Design of a Wearable Ultrasound System

by

Philip Joseph Cordeiro

A Thesis

Submitted to the Faculty

Of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in

Electrical Engineering

by

Phil Cordeiro

August 2006

APPROVED:

Prof. Peder C. Pedersen, Major Advisor

Associate Prof. R. James Duckworth, Committee Member

David Cyganski

Prof. David Cyganski, Committee Member

Abstract

Ultrasound imaging is a safe and powerful tool for providing detailed still and moving images of the human body. Most of today's ultrasound systems are housed on a movable cart and designed for use within a clinical setting, such as in a hospital or doctor's office. This configuration hinders its use in locations lacking controlled environments and stable power sources. Example locations include ambulances, disaster sights, war zones and rural medicine.

A wearable ultrasound system, in the form of a vest worn by a sonographer, has been developed as a complete solution for performing untethered ultrasound examinations. The heart of the system is an enclosure containing an embedded computer running the Windows XP operating system, and a custom power supply. The power supply integrates a battery charger, a switching regulator, two linear regulators, a variable speed fan controller and a microcontroller providing an interface for monitoring and control to the embedded computer. Operation of the system is generally accomplished through the use of voice commands, but it may also be operated using a hand-held mouse. It is capable of operating for a full day, using two batteries contained in the vest.

In addition, the system has the capability to wirelessly share live images with remote viewers in real-time, while also permitting full duplex voice communication. An integrated web-server also provides for the wireless retrieval of stored images, image loops and other information using a web-browser.

Preface

I would like to acknowledge the assistance of the Telemedicine and Advanced Technology Research Center (TATRC) in providing invaluable resources throughout the duration of this research. In addition, the diligent work and effort provided by the Informatics staff and Army medical professionals at Madigan Army Medical Center (MAMC) has helped to make this research a success.

The tutelage and mentoring provided by Professor Peder C. Pedersen and Professor R. James Duckworth has been fundamental to the success of this work and is greatly appreciated. Also, the craftsmanship provided by Robert Boisse contributed immensely to the quality and reliability of the final design.

Table of Contents

1 Introduction 1
  1.1 Ultrasound Imaging Primer 3
  1.2 Ultrasound Applications 15
  1.3 Portable Ultrasound 16
  1.4 Motivation and Justification 19
2 Wearable Ultrasound 21
  2.1 Introduction to Wearable Ultrasound 21
  2.2 Architecture 22
  2.3 Requirements 26
    2.3.1 Enclosure Requirements 27
    2.3.2 Enclosure Connector Requirements 27
    2.3.3 Power Supply Requirements 28
    2.3.4 Embedded Computer Requirements 29
    2.3.5 Software 29
  2.4 Development History 30
3 Embedded Computing Platform 33
  3.1 Embedded Computer 33
    3.1.1 PC/104 Standards 33
    3.1.2 Embedded Computer Selection 35
    3.1.3 IEEE 1394a Selection 37
    3.1.4 Hard Disk Drive Selection 37
    3.1.5 IEEE 802.11b/g Selection 38
  3.2 EDCM Integration 38
  3.3 Enclosure Design 39
    3.3.1 Internal Arrangement 43
    3.3.2 Enclosure Connectors 49
    3.3.3 Enclosure Assembly 50
4 Power Supply and Management 54
  4.1 Justification 54
  4.2 Introduction 56
  4.3 Smart Battery System Manager 58
  4.4 Li-Ion Rechargeable Batteries 63
  4.5 5V Switching Regulator 66
  4.6 Linear Regulators 70
  4.7 SMBus to RS-232 Host Interface 72
  4.8 Fan Controller 78
  4.9 Power Supply PCB Design 80
  4.10 IEEE 1394a Power Supply 82
  4.11 User Interface 83
5 Speech Recognition 88
  5.1 Background 88
  5.2 Implementation 92
    5.2.1 Speech Recognition Initialization 92
    5.2.2 Speech Recognition Runtime 95

5.3 User Interface 99
5.4 Terason Application Integration 103
5.5 Patient Information 105
5.6 Array Microphone 107
6 Remote Data Facilities 108
6.1 Physical Layer 108
6.2 Transport Layer 109
6.3 Real-Time Transport Protocol 111
6.4 Real-Time Ultrasound Imaging 115
6.5 Voice Communications 123
6.6 Remote Administration 125
7 Logging 129
7.1 Logging Method 129
7.2 Logging Data Store 131
7.3 Data Analysis 137
8 System Integration 146
8.1 Hardware Integration 146
8.2 Software Integration 149
8.3 User Integration 151
9 Technical Performance 153
9.1 Battery Charger 153
9.2 5 V Switching Regulator 163
9.3 Embedded Computing Platform Thermals 166
9.4 Speech Recognition 168
9.5 Specifications 172
10 Clinical Usage and Value 174
10.1 Applications 175
10.1.1 Telemedicine 175
10.1.2 Disaster Relief 176
10.1.3 Medical Transport 177
10.1.4 Rural Healthcare 178
10.1.5 Military 178
10.2 Out-of-Box Experience 179
11 Conclusion and Further Work 182
References 191
Appendix I – Bill of Materials 194
Appendix II – Internal Cable Assemblies 198
Appendix III – External Cable Assemblies 205
Appendix IV – Schematics 209
Appendix V – PCB Layout 211
Appendix VI – Speech Recognition Grammar 214
Appendix VII – Database Schema 216
Appendix VIII – Training Video Scripts 218

Table of Figures

Fig. 1: Sample A-Mode Image [2]....4
Fig. 2: Early B-Mode Ultrasound Machine [2]....6
Fig. 3: Early B-Mode Ultrasound Image [3]....6
Fig. 4: M-Mode Ultrasound Image [4]....7
Fig. 5: Pulsed Wave Doppler Ultrasound Image [4]....8
Fig. 6: Power Doppler Ultrasound Image [4]....9
Fig. 7: Color Doppler Ultrasound Image [4]....10
Fig. 8: 3D Volume Image [5]....11
Fig. 9: Rendered 3D Volume Image [6]....12
Fig. 10: 4D Ultrasound Image [7]....13
Fig. 11: 4-2 MHz Convex Array Transducer [4]....14
Fig. 12: 10-5 MHz Linear Array Transducer [4]....14
Fig. 13: 10-5 MHz Phased Array Transducer [4]....14
Fig. 14: 3.5 MHz Ultrasound Image [8]....15
Fig. 15: 5 MHz Ultrasound Image [8]....15
Fig. 16: GE LOGIQ 9 [9]....16
Fig. 17: SonoSite 180 Plus [10]....17
Fig. 18: Example Portable Ultrasound Machines....18
Fig. 19: Terson 2000 SmartProbe....22
Fig. 20: Head Mounted Displays....24
Fig. 21: Trackball Mouse....24
Fig. 22: Block Diagram of WUC....25
Fig. 23: First Generation WUC....30
Fig. 24: Second Generation Embedded Computer, Power Supply and Enclosure...31
Fig. 25: PC/104-Plus Board Stackup [21]....34
Fig. 26: Lippert-AT Cool RoadRunner 4 [23]....36
Fig. 27: Advanced Digital Logic MSM855 [24]....36
Fig. 28: EDCM Enclosure....39
Fig. 29: EDCM PCB....39
Fig. 30: Embedded Computer Enclosure....40
Fig. 31: Enclosure Components....41
Fig. 32: Dimensioned Embedded Computer Enclosure Drawing....43
Fig. 33: Two Compartments of Enclosure....44
Fig. 34: Top Compartment of Enclosure....44
Fig. 35: CPU Board and IEEE 1394a Board Assembly....46
Fig. 36: Power Supply and HDD Assembly....47
Fig. 37: Two Internal Assemblies....47
Fig. 38: EDCM Mounting in Enclosure....48
Fig. 39: Complete Internal Assembly of Lower Compartment....48
Fig. 40: Cable Strain Relief Alcove....49
Fig. 41: Enclosure Connector Model....50
Fig. 42: Step One of Assembling the Enclosure....51
Fig. 43: Step Two of Assembling the Enclosure....52
Fig. 44: Enclosure....52

Fig. 45: OceanServer Battery Charger and ATX Power Supply [28,29] 55
Fig. 46: 1/8 Brick DC-DC Converter [30] 55
Fig. 47: Block Diagram of Power Supply 57
Fig. 48: Example Smart Battery system [32] 59
Fig. 49: Power Path Switch 62
Fig. 50: Inspired Energy NL2024A22 Rechargeable Li-Ion Battery 65
Fig. 51: Block Diagram of Smart Battery Pack [37] 66
Fig. 52: Power Supply Reference Design [39] 68
Fig. 53: Output Voltage Adjustment of Linear Voltage Regulator 71
Fig. 54: Power Supply SMBus Block Diagram 74
Fig. 55: Generic SMBus Topology [40] 75
Fig. 56: SMBus START and STOP Conditions [40] 75
Fig. 57: SMBus Protocols 76
Fig. 58: Host SMBus Command Packet 77
Fig. 59: Local Temperature Sensor Control Loop 80
Fig. 60: Remote Temperate Sensor Control Loop 80
Fig. 61: Populated Power Supply PCB 81
Fig. 62: Dashboard 84
Fig. 63: Power supply area of the Dashboard 84
Fig. 64: Low Battery Warning Indicator 86
Fig. 65: Power Supply Dialog Box 86
Fig. 66: Context Creation 93
Fig. 67: Speech Recognition System Runtime 95
Fig. 68: Circular Buffer 96
Fig. 69: WPI Application Overview 98
Fig. 70: Push-To-Talk Button 99
Fig. 71: Speech Recognition States 100
Fig. 72: Successful Recogntion of “live image” 101
Fig. 73: Poor Recognition of “power doppler” 101
Fig. 74: ASR Details Dialog Box 102
Fig. 75: View Utterances Dialog Box 103
Fig. 76: Shutdown Dialog Box 105
Fig. 77: Shutdown Progress Dialog Box 105
Fig. 78: Patient Information Dialog Box 106
Fig. 79: Patient Information Header 106
Fig. 80: Linear Array Microphone 107
Fig. 81: Linear Array Microphone Directional Sensitivity 107
Fig. 82: OSI Reference Model [43] 108
Fig. 83: RTP Network Stack 112
Fig. 84: Buffer Backed GUI 119
Fig. 85: Lost Image Tile 119
Fig. 86: RID Without Client 121
Fig. 87: RID With Client Connected 121
Fig. 88: RID Client Connection Dialog Box 122
Fig. 89: RID Client Application 122
Fig. 90: Web Server Home Page 126

Fig. 91: User's Guide on Web Server 126
Fig. 92: Saved Images on Web Server 127
Fig. 93: Data Analysis Application Connection Dialog 138
Fig. 94: Database Analysis Application Database Menu 139
Fig. 95: Database Analysis Application View Menu 140
Fig. 96: Database Analysis Application Filters Menu 141
Fig. 97: Date Filter Dialog Box 141
Fig. 98: Database Analysis Program Utterance View 142
Fig. 99: Database Analysis Program Word Occurrence View 143
Fig. 100: Database Analysis Program ASR Errors View 144
Fig. 101: Temperatures View Plot 145
Fig. 102: Vest Front 146
Fig. 103: Vest Back 146
Fig. 104: Vest Component Layout 148
Fig. 105: Single Smart Battery Relative Charge Capacity vs. Time While Charging 154
Fig. 106: Manufacturer Single Cell Charge Characteristics [37] 155
Fig. 107: Single Smart Battery Charge Characteristics 156
Fig. 108: Single Smart Battery Relative Charge Capacity vs. Time While Discharging 157
Fig. 109: Single Smart Battery Discharge Characteristics 157
Fig. 110: Smart Battery Charger Switching Regulator Providing 3 A (DC Coupled) 160
Fig. 111: Smart Battery Charger Switching Regulator Providing 3 A (AC Coupled) 161
Fig. 112: Smart Battery Charger Switching Regulator Providing 0.5 A (DC Coupled) 162
Fig. 113: Smart Battery Charger Switching Regulator Providing 0.5 A (AC Coupled) 163
Fig. 114: 5 V Switching Regulator with 35 W Load (DC Coupled) 164
Fig. 115: 5 V Switching Regulator with 35 W Load (AC Coupled) 165
Fig. 116: 5 V Switching Regulator with No Load (DC Coupled) 166
Fig. 117: Temperature Testing 167
Fig. 118: Utterance Frequency 169
Fig. 119: Average Utterance Confidence 170
Fig. 120: Sonosite MicroMaxx [55] 174
Fig. 121: Bag Based Ultrasound System 189
Fig. 122: Cable Length Measurement 198
Fig. 123: Cable Length Measurement Example 198
Fig. 124: Cable Length Measurement 205
Fig. 125: Cable Length Measurement Example 205
Fig. 126: Top Silkscreen 211
Fig. 127: Top Copper 211
Fig. 128: Layer 2 Copper 212
Fig. 129: Layer 3 Copper 212
Fig. 130: Bottom Copper 213

Fig. 131: Bottom Silkscreen (horizontally mirrored) 213
Fig. 132: Database Schema 217

Table of Tables

Table 1: Component Terminology 25
Table 2: Available CPUs for MSM855 36
Table 3: Properties of Delrin [27]...42
Table 4: Power Requirements for WUC Components 57
Table 5: Power Requirements by Regulated Voltage 58
Table 6: Characteristics of Commonly Used Rechargeable Batteries [36]...............63
Table 7: Attributes of Linear and Switching Regulators [38].........................67
Table 8: SMBus Memory Map...74
Table 9: SMBus Protocol Mnemonics 76
Table 10: PCB Design Rules...81
Table 11: Speech Recognition Engine Types 88
Table 12: Chomsky Hierarchy 90
Table 13: WUC Application Defined Messages..130
Table 14: MySQL Numeric Data Types...132
Table 15: MySQL Binary Data Types..133
Table 16: MySQL String Data Types...133
Table 17: tblPackets Definition..133
Table 18: tblIMessages Definition 134
Table 19: tblUtterance Definition 134
Table 20: tblWords Definition 135
Table 21: tblAudio Definition 135
Table 22: tblBattery Definition 136
Table 23: tblCPUTemp Definition..136
Table 24: tblErrors Definition...137
Table 25: tblImages Definition...137
Table 26: Software Components...149
Table 27: Training Videos 152
Table 28: WUC Specifications...173
Table 29: Power Supply Bill of Materials...194
Table 30: Embedded Computer Bill of Materials 195
Table 31: Internal Cable Bill of Materials...196
Table 32: External Cable Bill of Materials 196
Table 33: Assembly Bill of Materials 196
Table 34: Internal 802.11g Cable Assembly...199
Table 35: Internal Audio Cable Assembly 199
Table 36: Internal Battery 1 Cable Assembly 199
Table 37: Internal Battery 2 Cable Assembly 200
Table 38: Internal Charger Cable Assembly...200
Table 39: Internal CMOS Battery Cable Assembly 200
Table 40: Internal Fan Power Cable Assembly 201
Table 41: Internal HDD Cable Assembly..201
Table 42: Internal IEEE 1394a Auxiliary Power Cable Assembly..................201
Table 43: Internal IEEE 1394a Cable Assembly 202
Table 44: Internal Mouse Cable Assembly...203

Table 45: Internal MSM855 CPU Power Cable Assembly 203
Table 46: Internal Power Switch Cable Assembly 203
Table 47: Internal Temperature Probe Cable Assembly 204
Table 48: Internal USB Cable Assembly.. 204
Table 49: Internal VGA Cable Assembly.. 204
Table 50: External VGA Cable Assembly 206
Table 51: External Audio Cable Assembly... 206
Table 52: External Mouse Cable Assembly 207
Table 53: External USB Cable Assembly... 207
Table 54: External Battery 1 Cable Assembly.. 207
Table 55: External Battery 2 Cable Assembly.. 208
Table 56: External Charger Cable Assembly 208
Table 57: MySQL and ODBC Data Type Mappings... 216

