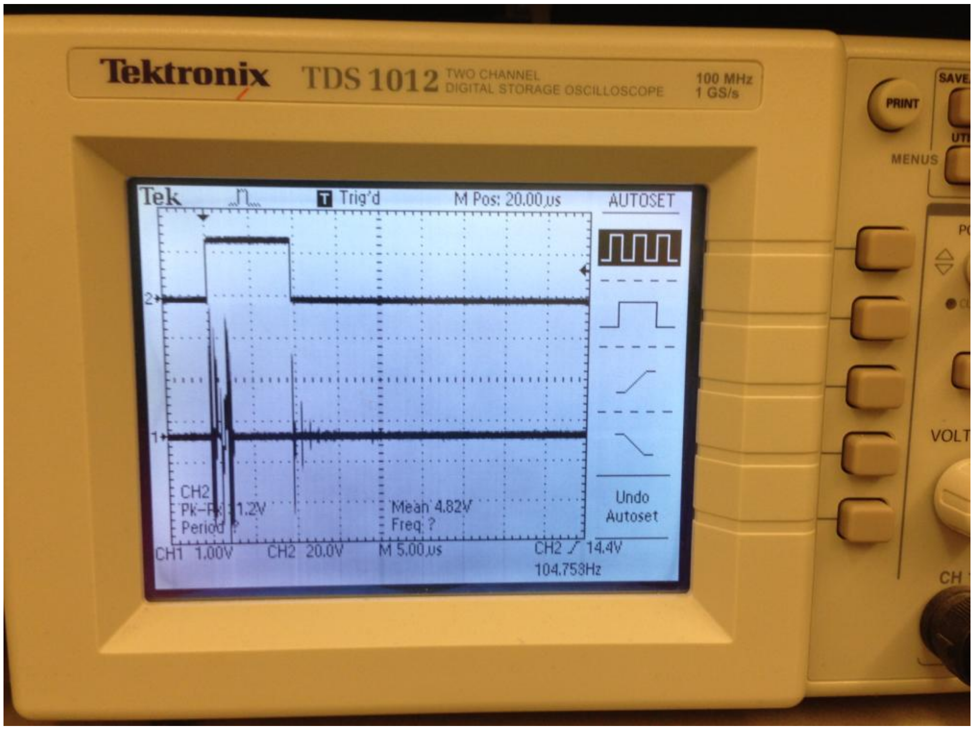


Figure 8-3 represents the received echo signals from the same target material utilizing the Sonopen transducer. One of the main advantages of using Sonopen is its small tip diameter size which results in an increase in the resolution of the signals. However, as mentioned previously, the small diameter size bears the disadvantage of difficulty in handling the device. By zooming the oscilloscope, the echo signals can be identified more clearly. In fact Figure 8-4 is the clone of Figure 8-3 with the slight difference of zooming into the received signals. Evidently, by doing so, the echo signals are much more clear to identify.

***Figure 8-4. Sonopen V260-SM Echo Signals (3 mm thick Aluminum Block-Zoomed)***