Table of Abbreviations

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional (Three-Dimensional plus time)
A	Ampere
Ah	Ampere-hours
A-Mode	Amplitude Mode
API	Application Programming Interface
ATA	American Telemedicine Association
AWG	American Wire Gauge
B-Mode	Brightness Mode
CAT	Computer Aided Tomography
CFM	Cubic Feet per Minute
cm	Centimeter
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CSH	Combat Surgical Hospital
CSV	Comma Separated Values
dB	Decibel
dBA	Decibel (A weighted)
DCR	DC resistance
DDK	Driver Development Kit
°C	Degrees Celsius
°F	Degrees Fahrenheit
FET	Field Effect Transistor
DLL	Dynamic Link Library
DC	Direct Current
EL	Energy Level
EDCM	External DC Module
fps	frames per second
ft.	foot
g	Acceleration due to gravity (9.8 m/s^2 [32.2 $ft./s^2$])
g	gram
GB	Giga-Byte (1,073,741,824 Bytes)
GHz	Giga-Hertz
GSM	Global System for Mobile communications
HDD	Hard Disk Drive
HMD	Head-Mounted Display
ICU	intensive care unit
IDE	Integrated Drive Electronics
IETF	Internet Engineering Task Force
in.	Inch
IP	Internet Protocol

ISA	Industry Standard Architecture
ITU	International Telecommunication Union
kB	kilo-Byte (1,024 Bytes)
kb/s	kilo-bits per second
kg	kilogram
kHz	kilo-Hertz
L2	Level-2
Lb.	Pound
Lbs.	Pounds
mA	milli-Ampere
MAMC	Madigan Army Medical Center
min.	minute
m	meter
M-Mode	Motion Mode
MB	Mega-Byte (1,048,576 Bytes)
MB/s	Mega-Bytes per second
Mb/s	Mega-bits per second
MHz	Mega-Hertz
μ	micro (10^{-6})
mm	millimeter
mΩ	milli-Ohm
MRI	Magnetic Resonance Imaging
μF	micro-Farad
μs	microsecond
ms	millisecond
mV	milli-Volt
nm	nanometer
ODBC	Open Database Connectivity
Ω	Ohm
OS	Operating System
OSI	Open Systems Interconnection
oz.	Ounce (1/16 Lb.)
PACS	Picture Archiving and Communication System
PCB	Printed Circuit Board
PCI	Peripheral Component Interconnect
PCM	Pulse-Code Modulation
PSTN	Public Switched Telephone Network
PTT	Push-To-Talk
RFC	Request For Comment (IETF standards document)
RID	Remote Imaging Daemon
ROI	Region Of Interest
RPELPC	Regular Pulse Excited – Linear Predictive Coder
RPM	Revolutions Per Minute
SBS-IF	Smart Battery System Implementer’s Forum
SDK	Software Development Kit
SMBus	System Management Bus

SNR	Signal to Noise Ratio
SOAP	Simple Object Access Protocol
SQL	Structured Query Language
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
UART	Universal Asynchronous Receiver/Transmitter
UDP	User Datagram Protocol
USB	Universal Serial Bus
V	Volt
VGA	Video Graphics Array
VoIP	Voice over Internet Protocol
W	Watt
Wh	Watt-hours
WUC	Wearable Ultrasound Computer
XML	Extensible Markup Language

1 Introduction

Currently, there are several major imaging technologies used in medicine. While each has the capability of producing two-dimensional (2D) images of cross sections of the human body, or even three-dimensional (3D) volumetric images without the need to perform surgery, each also has its own unique advantages and disadvantages.

Different imaging modalities use different methods to produce these images. For instance, X-Rays and Computer Aided Tomography (CAT) scans use ionizing radiation to penetrate the human body and record the resulting absorption pattern using a detector, such as photographic film or by using electronic methods. Magnetic Resonance Imaging (MRI) uses a combination of strong magnetic fields and radio frequency (RF) energy to produce images. Each of these imaging modalities has its own unique sensitivity to different anatomies and tissues found within the human body.

The suitability of X-Ray, CAT scans and MRI imaging modalities, for portable applications, is severely hindered by either the physical size or power requirements of the imaging apparatus. Ultrasound is uniquely suited to portable imaging applications due to its low power requirements and its use of sound energy. Using sound energy to image the human body is also generally considered safer than using ionizing radiation.

This thesis involves the adaptation of portable ultrasound into a new wearable form-factor. A wearable form-factor, along with other design improvements, addresses some of the shortcomings of the current generation of portable ultrasound machines. The remainder of this thesis presents the design of a wearable, untethered ultrasound system. The key features of the system are: a wearable form factor, untethered operation, voice-activated command and control, one-handed operation, wireless communications and a head mounted display. A complete overview of wearable ultrasound is presented in Section 2.

The majority of the work this thesis work involved systems integration. Wherever possible, commercially availably products were used to complete the design. However, commercial products were not always suited to the unique requirements of producing a wearable ultrasound system, and some amount of custom design work was necessary. To this end, a power supply and enclosure were designed.

The power supply, which is detailed in Section 4, provides power for every device that comprises the wearable ultrasound system. It is housed with an ergonomically designed enclosure that is designed to sit comfortably against the back of the person wearing the system. In addition to the power supply, the enclosure houses an embedded computer, which is detailed in Section 3, and a wireless network interface. The applications for the wireless network interface are described in Section 6.

In addition to the unique hardware that was required to make this thesis a reality, several software applications were written. The main piece of software provides speech recognition functionality, which is detailed in Section 5. Additionally, this software also provides much of the remote services functionality, which is described in Section 6. Finally, it provides for extensive data logging capabilities, as described in Section 7.

In addition to the hardware and software that was developed, there were also training materials provided to first-time users of the system. This training material includes both written manuals and short videos. This material is discussed in Section 8.

Section 9 details he technical performance of both the hardware and software that was designed for the system; and Section 10 discusses the clinical applications for the system, as well as the conclusions that were drawn from clinical testing.

A primary goal of this thesis research was to provide units for clinical evaluation at Madigan Army Medical Center (MAMC) in Tacoma, WA. To this end, a total of four complete systems were built and tested in the Vascular and Emergency departments in the hospital. Section 11 presents an evaluation of the performance of the system in a real clinical setting, as well as some valuable lessons that were learned during the trials.

1.1 Ultrasound Imaging Primer

Ultrasound works by emitting impulses of sound energy into the human body. This impulse travels as a thin beam through the body and is reflected at tissue interfaces. By detecting the echoes from the original sound wave, an image can be reconstructed from which information about the tissues can be determined. A close analogy of this is clapping your hands in an empty room. The sound produced by a hand clap is an impulse. This impulse is then reflected off the various surfaces in the room until it eventually reaches your ears. The reflections probably sound different than the original sound produced by the clap, and these differences can be used to interpret characteristics about the room. For instance, a room with a large open door will sound different than that same room with the door closed. While ultrasound uses a directional beam of sound energy, and a clap produces an omnidirectional wave of sound energy, the underlying principal is the same.

When applied to sonar, where sound energy is transmitted through water, the echoes provide a great deal of information about the surrounding environment. Radar works similarly, although radio waves are used instead of sound waves.

The use of ultrasound for imaging the human body was first performed in the late 1940’s [1]. The technological advances were facilitated by the relative abundance of surplus radar and sonar equipment from World War II. One of the first uses of ultrasound to probe the human body occurred in the early 1950’s [1]. Dr. Inge Edler and Professor Helmuth Hertz used a commercial reflectoscope to view heart motions. The primary purpose of a reflectoscope was to look for flaws in metal welds and was also called a flaw detector. It would transmit ultrasound energy into a metal weld and display the resulting reflections on an oscilloscope. Any perturbations in the displayed waveform indicated a flaw in the weld.

Edler and Hertz adapted one of these devices to produce an A-Mode ultrasound machine, where the "*A*" stands for amplitude. A-Mode produces an image containing depth information along one axis and the received echo amplitude along another. Put another way, the A-Mode image is the received ultrasound energy after being processed by an envelope detector. A sample A-Mode image of a stomach wall is shown in Fig. 1:

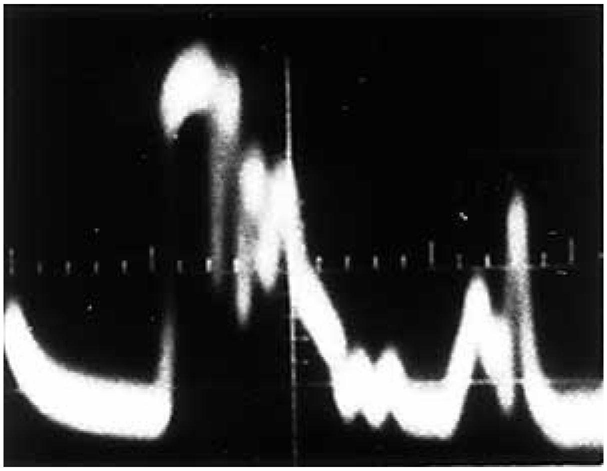


Fig. 1: Sample A-Mode Image [2]

A transducer, operating in A-Mode, consists of a single element transmitting pulses of ultrasound energy into the human body, and then receiving and amplifying the return echoes. A transducer is a device that converts energy from one form into another. Ultrasound transducers convert electrical energy into sound energy.

The next development in ultrasound was the introduction of B-Mode, where the "*B*" stands for brightness. This is an improvement upon A-Mode and introduces the concept of a scan line and a scan plane. B-Mode works by moving the single element transducer along a line or leaving it in one position and rocking it or a combination of the two. Each pulse creates a scan line whose brightness is proportional to the amplitude of the returned echo and the depth increases along the line. By combining multiple scan lines, where each scan line is a one-dimensional (1D) image, a scan plane is created. A scan plane is a complete 2D image, created from multiple scan lines. Early B-Mode machines had arms attached to the transducer so that the position and orientation of the transducer was known in order to place the scan line in the appropriate position on a display. A long exposure photograph or a storage scope was used to display the final scan plane [1]. This procedure was similar to having your portrait taken during the early years of photography. The subject could not move during the procedure as the individual scan lines were acquired. Fig. 2 shows an early ultrasound machine. Note the transducer attached to an armature. Fig. 3 shows a B-Mode image created by rocking the transducer while keeping it in the same location:

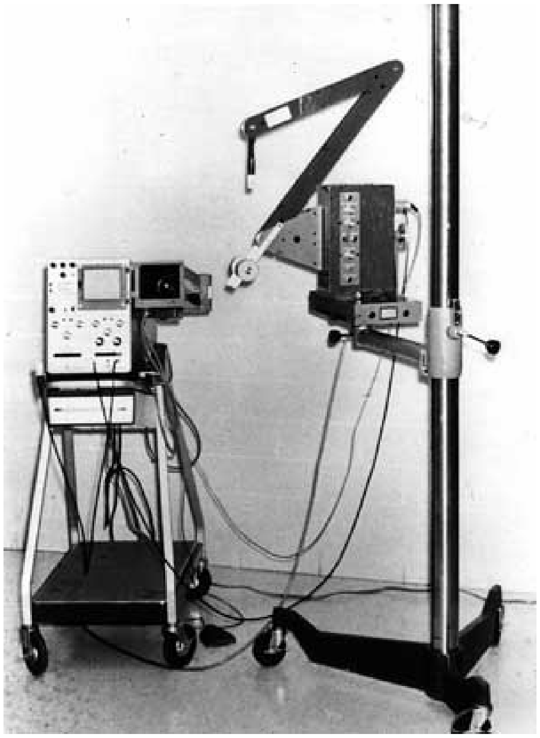


Fig. 2: Early B-Mode Ultrasound Machine [2]

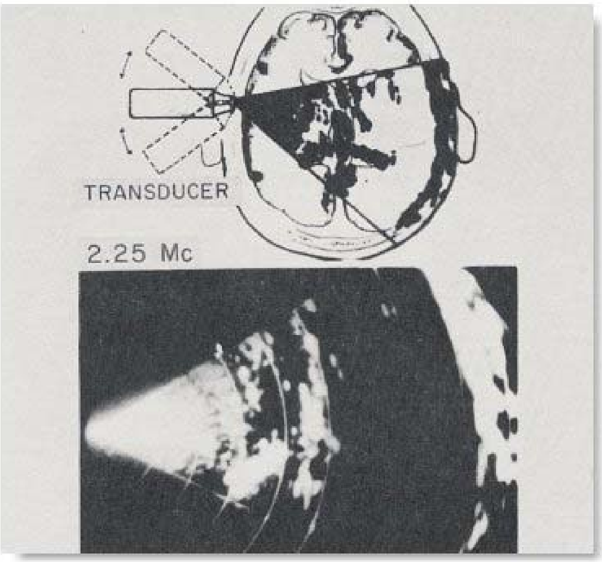


Fig. 3: Early B-Mode Ultrasound Image [3]

In the 1970's, manually sweeping the transducer (either by hand or mechanically) was replaced by incorporating a linear array of elements in the transducer, in order to electronically steer the beam. These phased array transducers use multiple elements to steer the beam and sweep the scan plane in real-time. The imaging modes, described in the following paragraphs, all use phased array transducers to acquire real-time 2D images.

Another mode of ultrasound imaging is called M-Mode, where "*M*" stands for motion. An M-Mode image is derived from a B-Mode image with a line indicating a region of interest (ROI), corresponding to a scan line. This scan line is displayed versus time in another display, showing how the structures along the chosen scan line changes over time. This is useful for studying tissues that are in motion, such as the heart. Fig. 4 shows an M-Mode image, where the scan line is indicated on the upper B-Mode image by a dashed line and the lower image is the time verses depth display of the scan line:

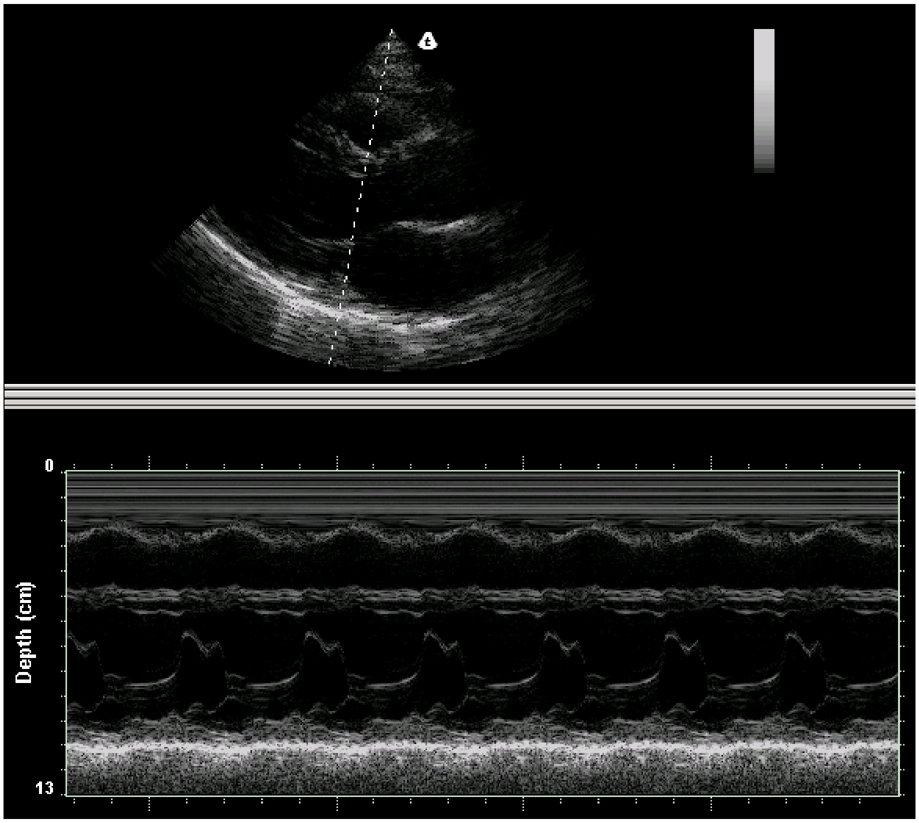


Fig. 4: M-Mode Ultrasound Image [4]

M-Mode imaging can also be accomplished with a single element transducer aimed such that the resulting scan line defines the ROI. This would result in only the time verses depth being available, without an accompanying B-Mode image.

The final set of imaging modes is a family of Doppler imaging modes. Doppler imaging takes advantage of the Doppler shift produced when the ultrasound energy encounters a moving structure. The movement of this structure will produce a Doppler shift in the frequency of the returned echoes. This is the same effect as when a person is standing still and a train goes by while sounding its horn. The horn will appear to have a higher pitch when approaching, and a lower pitch after it has passed.

Doppler imaging is mainly used to characterize blood flow in vessels and tissues, and presents this information using several methods. The first modes, called Pulsed Wave Doppler, takes advantage of the Doppler shift to present the information audibly. The ultrasound user can actually hear blood flow in a vessel and can plot the blood velocity over time. Fig. 5 shows an example of a Pulsed Wave Doppler image of the carotid artery. The ROI is indicated by the equal sign intersecting the long line and the lower image shows the time verses blood velocity.

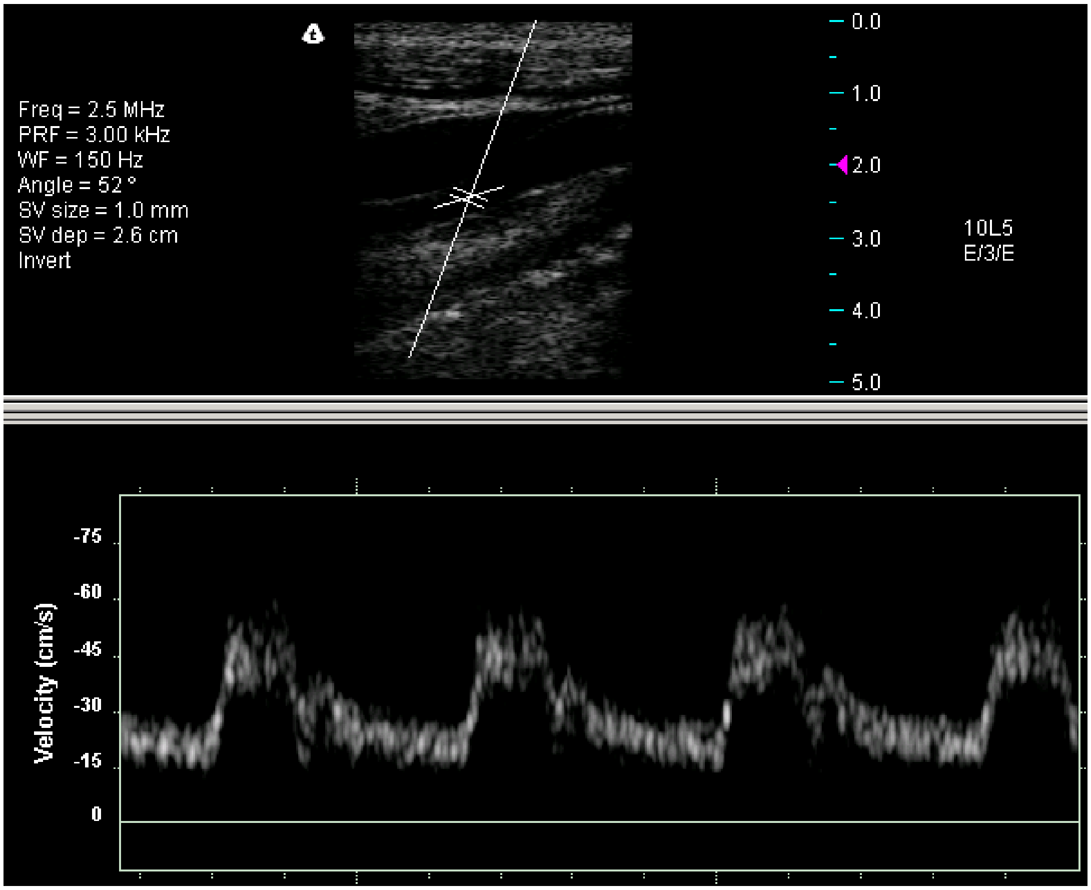


Fig. 5: Pulsed Wave Doppler Ultrasound Image [4]

Power Doppler mode can be used to show the relative density of blood. Fig. 6 shows the jugular artery with the ROI indicated by the parallelogram:

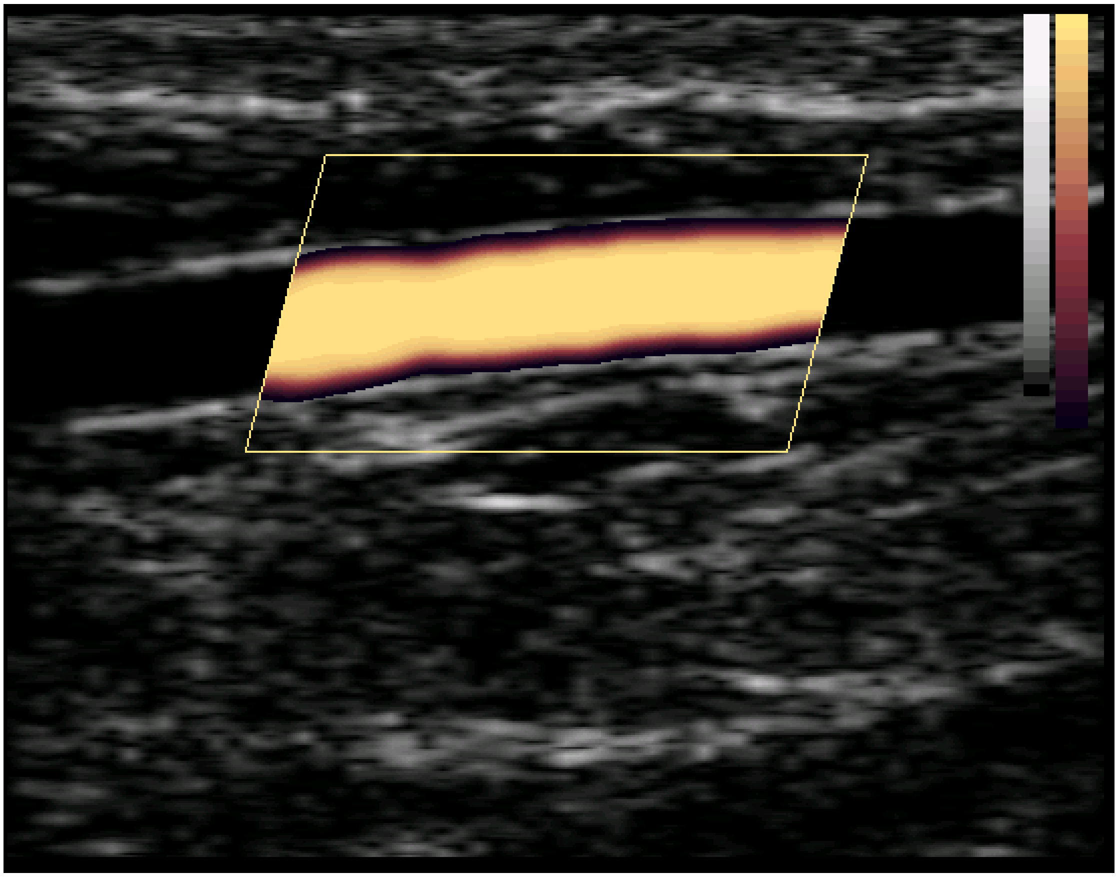


Fig. 6: Power Doppler Ultrasound Image [4]

Finally, Color Doppler imaging can be used to quantitatively determine blood velocity and direction. Fig. 7 shows an example image of the carotid artery, which has a ROI indicated by the parallelogram, with blood flowing down:

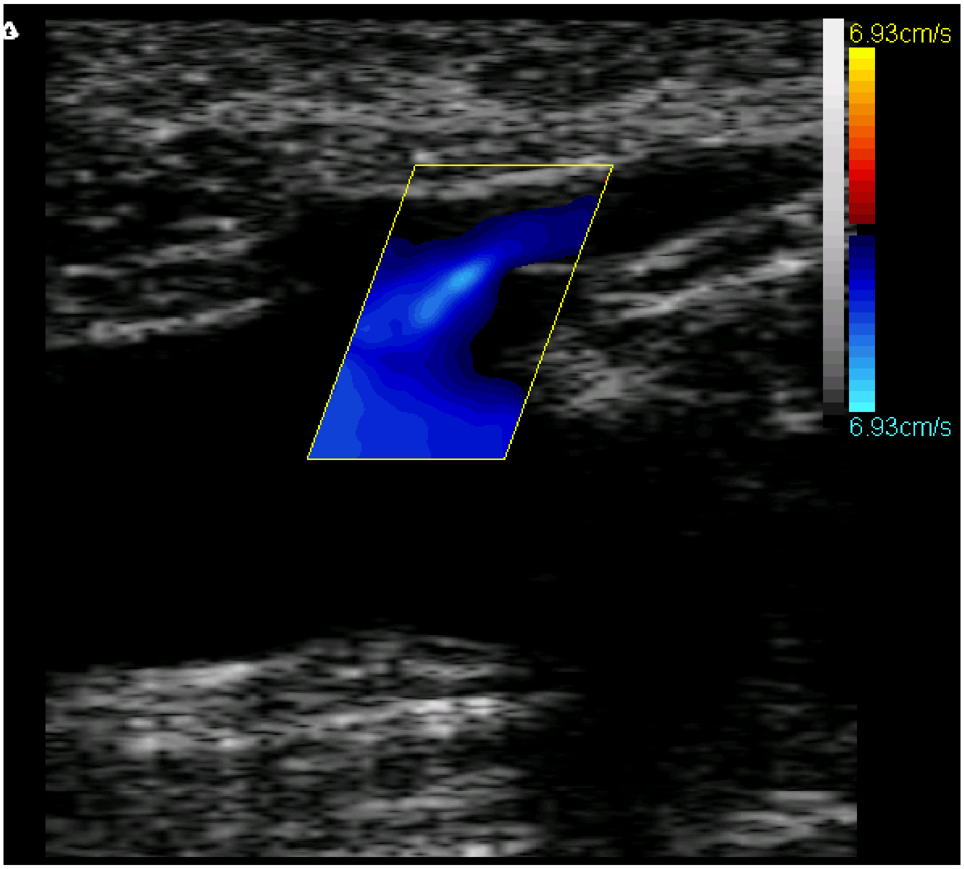


Fig. 7: Color Doppler Ultrasound Image [4]

Some machines may even have the ability to mix some of the aforementioned scan modes into hybrid displays. For example, Pulsed Wave Doppler can be combined with Color Doppler and displayed simultaneously.

A relatively recent development in ultrasound imaging is the use of three-dimensional (3D) ultrasound. 3D ultrasound involves creating three-dimensional volumes from the individual scan planes produced in traditional ultrasound imaging. This volume information can then be presented as a surface or volume rendering. To do this, a similar method to creating 2D images from a single element transducer is employed. A traditional transducer, containing a linear array of elements, is swept over the area to be imaged. An off-line reconstruction is performed to create a 3D volume from the individual scan planes acquired over the imaged area.

3D imaging creates new methods and applications for using ultrasound. Once a 3D volume is acquired, it can be viewed from any angle by slicing into it. This allows for the creation of 2D images from viewpoints not previously attainable with ultrasound. Before the introduction of 3D ultrasound imaging, ultrasound images could only be obtained from planes perpendicular to the skin. With a 3D volume available, image planes can now have any orientation. Additionally, the 3D volume can also be rendered into a 3D object, which can then be rotated for viewing from any angle. Fig. 8 shows an example 3D volume image with a plane cut into the volume:

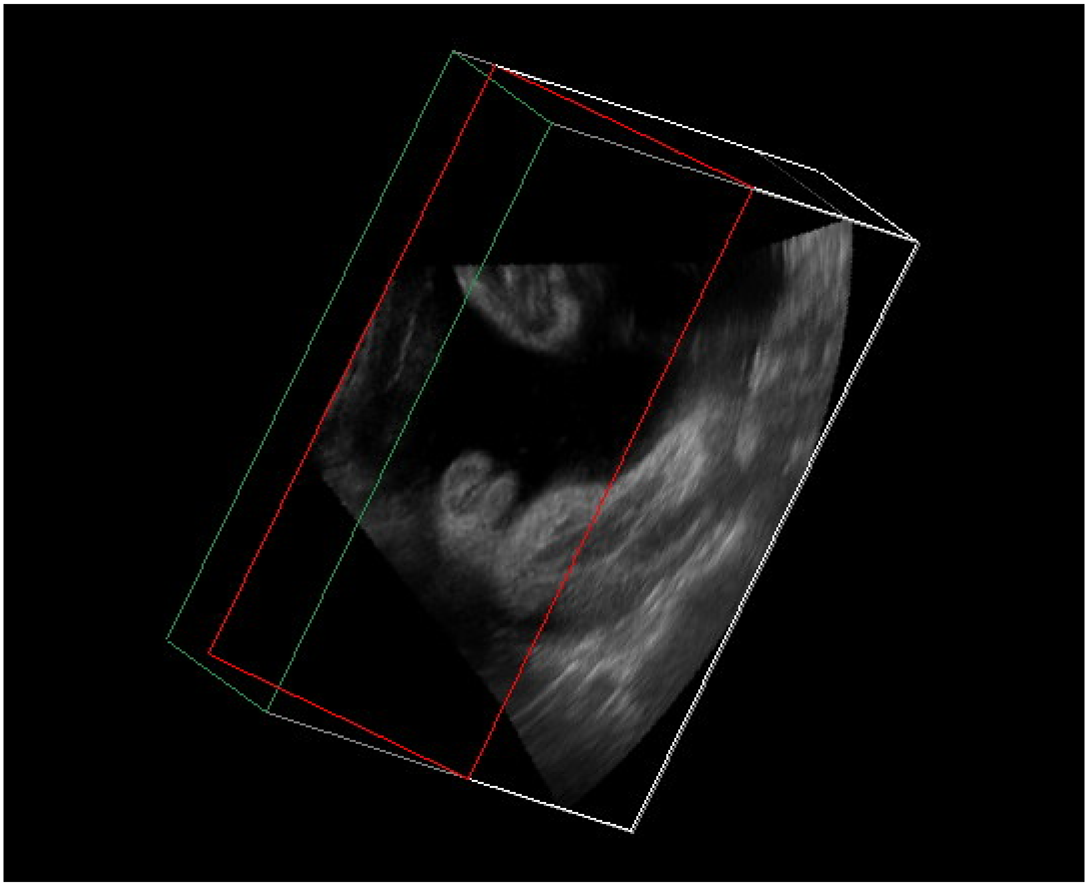


Fig. 8: 3D Volume Image [5]

Fig. 9 shows a rendered 3D volume:

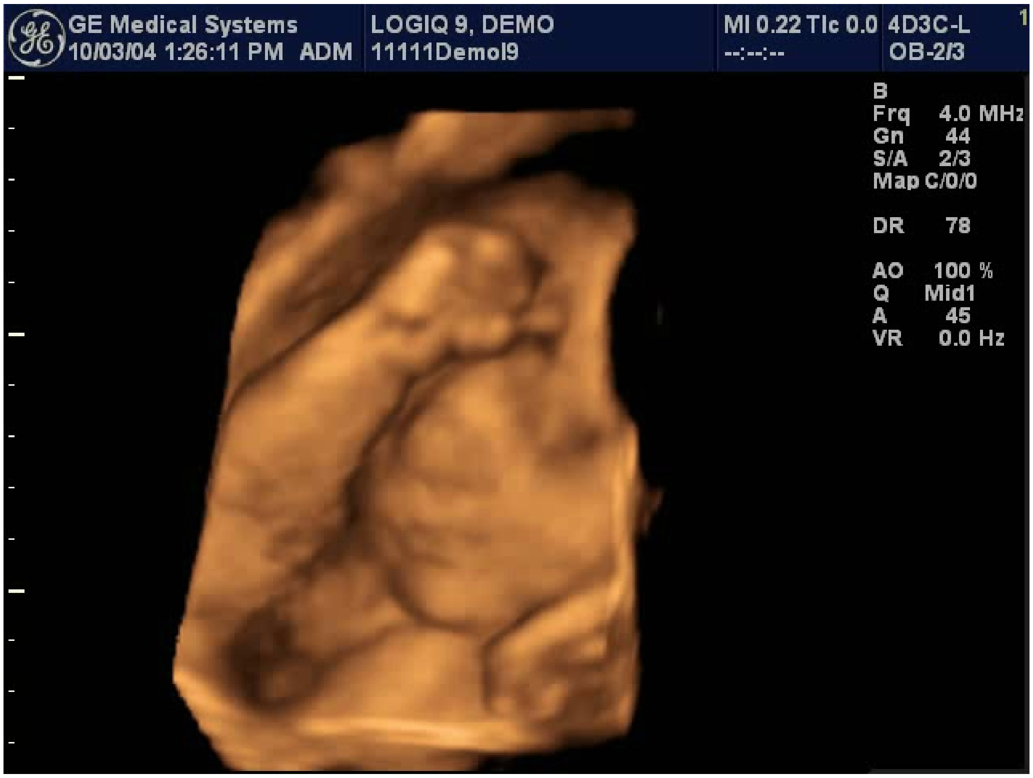


Fig. 9: Rendered 3D Volume Image [6]

The latest development in 3D imaging for ultrasound is 4D imaging. 4D imaging brings real-time imaging to 3D images. This requires the use of a transducer that uses a 2D array of elements in order to acquire 3D volumes in real-time. The 2D array transducers have many thousands of elements.

A 4D image is generally viewed by placing a marker within the volume and displaying all three orthogonal planes that intersect at that point in the volume, along with a rendering of the volume. Fig. 10 shows an example 4D ultrasound image:

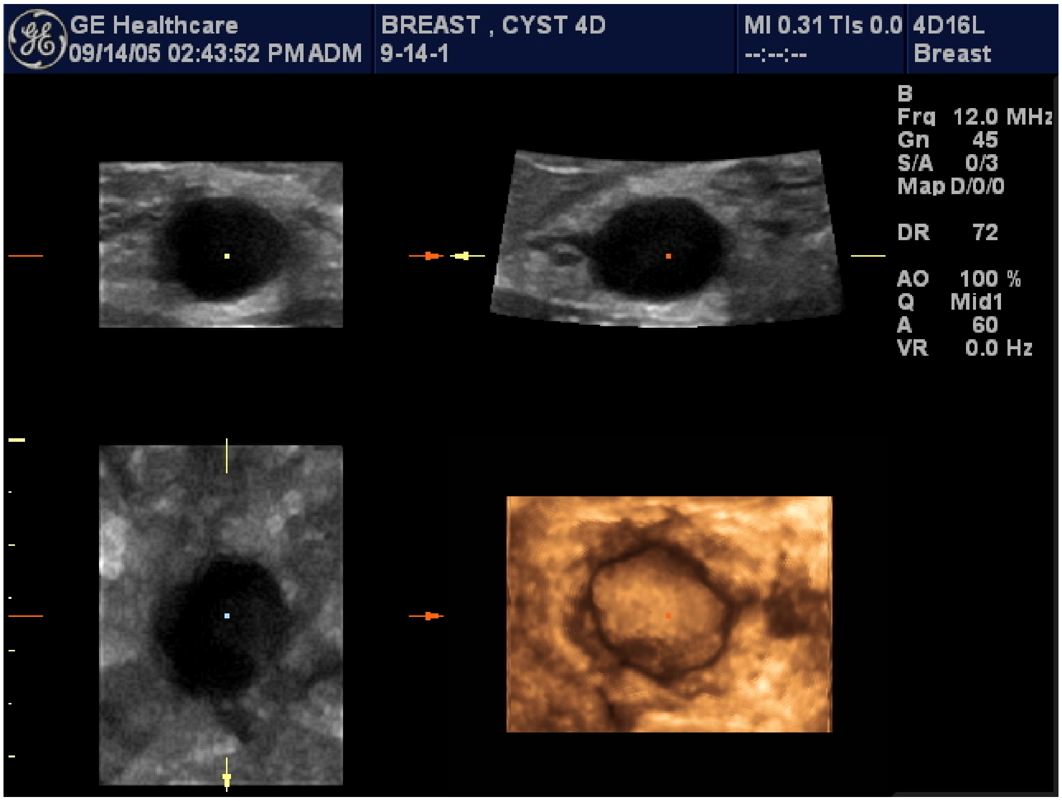


Fig. 10: 4D Ultrasound Image [7]

There are a variety of different ultrasound transducers for different exams. The transducers can vary in the number of elements contained in the transducer head, the shape of the head and the frequency range that the transducer uses for imaging. The following figures show the transducer most often employed in medical imaging:

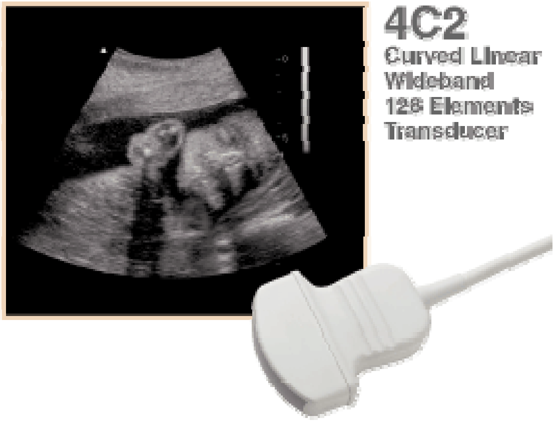


Fig. 11: 4-2 MHz Convex Array Transducer [4]

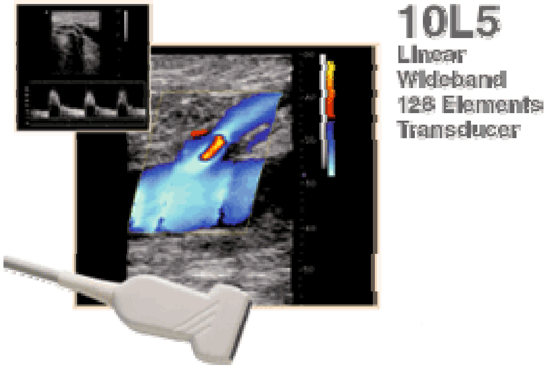


Fig. 12: 10-5 MHz Linear Array Transducer [4]

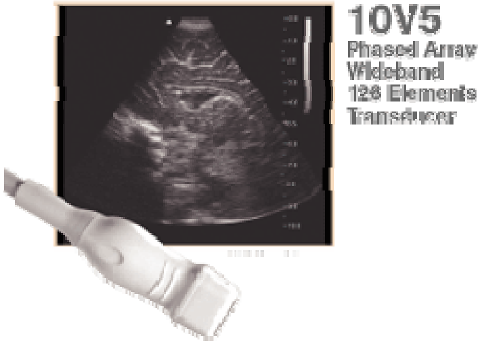


Fig. 13: 10-5 MHz Phased Array Transducer [4]

Ultrasound transducers for imaging the human body typically operate between 1 and 15 MHz. Lower frequency transducers provide for deeper tissue penetration, but have poorer resolution than higher frequency transducers. Fig. 14 and Fig. 15 each show a similar ultrasound image. The image on the left was imaged with a 3.5 MHz transducer, while the image on the right was imaged with a 5 MHz transducer:

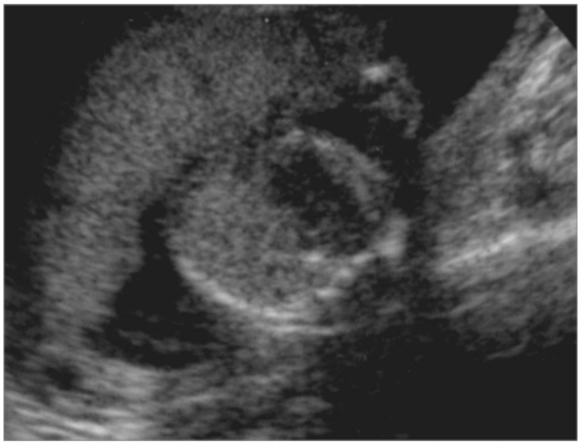


Fig. 14: 3.5 MHz Ultrasound Image [8]

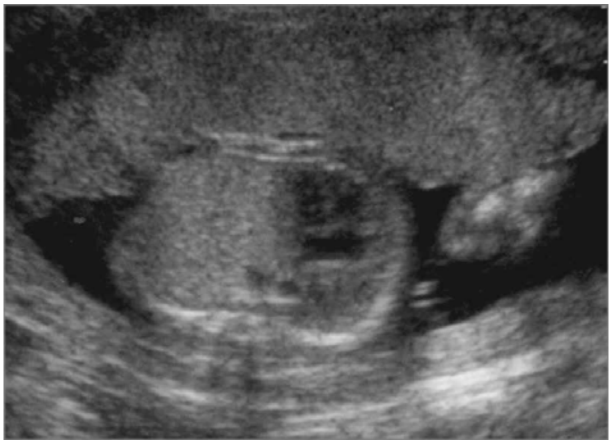


Fig. 15: 5 MHz Ultrasound Image [8]

Note the difference in resolution between the images. More detail is evident in the 5 MHz image as opposed to the 3.5 MHz image.

1.2 Ultrasound Applications

Ultrasound imaging is used in a wide variety of diagnostic examinations. It is capable of imaging soft tissues, as well as bone structures, safely and inexpensively. Ultrasound is widely used in a variety of medical fields:

- Cardiology
- Urology
- OB/GYN
- Gastroenterology
- Nephrology
- Vascular
- Abdominal
- Veterinary

Ultrasound transducers are available in a wide variety of configurations. Certain high-frequency and high-resolution transducers are even designed to be used within the body itself. These transducers are able to provide high-resolution images of structures that would not normally be so well visualized. Examples of such probes include transesophageal, transvaginal and transrectal probes for imaging structures such as the heart, uterus and prostate respectively.

1.3 Portable Ultrasound

Compared to other imaging modalities, such as MRI, CAT Scans and X-Ray, ultrasound is the most portable medical imaging modality. However, most ultrasound machines are still generally cart-based systems that require an installed infrastructure for support. Fig. 16 shows a typical ultrasound machine found in hospitals and clinics today:

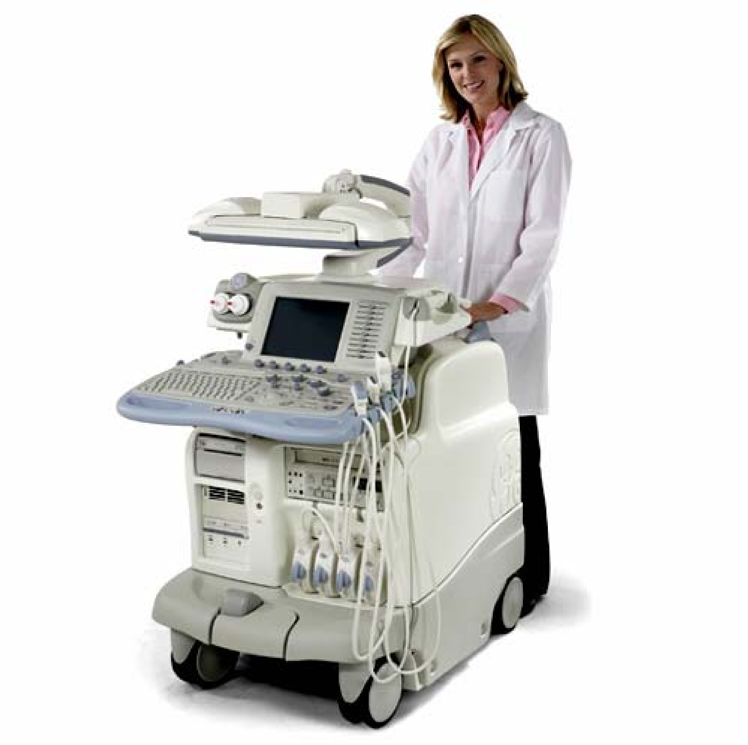


Fig. 16: GE LOGIQ 9 [9]

To the extent that the machine can be moved within a clinical setting, even the largest ultrasound machines are portable to some degree. However, their large size and weight means that most often it is the patient that is brought to the ultrasound machine.

Portable ultrasound complements the traditional ultrasound machine by providing nearly the same image quality and features in a small and portable form-factor, as shown in Fig. 17:

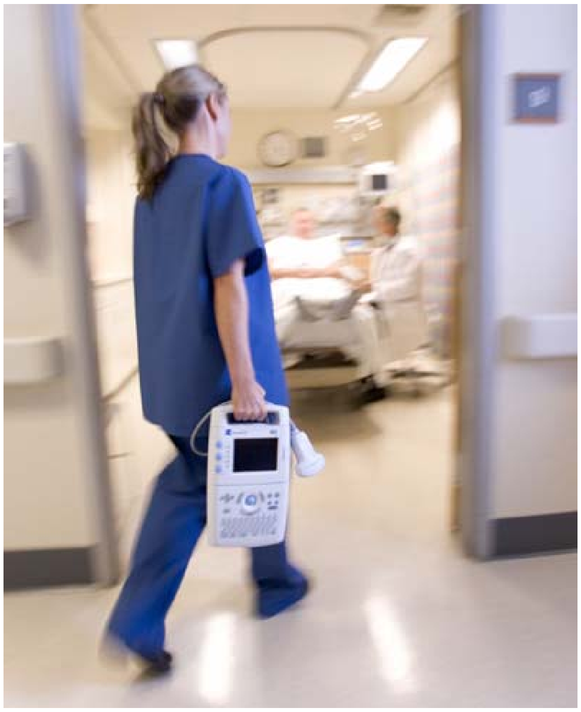


Fig. 17: SonoSite 180 Plus [10]

The portable form-factor has changed how ultrasound is used in the traditional clinical environment, as well as created new applications.

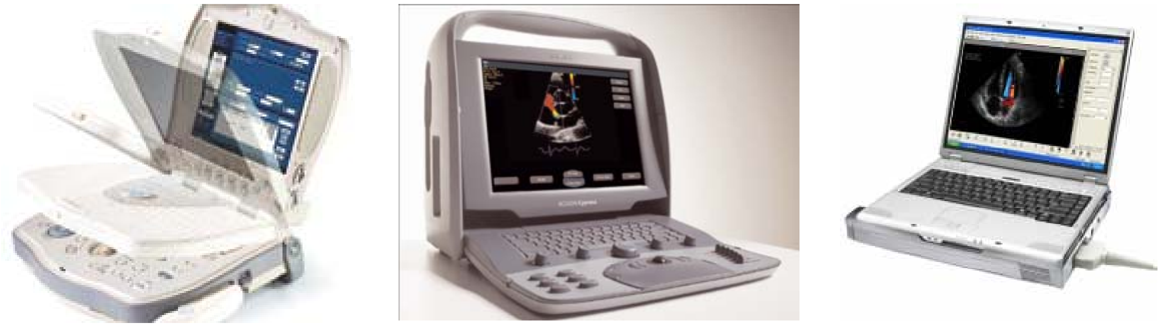
With a portable ultrasound machine, the machine can easily be brought to the patient. The reduced size often means greater maneuverability in crowded areas, such as in an intensive care unit (ICU) or a trauma bay. Moreover, battery operation allows ultrasound examinations to be performed without having to first locate an electrical outlet.

A single practitioner, working out of several offices, could carry a single portable ultrasound machine, and not have to have an individual ultrasound machine in every office [11]. The practitioner also benefits by having a single familiar ultrasound machine that can travel from site to site, instead of potentially encountering different ultrasound machines with differing capabilities and image quality.

This greater access to ultrasound has led to its increased usage for procedures such as the placement of lines and catheters. These routine procedures can be performed faster and more safely with the assistance of ultrasound [11].

The portable ultrasound market became a reality in 1999 with the introduction of the SonoSite 180 product from SonoSite [12]. Since then, numerous other manufacturers have released, or are planning to release, portable ultrasound products.

Portable ultrasound differs from conventional ultrasound in several ways. The main difference is in the actual form-factor of the devices. Traditional ultrasound machines are typically cart-based systems that take on a variety of sizes and shapes. Portable ultrasound systems are also available in a variety of shapes and sizes; however, the laptop style form-factor is the most prevalent. Some example portable ultrasound machines are shown in Fig. 18:



(a) GE LOGIQ Book XP [13] *(b) ACUSON Cypress [14]* *(c) Terason Echo [15]*

Fig. 18: Example Portable Ultrasound Machines

Compared to cart-based systems, portable machines often support fewer types of transducers. Also, only a single transducer can be attached at one time, whereas cart-based machines often support multiple transducers (although only one transducer can actually be used at any given time). Another general limitation is the number of beam formers, which directly affects ultrasound image quality. Lastly, the displays on portable machines may not be as good.

Most of these differences, except for the form-factor, are rapidly narrowing. Portable machines are beginning to offer similar features and image quality as the larger machines. They may even offer features not found on their larger cart-based brethren. For example, most of the portable machines are capable of operating on battery power alone for short durations of about an hour or two.

1.4 Motivation and Justification

The current generation of portable ultrasound machines are designed for use within clinical environments, much like the cart-based systems that they supplement. While this has increased the use of ultrasound procedures and created new applications, it is still primarily a tool for use within the clinical environment.

The clinical environment can best be summarized as an indoor location, whether within a building, tent or vehicle, that is temperature controlled, has stable power sources and is protected from the elements. It is also the final destination for most patients requiring medical care, whether routine or emergency in nature.

Clinical environments, however, are only a small subset of the possible locations that ultrasound procedures could be employed.

Pre-hospital care, defined as any medical procedures that occur before reaching a clinical setting, is becoming more of a focus within the healthcare community. The “golden-hour”, defined as the first hour after an injury has occurred, is often toted as the most critical time period in which to successfully treat injury. The golden-hour most often occurs in the per-hospital setting.

Ultrasound is useful in the detection and treatment of critical-care injuries in the pre-hospital setting. Some examples include detecting the presence of bleeding within the abdomen, or a pneumothorax condition (collapsed lung). Both of these conditions would immediately change the course of treatment in the pre-hospital setting. In particular, the availability of ultrasound within the golden-hour can help in performing procedures such as central-line placement, or observation of certain characteristics of the heart.

Routine medical care can also benefit from the availability of ultrasound outside of the clinical environment. In certain situations, it may be better for the patient, or simply more economical, to bring ultrasound imaging to the patient. For example, certain high-risk pregnancies requiring regular ultrasound examinations could be performed outside of the clinical environment, such as at home. Also, remote locations, such as rural settings, may not be located near facilities that possess ultrasound equipment. These patients must often travel great distances for routine care. A more portable ultrasound machine could better service rural populations.

The current generation of portable ultrasound machines are only portable to the extent that they can only operate for one or two hours on battery power. This limits the amount of time that the machine can be operated without returning to a stable power source. These machines are also not suited to operation in harsh environments, such as in the rain or in a desert. They also require a stable work surface to operate them, such as a table or chair. These limitations limit their suitability outside of the clinical environment. The wearable ultrasound system, detailed in this thesis, addresses these deficiencies to make portable ultrasound suitable to almost any environment.

2 Wearable Ultrasound

This section introduces the wearable ultrasound computer (WUC) and includes the motivation for performing this work, the requirements of such a system, and the development history preceding this thesis work.

2.1 Introduction to Wearable Ultrasound

The WUC, as the name implies, is a wearable system. It has been designed for long-term use in harsh environments without the need for installed infrastructure. The WUC is worn by the individual performing the examination. It is in the form of a vest that contains all the equipment necessary for carrying out completely untethered ultrasound examinations. The vest has been modified to provide conduits for cables to interconnect the various components.

The WUC is intended to operate for a full day (approximately 8 hours) on battery power alone. It includes wireless data communications to allow for remote viewing of ultrasound images (up to 100 meters wirelessly) and for voice communications.

This system is intended to be used anywhere that a portable and rugged ultrasound system can contribute to the quality of care. Some examples of its uses are:

- Rural Medicine
- Emergency Room
- Disaster Response
- Medical Transport
- Military Triage

One of the most unique features is the ability to control the ultrasound scanning system using voice commands. This frees one hand of the ultrasound operator to support the patient or stabilize themselves during transport.

2.2 Architecture

The major components, housed in various compartments and pockets within the vest, are:

- Ultrasound Transducer
- Embedded Computing Platform
- Two Li-Ion rechargeable batteries
- Head-mounted display
- Microphone
- Mouse

The ultrasound transducer, along with its front-end electronics, is a commercial off-the-shelf (COTS) device from *Terason*, a medical ultrasound company. The combination of ultrasound transducer and front-end electronics is called a *SmartProbe* by Terason. A phased array transducer SmartProbe is pictured in Fig. 19:

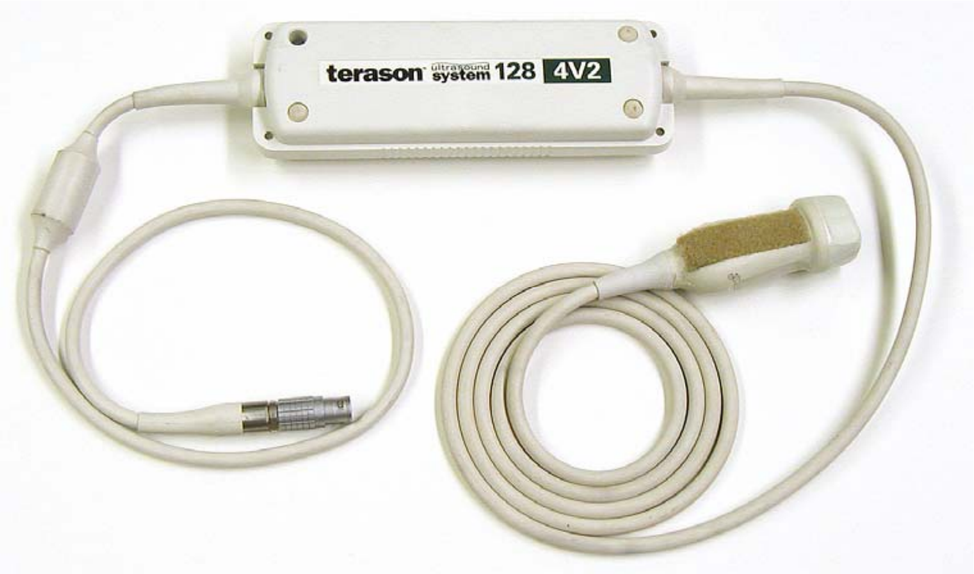


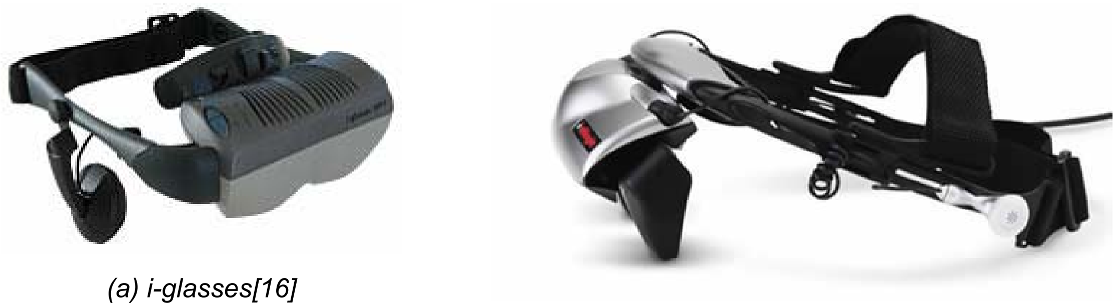
Fig. 19: Terson 2000 SmartProbe

Terason's product, called the Terason 2000, is designed to operate using a laptop and their SmartProbe system of ultrasound transducers. There are currently nine different ultrasound transducers available to support a wide variety of examinations. The ultrasound transducer and front-end electronics are a single unit. The transducer cannot be detached from the front-end electronics.

The embedded computing platform contains a complete COTS embedded computer, manufactured by a company called Advanced Digital Logic. It is similar to a laptop class computing device, but in an embedded form factor. The embedded computing platform also contains a custom designed power supply, hard-disk drive (HDD), and an interface for the Terason 2000 called an External DC Module (EDCM). These parts are all contained in a hermetically sealed enclosure that is further detailed in Section 3. Also included within the embedded computing platform is a wireless interface. The uses of this interface, and its implementation, are discussed in Sections 3 and 6. The enclosure, that houses the embedded computing platform, is custom designed.

Each of the two rechargeable Li-Ion batteries is capable of storing up to 95 Watt-hours (Wh) of energy, for a total capacity of up to 190 Wh when both batteries are fully charger. Each battery can be hot-swapped while the WUC is in operation, as well as charged within the vest, regardless of whether the embedded computer is running or not. Section 4 discusses the batteries and integrated charging system in further detail.

In order to view the ultrasound images, a head-mounted display (HMD) is worn by the operator. There are two displays that can currently be used with the system, shown in Fig. 20:



(a) i-glasses[16]

(b) eMagin [17]

Fig. 20: Head Mounted Displays

Each HMD interfaces to the embedded computing platform via a standard video graphics array (VGA) interface and has a resolution of 800x600 pixels. They also each have headphones and one even has a built-in microphone.

An integral part of the voice command system is the microphone that receives the spoken commands. The microphone is explained in Section 5.

Finally, a mouse is also included within the vest. The particular mouse being employed is a trackball mouse that can be operated with one hand and does not require a surface for operation. The mouse is shown in Fig. 21:

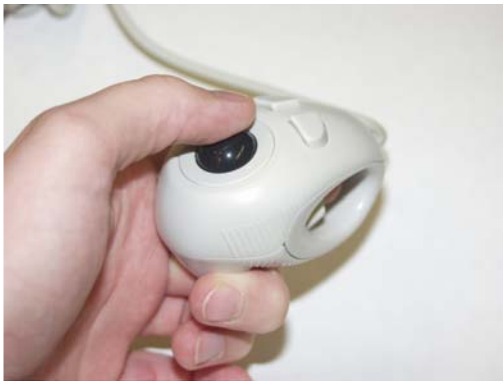


Fig. 21: Trackball Mouse

Fig. 22 shows an overall block diagram of the WUC, containing all of the components introduced above:

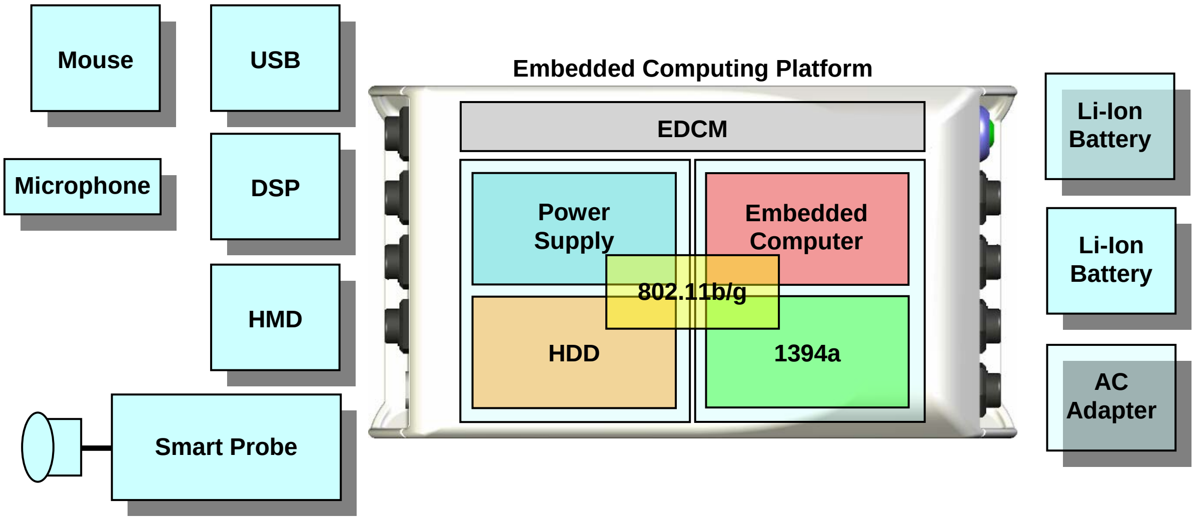


Fig. 22: Block Diagram of WUC

In support of clinical trials being performed at MAMC, training materials in the form of manuals and short tutorial videos were also created. This material was made available on-line for evaluation participants, and was updated based on feedback received from the trials. Section 9 provides results from clinical trials, as well as other performance metrics.

Table 1 summarizes what was designed during this thesis and also introduces the component terminology:

Table 1: Component Terminology

Name	Description	Design	Location
1394a	PC/104-*Plus* peripheral providing a 1394a (Firewire) interface for the embedded computer	Modified COTS	Embedded Computing Platform
802.11b/g	USB Peripheral providing a 802.11b/g (WiFi) interface for the embedded computer	Modified COTS	Embedded Computing Platform
AC Adapter	A 120-240 V AC – 24 V DC converter	Modified COTS	Not Applicable
DSP	A digital signal processor housed in a small enclosure and connecting between the microphone and the embedded computer	COTS	Vest
EDCM	External DC Module that connects between the SmartProbe and the 1394a interface	Modified COTS	Embedded Computing Platform
Embedded Computer	PC/104-*Plus* form-factor embedded computer containing an Intel Pentium-M 738 CPU, an Intel 855GME chipset, 1 GB of memory and various other peripherals	Modified COTS	Embedded Computing Platform
Embedded Computing Platform	The enclosure, enclosure connectors and all components contained within	WPI	Vest

Enclosure	The ruggedized container housing the embedded computing platform electronics	WPI with Consulting	Embedded Computing Platform
HDD	A 2.5" form-factor Hard-Hisk Hrive	COTS	Embedded Computing Platform
HMD	Head-Mounted Display	COTS	Vest
Li-Ion Battery	Rechargeable 14.4 V 6.6 Ah Li-Ion battery	COTS	Vest
SmartProbe	Terason 2000 SmartProbe containing a transducer and front-end electronics	COTS	Vest
Microphone	4-element array microphone	COTS	Vest
Mouse	Hand-held trackball mouse	COTS	Vest
Power Supply	PCB containing various power supplies, battery charger, microcontroller and fan controller	WPI	Embedded Computing Platform
USB	USB peripheral connector for the embedded computer	Modified COTS	Embedded Computing Platform
WUC	Wearable Ultrasound Computer refers to the vest and all components contained within	WPI	Not Applicable

2.3 Requirements

The requirements for the WUC were developed from experience building prior generation devices and the desire to add important new features. The second generation prototype was also a wearable system housed within a vest [19]. A development history is included in Section 2.4.

The following is a list of overall design goals for improvements to the second generation device:

- Reduce the size of the embedded computer
- Increase the run-time on batteries
- Integrate wireless communications into the embedded computer
- Integrate the Terason 2000 power supply (EDCM) into the enclosure
- Create robust packaging capable of withstanding outdoor environments
- Implement real-time remote viewing of ultrasound images
- Increase the performance and reliability of voice commands
- Improve cable management within the vest
- Improve head-mounted display
- Make the embedded computer more "medical" in appearance
- Reshape the embedded computer for a more ergonomic fit when worn by the

operator

The following sections introduce the individual requirements for the system components that are changes or additions to the second generation WUC.

2.3.1 Enclosure Requirements

The enclosure was required to fit into the rear pocket of the photographer's vest that was modified to fit the second generation prototype. While the overall length and width of the previous enclosure was acceptable (18.3 x 13.2 x 6.5 cm [7.2 x 5.2 x 2.6 in.]), there was a general desire to decrease the height when designing the new enclosure.

The enclosure also needed to be rugged enough to operate in outdoor environments. This need brought forth two major requirements: to have an enclosure that could withstand moisture (rain), foreign particles (dirt, dust) while also providing effective cooling for continuous operation in hot climates, as well as use in a clinical setting.

Lastly, the overall look of the enclosure should be made to be more "medical" in appearance by having a matte white finish with rounded shapes. This also provides a more comfortable form factor when it is worn as part of the vest.

In an effort to further integrate the design from the second generation WUC, the enclosure should be designed to incorporate the Terason EDCM. The printed circuit board (PCB) for the EDCM is mounted inside the enclosure, with the LEMO connector presented externally, similar to the other connectors on the enclosure.

2.3.2 Enclosure Connector Requirements

The sockets are an integral part of maintaining a water-tight seal for the enclosure; therefore, they must create a seal with the enclosure. They need to be small enough so as to not add greatly to the overall enclosure dimensions and to allow a separate connector for each external peripheral. Also, the connectors must be robust enough to endure physical and environmental stresses likely to be encountered with daily use in the field. The connectors must be dense enough to fit as many as 8 wires on a single socket, where a wire may carry as much as 5 A of current. The connectors must also have a locking mechanism to prevent unintended disconnection. The impedance of the connector must be compatible with signaling in excess of 400 MHz while attenuating no more than 5.8 dB (1394a physical layer). Finally, as much as possible, each socket should be keyed to prevent the accidental connection of a cable into the wrong socket.

2.3.3 Power Supply Requirements

The power supply must be capable of powering all the devices incorporated into the system. This includes:

- Embedded Computer
- Ultrasound Transducer
- Wireless Interface
- Head-Mounted Display
- Microphone

The power supply should provide for adjustable voltage outputs to support various devices that may be added in the future.

A battery charger that is capable of charging two Li-Ion batteries simultaneously, while the system is in operation, should be included. Moreover, the system should also be capable of seamlessly switching between battery power and external power, without interruption of power to the power supply.

The power supply should also include a fan controller. This is to reduce power consumption by not running the fans at full power all the time. The speed should be thermally controlled by a temperature sensor.

Lastly, the power supply should provide the embedded computer with an interface to monitor the status of the batteries, fan speeds and temperatures.

2.3.4 Embedded Computer Requirements

The Terason software can only be run on an x86 compatible CPU under Windows XP. Therefore, the CPU must be capable of executing the x86 instruction set. Also, the minimum performance of the CPU must exceed that of a 600 MHz Pentium III as required by Terason. The original CPU used in the second generation WUC was a 1.1 GHz Pentium-M CPU, model 713. This was found to be minimally acceptable for running the envisioned software, and therefore, a CPU with greater performance should be used.

Besides the CPU requirements, a small and standardized form factor is required to minimize the overall enclosure size, reduce system cost and ensure adequate availability of parts.

The embedded computer must also include an IEEE 1394a interface to support the use of the Terason 2000.

2.3.5 Software

The software must be capable of utilizing a commercial speech recognition package to control the ultrasound probe. Pervasive data logging should be employed to aid in gathering statistical data for off-line analysis. Also, the software is required to allow for the remote viewing of ultrasound images in real-time, as well as the convenient retrieval of stored ultrasound images.

2.4 Development History

The WUC is the third generation in a series of prototypes, each successively smaller, more portable and more ruggedized than the last. Each prototype used the Terason 2000 for the ultrasound imaging device.

The Terason 2000 is designed to be used with a laptop computer. The first generation system [18] used a standard laptop, contained within a backpack. The first generation system, along with its designer, is shown in Fig. 23:

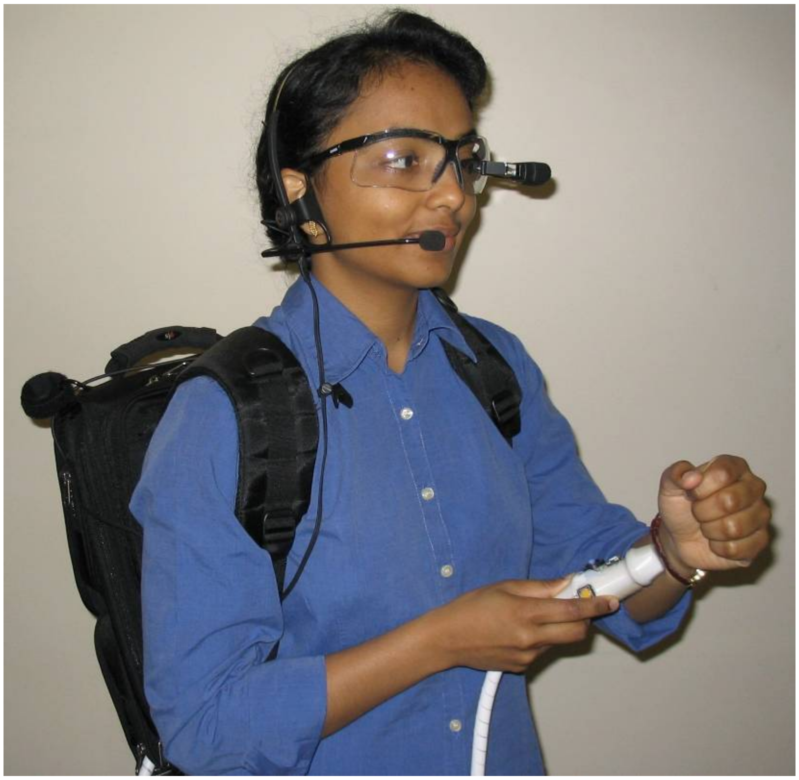


Fig. 23: First Generation WUC

The laptop contained an Intel Pentium 4-M processor along with 1 GB of memory. This system also had voice command capabilities; however, it used a different method to interface with the Terason 2000 than is described in Section 5. An HMD was also used to view ultrasound images, although it was a monocular design and had a resolution of 640x480 pixels. The mouse functionality was provided by a joystick mouse mounted on the transducer. Only one of these prototypes was produced.

The second generation system [19] replaced the laptop with an embedded computer in a non-standard 3.5” form-factor. This form-factor defines a 14.5 x 10.2 cm [5.7 x 4 in.] board with an unspecified height. It contained a 1.1 GHz Pentium-M and 1 GB or memory. This was housed, along with a COTS power supply, with a custom designed metal enclosure measuring 18.3 x 13.2 x 6.5 cm [7.2 x 5.2 x 2.6 in.]. The embedded computer and it associated enclosure, are shown in Fig. 24:

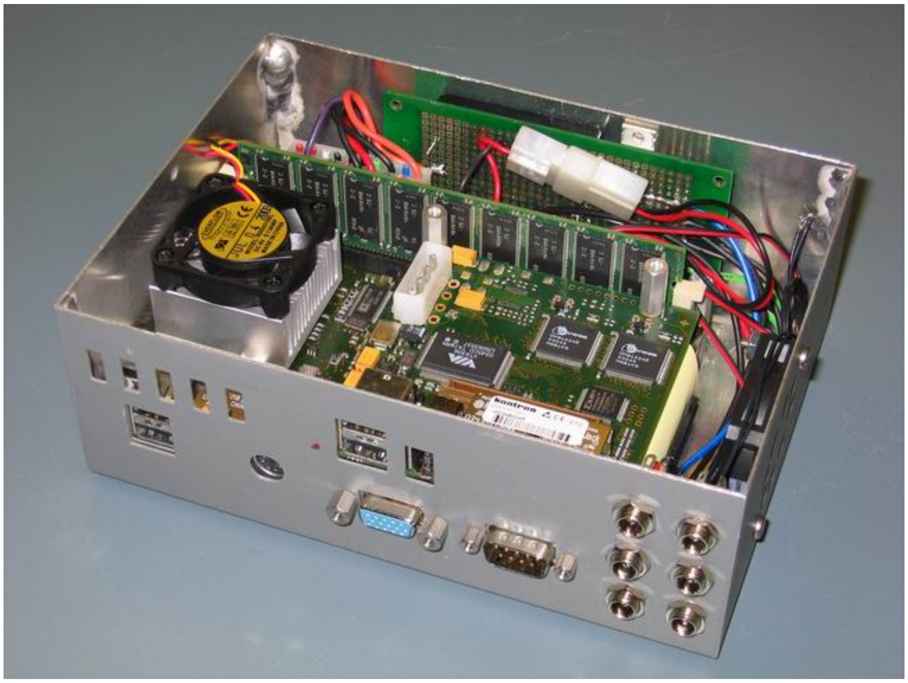


Fig. 24: Second Generation Embedded Computer, Power Supply and Enclosure

This generation also marked the first use of a vest to house the system. It also made use of two rechargeable Li-Ion batteries as a power source. The batteries were charged by removing them from the vest and using an external charger. The software was identical to the software used in the first generation. Two of these prototypes were produced.

Neither of these systems was weather-proof to any extent. Each of these systems was wearable and untethered, but neither was capable of operating in harsh environments. The third generation device, which is the focus of this thesis, was explicitly designed to be ruggedized. This means that the system would be impervious to foreign particles (dust) or moisture, and be capable of operating in moderately high temperatures for extended periods. To this end, a new embedded computing platform was developed.

3 Embedded Computing Platform

The embedded computing platform is the centerpiece of the WUC. All of the system peripherals are connected to the embedded computer. The embedded computer consists of the following:

- 1394a Interface
- 802.11b/g Interface
- Embedded Computer
- EDCM
- HDD
- Power Supply

Each of these items is enclosed within a custom-designed enclosure, forming a complete embedded computing platform.

3.1 Embedded Computer

There are several commercially available form-factors for embedded computers that support the necessary processing power required by the WUC. To further explain, a Pentium-M class CPU having a maximum clock speed of greater than 1.1 GHz. Of these, the PC/104 form factor is the smallest and most mechanically robust form-factor.

3.1.1 PC/104 Standards

The PC/104 standard is maintained by the PC/104 Embedded Consortium. There are three variations of the standard that are distinguished by the expansion busses that they support. The original PC/104 standard [20], released in March of 1992, defines the Industry Standard Architecture (ISA) bus for connecting peripheral boards to the system. A later update to the specification, called PC/104-*Plus* [21], added the Peripheral Component Interconnect (PCI) bus in addition to the ISA bus. The latest addition to PC/104, in November of 2003, is the definition of a PCI only form-factor, called PC-104 [22].

Each of the various standards are mechanically identical, and to some extent interoperable. The degree of interoperability is determined by the availability of either the ISA or PCI bus as necessary, for the interconnection of selected peripherals.

All PC/104 board variants are designed to be stacked one on top of each other. The mechanical design is such that the bus is passed from one board to another. Fig. 25 shows how different PC/104-*Plus* boards can be stacked:

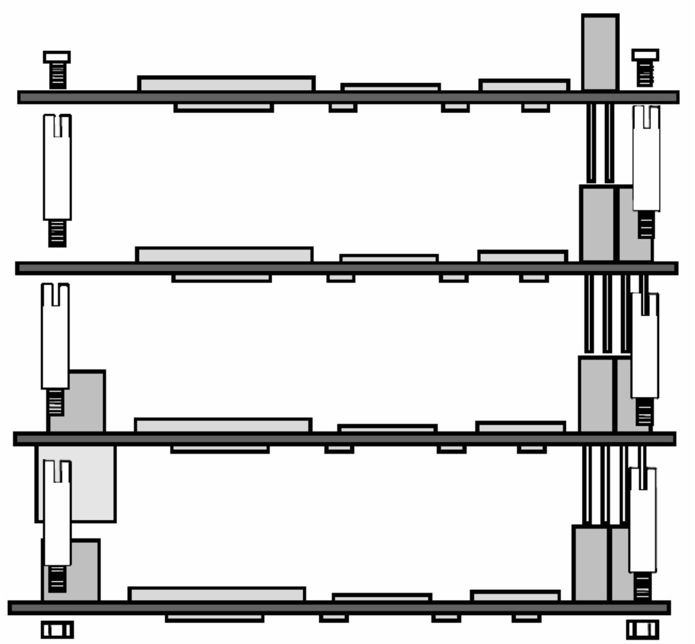


Fig. 25: PC/104-Plus Board Stackup [21]

In the example given in Fig. 25, each of the four boards has an ISA bus while two of the boards have a PCI bus and an ISA bus. The embedded computer contains both ISA and PCI busses on the underside of the PC/104-*Plus* board. These busses are used to stack a 1394a peripheral board below the embedded computer. The 1394a board, discussed in Section 3.1.3, has connectors for both the ISA and PCI busses, but only uses the PCI bus.

A PC/104-*Plus* board measures 9.589 x 9.017 cm [3.775 x 3.550 in.] for a total board area of 86.464 cm^2 [13.401 $in.^2$]. The max component height on the top-side of the board is 0.876 cm [0.345 in.], and on the bottom-side of the board is 0.483 cm [0.190 cm]. The top-side bus connectors are 1.105 cm [0.435 in.] tall. The bottom-side connectors are 1.118 cm [0.440 in.] tall.

Notice that there are four through-holes, with one on each corner of the board. Each board is secured with standoffs to the next board, ensuring a strong mechanical connection between boards.

3.1.2 Embedded Computer Selection

At the time of selecting an embedded computer for the WUC, there were only two vendors producing embedded computers with Pentium-M CPUs. The first board was by a company called *Lippert-AT*. The product is called “Cool RoadRunner 4” and is pictured in Fig. 26. The second board was from a company called *Advanced Digital Logic*. Their product is called “MSM855” and is pictured in Fig. 27.

Fig. 26: Lippert-AT Cool RoadRunner 4 [23]

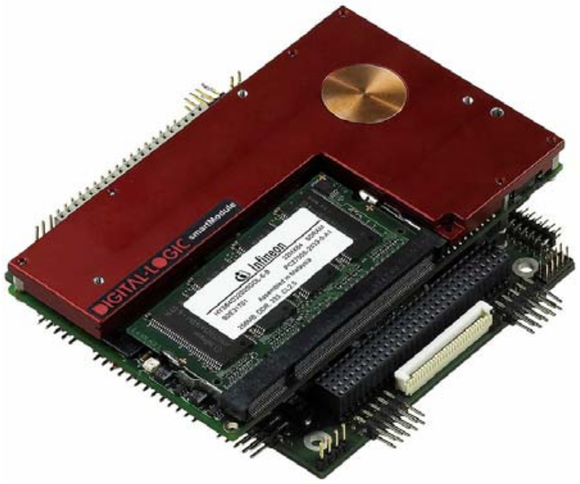


Fig. 27: Advanced Digital Logic MSM855 [24]

Each of these boards has an almost identical set of specifications. The MSM855 was chosen due to its integrated heatsink aiding in the effective cooling of the CPU. Also, at the time of final board selection, the Cool RoadRunner 4 was not generally available.

Table 2 summarizes the available CPU options for the MSM855:

Table 2: Available CPUs for MSM855

Model Number	Architecture	L2 Cache	Clock Speed	Bus Speed	Maximum Power
Celeron M ULV RJ80535VC600512	130 nm	512 kB	600 MHz	400 MHz	7.0 W
Celeron M ULV 373	90 nm	512 kB	1.0 GHz	400 MHz	6.7 W
Pentium M LV 738	90 nm	2 MB	0.6 - 1.4 GHz	400 MHz	13.0 W
Pentium M 745	90 nm	2 MB	0.6 - 1.8 GHz	400 MHz	31.6 W

The first two options, comprising two Celeron processors, have less processing power than the previous prototype of the WUC and do not meet the stated requirements. Of the two remaining choices, the Pentium M LV 738 offers the most performance per Watt and meets the stated requirements. Therefore, the Pentium M LV 738 was chosen for the design.

In order to avoid any future limitations, the maximum 1 GB of memory was included with the MSM855.

3.1.3 IEEE 1394a Selection

An important requirement was the inclusion of an IEEE 1394a (FireWire™) interface, in order to support the Terason 2000. The MSM855 does not have a 1394a interface, so it was necessary to use an additional board to provide this.

The IEEE 1394a specification [25] defines a four or six wire serial connection of up to 4.5 m [14.8 ft.] at a physical layer data rate of 400 Mb/s. Multiple devices may be connected in a non-cyclic bus arrangement. Data is transmitted using differential signaling on two twisted pairs of wires, creating a full-duplex serial connection. The six wire version includes two extra wires for providing power and ground. A 1394 node may consume up to 1.5 A of current with a supply voltage of 8 – 40 V.

The Terason 2000 requires a six wire IEEE 1394a connection, providing up to 10 W of power at between 12 V and 30 V. To provide this, a PC/104-*Plus* IEEE 1394a board from Ampro, having two 1394a ports, was used. In order to meet the power requirements of the Terason 2000, the Ampro board was provided with power directly from the power supply through an auxiliary header on the board. More detail on this is contained in Section 4.10.

3.1.4 Hard Disk Drive Selection

Storage for the embedded computer is provided by an industrial 2.5” form-factor HDD with a 44-pin Integrated Drive Electronics (IDE) interface and a capacity of 20 GB. The HDD is from Hitachi and is an Endurastar J4K20. The 44-pin IDE interface supports transfer of data from the HDD at up to 100 MB/s and also provides 5 V to power the HDD. An industrial HDD was used due to its extended temperature range of -20 to 85 °C and its capability to withstand shocks of up to 100 g while operating.

3.1.5 IEEE 802.11b/g Selection

The final piece of hardware used by the embedded computer is an IEEE 802.11b/g (Wi-Fi) interface. 802.11 is a suite of wireless standards with varying physical layer data rates and an approximate range of 100 m. This particular interface can operate in either the 802.11b or 802.11g modes. Each mode, 802.11b or 802.11g, is compatible at the physical layer and can interoperate with each other. 802.11b provides for physical layer data rates of up to 11 Mb/s and 802.11g provides for physical layer data rates of up to 54 Mb/s. The actual throughput of user data is somewhat less and is realistically 50% or less than the theoretical maximum.

The 802.11b/g interface is provided by way of a Universal Serial Bus (USB) peripheral. USB provides both power and data through a four wire connection. Two wires supply 5 V to the device, while the other two wires provide full-duplex single-ended communication at up to 480 Mb/s. The USB device is normally supplied as a USB key in a plastic housing. Within the plastic housing is a board measuring 6.0 x 2.5 x 0.5 cm [2.4 x 1.0 x 0.2 in.]. This board is removed from the plastic housing and mounted within the enclosure. Details on the placement within the enclosure are provided in Section 3.2.

3.2 EDCM Integration

The Terason 2000 is connected to a host computer, via IEEE 1394a, through an EDCM. The EDCM is a power supply that produces several voltages required by the Terason 2000, and also passes through the 1394a connection to the Terason 2000. It is normally supplied in a plastic housing that has two connectors on either end. One connector receives an IEEE 1394a cable and the other connects to the Terason 2000. The EDCM measures 14.8 x 3.8 x 2.7 cm [5.8 x 1.5 x 1.1 in.] and weighs 95 g [0.20 Lbs.].

Within the plastic housing is a small PCB measuring 14.2 x 3.1 x 1.8 cm [5.6 x 1.2 x 0.7 in.] and weighing 45 g [0.10 Lbs.]. Fig. 28 and Fig. 29 show the EDCM enclosure and the EDCM PCB:

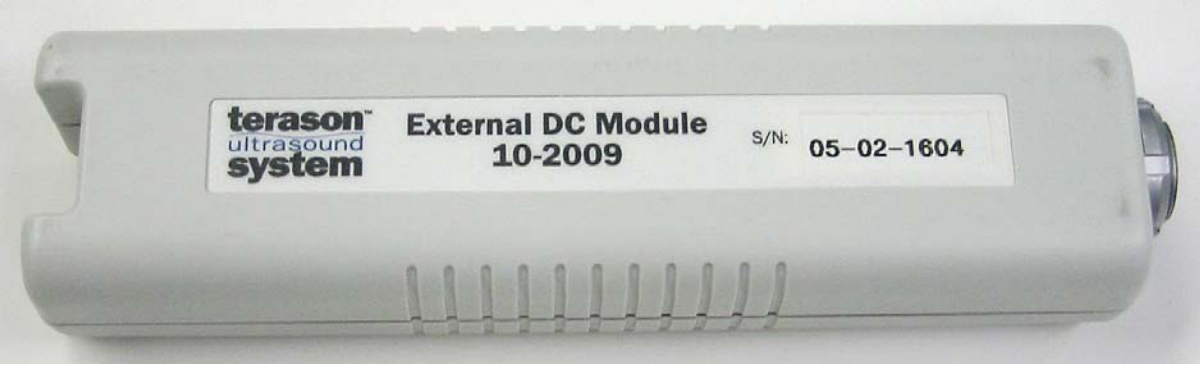


Fig. 28: EDCM Enclosure

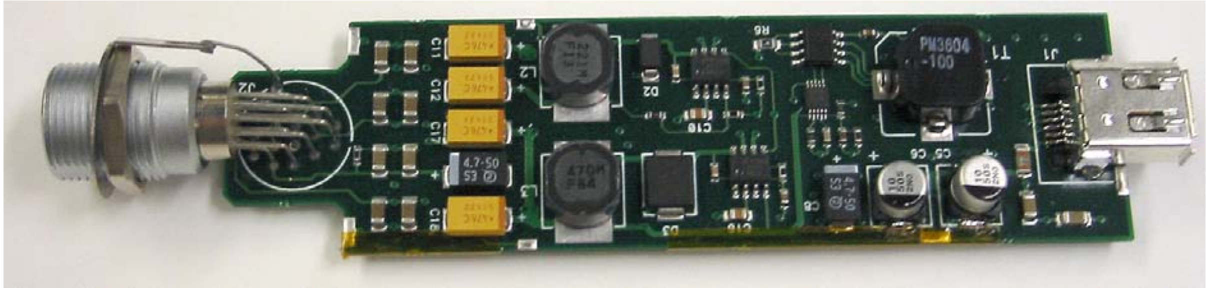


Fig. 29: EDCM PCB

The EDCM is removed from its plastic housing, prior to being placed within the enclosure due to space constraints. The reasoning is that having a plastic housing within the enclosure would be redundant.

3.3 Enclosure Design

One of the key features of the WUC is the enclosure housing the embedded computer and the EDCM. The unique requirements of the embedded computer enclosure, as described in Section 2.3.1, necessitated a fully custom design.

An outside vendor, DaTuM 3D, was contracted to assist in the development and manufacturing of the enclosure. Using requirements developed by WPI, a complete three-dimensional (3D) model was developed using SolidWorks. This model allowed for an interactive and iterative design process that culminated in an initial prototype. The 3D modeling process was invaluable in communicating design decisions between DaTuM 3D and WPI, and proved to be a powerful collaboration tool.

An initial prototype was manufactured by DaTuM 3D and tested by WPI. The total time between initially meeting with DaTuM 3D and receiving a prototype was four months. Over the next three months, a new set of requirements was developed, using the initial prototype as a basis. A second prototype was developed and ultimately accepted as the final design. The second prototype took less than two months to design and build. Fig. 30 shows the final version of the embedded computer enclosure model:

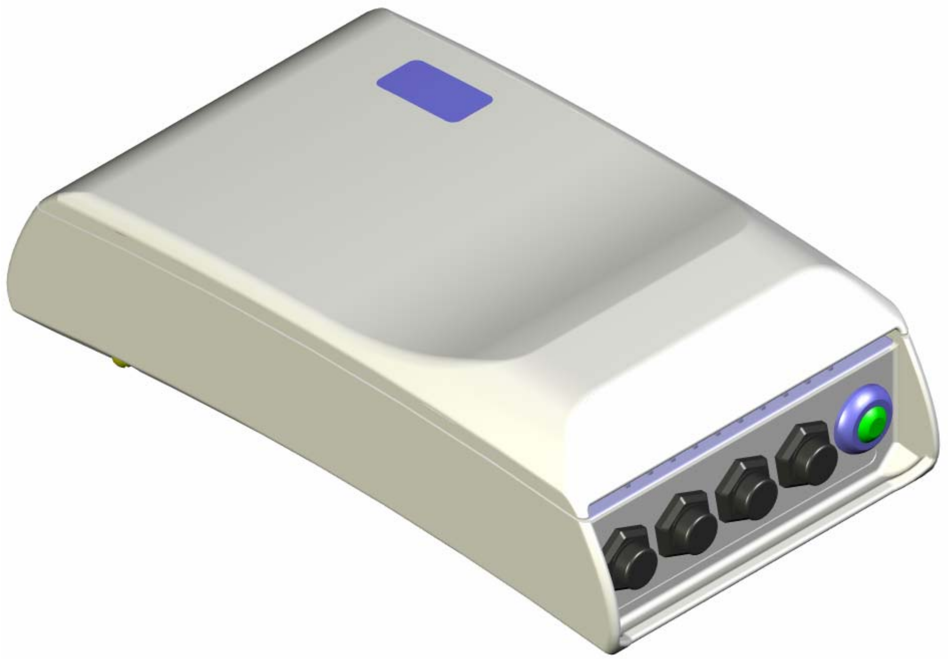
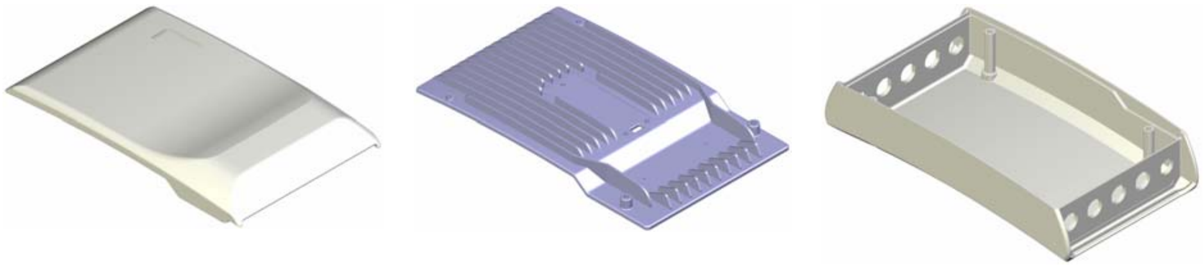


Fig. 30: Embedded Computer Enclosure

The enclosure consists of three main pieces, along with some mounting hardware. There is a top and bottom cover and a heatsink. The final enclosure design is segmented into two compartments internally. One compartment is hermetically sealed and contains the embedded computer, HDD, power supply, 1394a interface and the EDCM. A gasket on the bottom covers helps to seal this compartment. The second compartment is used for cooling the sealed compartment. It contains two fans and the 802.11b/g board. Separating the two compartments is an aluminum heatsink that serves two purposes. The heatsink, as the name implies, acts as an efficient conduit for heat transfer between the compartments. The cooling performance of the design is detailed in Section 9.3. It also acts as a backbone that all components are attached to. Fig. 31 shows the three main pieces of the enclosure:



(a) Top Enclosure Cover

(b) Enclosure Heatsink

(c) Bottom Enclosure Cover

Fig. 31: Enclosure Components

When a person is wearing the vest, the enclosure is oriented such that the person’s back is in contact with the curved bottom of the enclosure. Due to this orientation, the 802.11b/g interface is mounted on the heatsink, so as to not interfere with the 802.11b/g transceiver. Mounting the 802.11b/g interface within the sealed compartment would have located it between an aluminum plate and the back pf the person wearing the vest. This would have resulted in poor radiation of the 802.11b/g signals.

The entire enclosure is milled from two solid pieces of Delrin. This material was created by DuPont in 1952 as a general substitute for nonferrous metals [26], such as aluminum, tin, zinc or brass. It is characterized by the manufacturer as, “lightweight but durable low wear, low friction plastic [26].” Some selected properties of Delrin are shown in Table 3:

Table 3: Properties of Delrin [27]

Property	Test Method	Units	Value
Yield Stress	ISO 527	MPa (kpsi)	70 (10.2)
Yield Strain	ISO 527	%	25
Strain at Break 50mm/min	ISO 527	%	65
Nominal Strain at Break	ISO 527	%	45
Tensile Modulus	ISO 527	MPa (kpsi)	2900 (420)
Tensile Creep Modulus	ISO 899	MPa (kpsi)	
1h			2700 (392)
1000h			1500 (218)
Flexural Modulus	ISO 178	MPa (kpsi)	2600 (377)
Flexural Stress @ 3.5% Strain	ISO 178	MPa (kpsi)	74 (10.7)
Melting Temperature	ISO 11357-1/-3	°C (°F)	178 (352)
Vicat Softening Temperature 50N	ISO 306	°C (°F)	160 (320)
Surface Resistivity	IEC 60093	Ω	> $1x10^{15}$
Volume Resistivity	IEC 60093	Ωm	$1x10^{12}$
Dielectric Strength 1.0mm	IEC 60243-1	kV/mm	23
Dielectric Constant 1 MHz	IEC 60250		3.7
Density	ISO 1183	kg/m^3 (g/cm^3)	1420 (1.42)

The final dimensions of the enclosure are 25.7 x 14.0 x 7.6 cm [10.1 x 5.5 x 3.0 in.] and a dimensioned drawing is shown in Fig. 32:

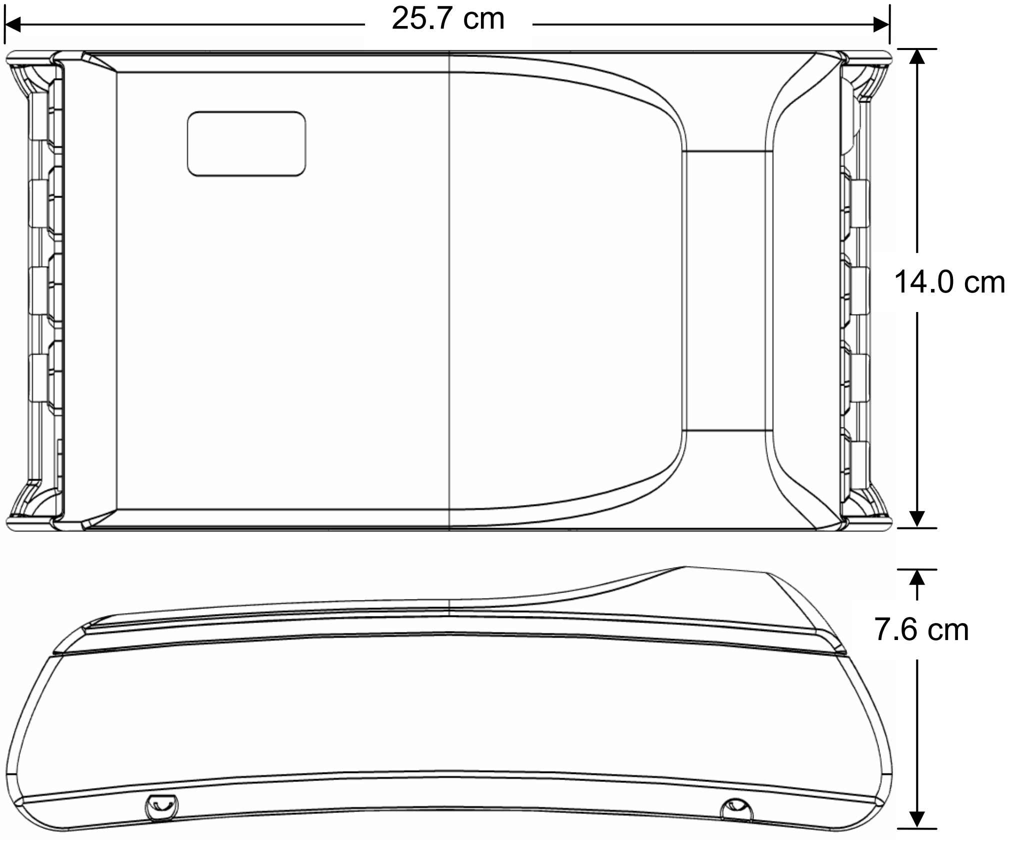


Fig. 32: Dimensioned Embedded Computer Enclosure Drawing

The final weight of the embedded computing platform, which comprises the enclosure along with all of its internal electronics, is 1795 g [3.949 Lbs.].

3.3.1 Internal Arrangement

The enclosure is separated internally into two compartments. Fig. 33 shows a cut section of the enclosure, without any internal components:

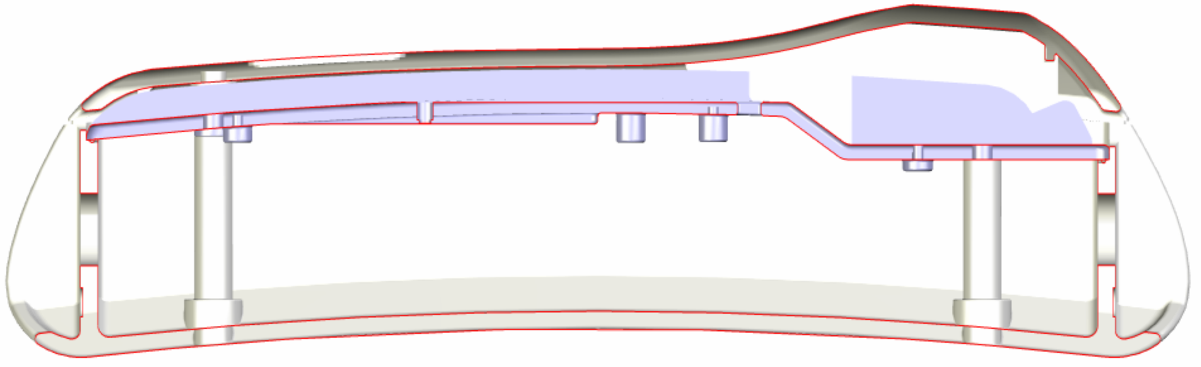


Fig. 33: Two Compartments of Enclosure

The top compartment in Fig. 33 contains the two fans and the 802.11b/g interface. It is open to the environment to allow air to be forced across the heatsink by the two fans. Fig. 34 shows the top compartment with an arrow indicating the direction of airflow:

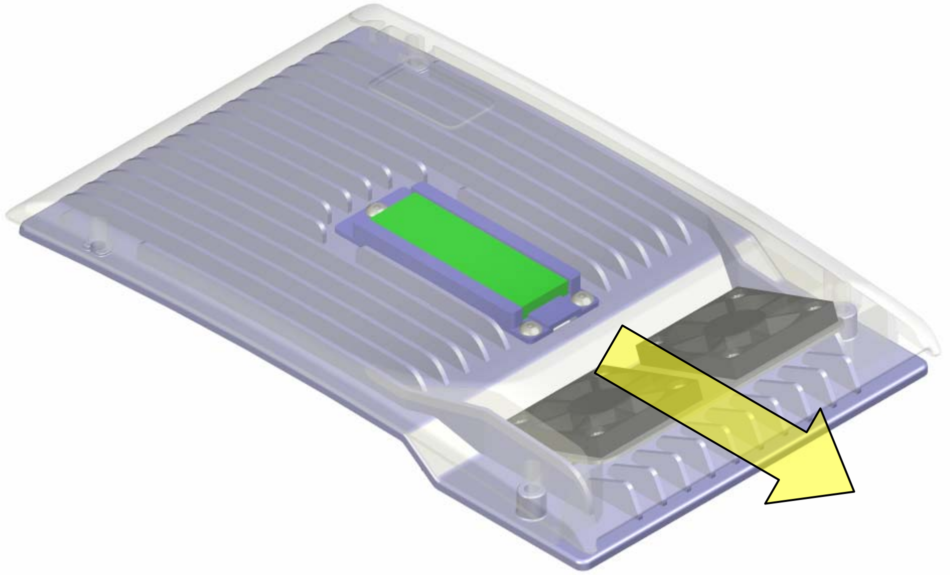


Fig. 34: Top Compartment of Enclosure

Air is pulled in from the left-hand side of the enclosure, and exhausted out of the right-hand side by two fans. Each fan can spin as fast as 6000 RPM and move up to 5.5 CFM of air, for a total of 11 CFM. Each fan produces no more than 26 dBA of noise, for a maximum of 29 dBA, resulting in quiet operation.

The heatsink has fins to increase the surface area for heat transfer. It is also shaped so that air must flow through the fans to traverse the heatsink. This ensures that the entire 11 CFM of air flows over the heatsink and cannot short-circuit around the fans.

The 802.11b/g board is held in place, on the heatsink, by a small retention bracket. A small hole in the heatsink allows the wires, for the fans and the 802.11b/g board, to pass through the otherwise solid heatsink. It is located under the retention bracket for the 802.11b/g board.

The lower compartment is organized into two assemblies positioned alongside the EDCM. This arrangement creates an overall shape to the enclosure that makes it convenient for its location against a person's back. It minimizes the overall height of the enclosure and allows for a gentle curve to be integrated into the lower compartment to fit more comfortably against the lower back of the person wearing the WUC. The orientation of the individual assemblies is dictated by the locations of the connectors on each assembly and the internal cable routing requirements. They have been optimized to reduce cable lengths and maximize access to cabling locations during manufacture.

The first assembly consists of the CPU board and IEEE 1394a board stack and is shown in Fig. 35:

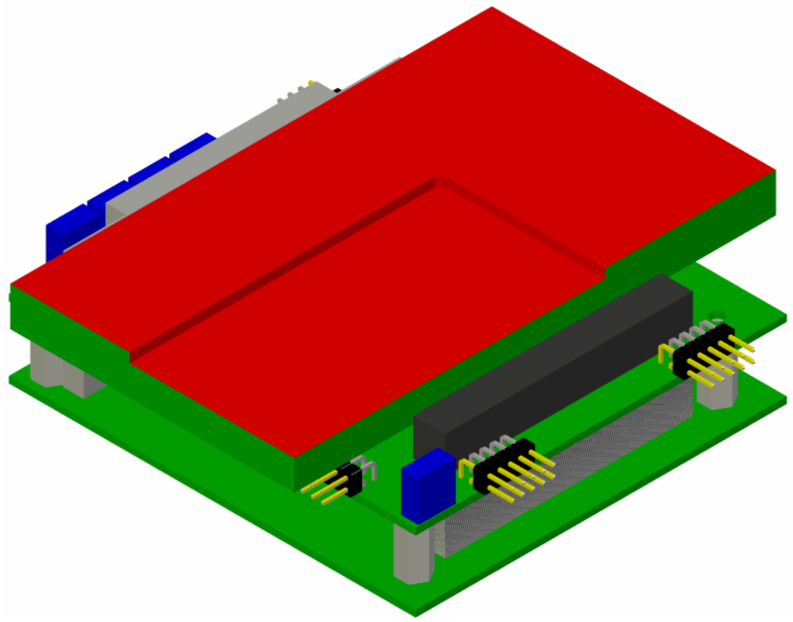


Fig. 35: CPU Board and IEEE 1394a Board Assembly

The integrated heatsink, on the CPU board, is in direct contact with the aluminum heatsink. Thermal grease is used to reduce the thermal resistance between the two heatsinks to promote heat transfer.

The second assembly consists of the power supply and the HDD. The HDD is secured in a bracket that also holds the power supply. Fig. 36 shows the power supply and HDD assembly:

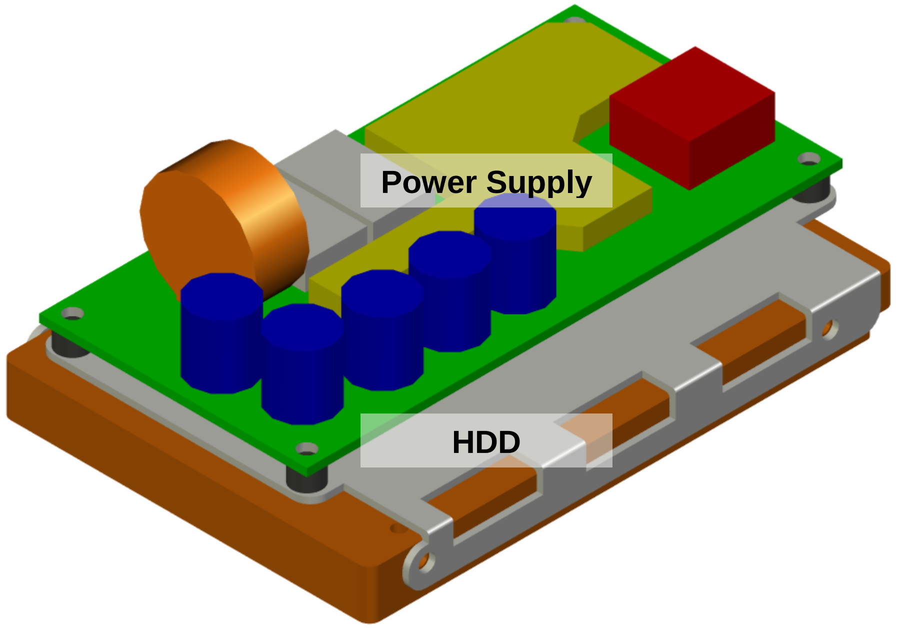


Fig. 36: Power Supply and HDD Assembly

Both of these assemblies are attached to the heatsink by eight standoffs, as shown in Fig. 37:

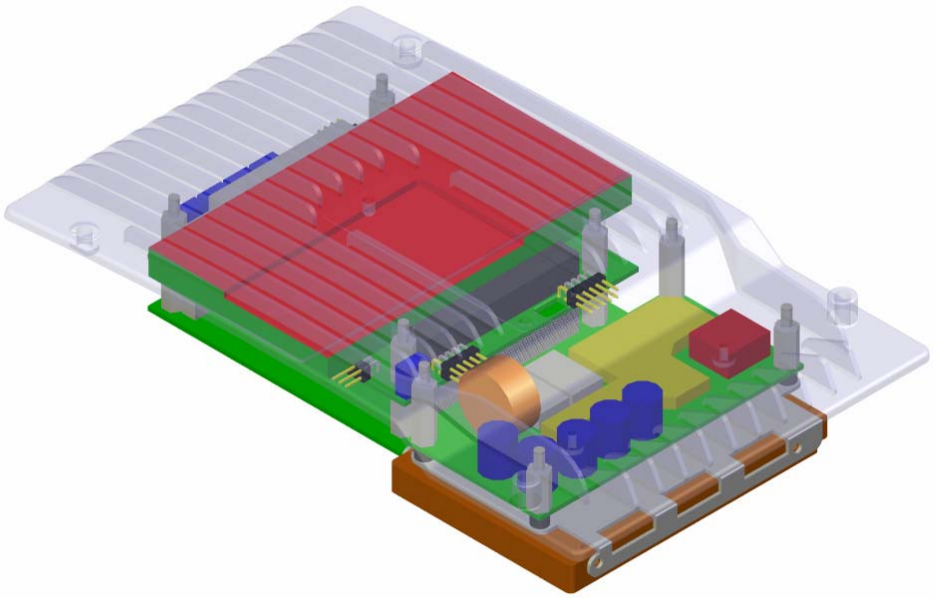


Fig. 37: Two Internal Assemblies

The EDCM is held in place within the enclosure by a groove in the bottom cover.

The end of the EDCM that connects to the Terason 2000 has a retaining nut. The EDCM exits the enclosure through an opening and is held in place by this retaining nut. Fig. 38 shows the mounting of the EDCM within the enclosure:

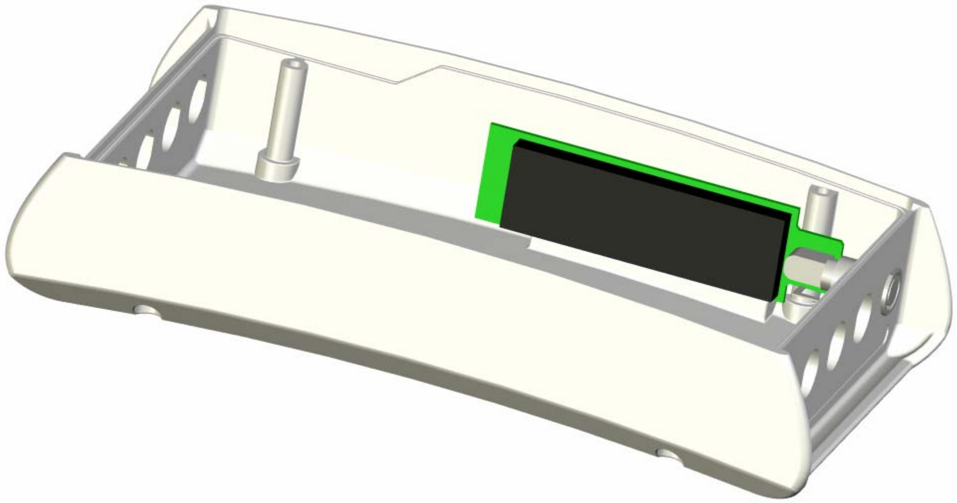


Fig. 38: EDCM Mounting in Enclosure

The complete internal assembly of the lower compartment is shown in Fig. 39:

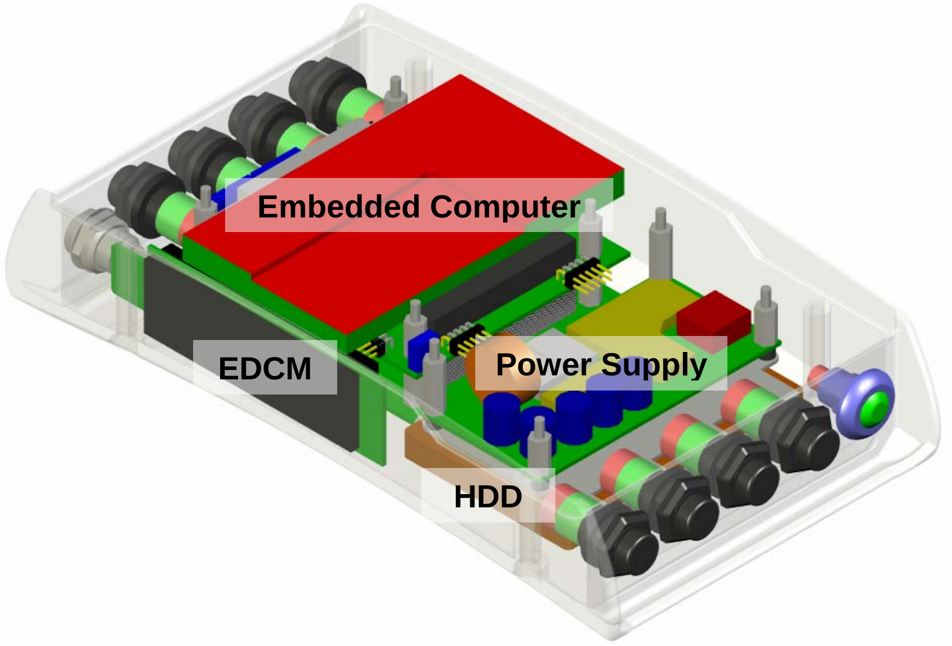


Fig. 39: Complete Internal Assembly of Lower Compartment

3.3.2 Enclosure Connectors

Each connector used on the WUC is a circular panel-mount connector. They support as many as 18 conductors per connector. Solder cups are used to attach wires to the backside of the connectors. The connector is attached to the enclosure by passing through a keyed hole from the rear, and then it is secured with a nut on the front. The corresponding cord-connector, which is used by attaching cables to mate with the panel-mount connector, has a locking ring to ensure that the cables do not come loose unintentionally. The panel-mount connectors include an integrated gasket to ensure water tightness exceeding Coast Guard specifications (CFR 46 Part 110.20) and are also MILSPEC rated for both shock and vibration. Each pin can carry a maximum of 6.5 A of current and have a maximum contact resistance of 5 mΩ. This combination of high current carrying capacity and low contact resistance make these connectors well suited for both signaling and power applications.

The connectors on the embedded computer enclosure are located at both ends of the enclosure. This location allows the exiting cables to pass directly into the vest, containing the embedded computing platform. There is a slight overhang of material beyond the enclosure wall, containing the connectors, that helps to protect the connected cables from excessive strain. The alcove formed by the overhang is detailed in Fig. 40:

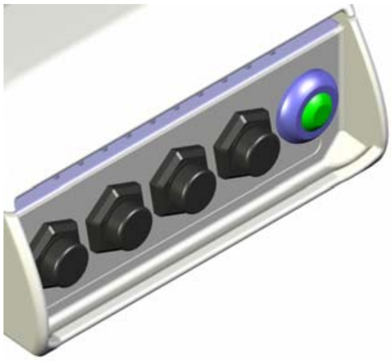


Fig. 40: Cable Strain Relief Alcove

The location of the connectors also allows for adequate internal clearance for cable entry into the solder cups on the connectors.

Each connector is modeled with two cylindrical regions extending rearwards, away from the connector. The green region, as shown in Fig. 41, represents the region of the connector that contains solder cups.

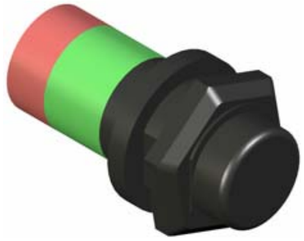


Fig. 41: Enclosure Connector Model

The red region encompasses the minimum bend-radius of the wire attached to the connector. This “keep-out” region was used as a modeling aid to help prevent internal interference with cable routing caused by the internal assemblies.

One side of the enclosure is dedicated to connectors for the power supply. This includes a connector for an AC adapter, two rechargeable batteries, and a spare. The other side has two connections for the Terason 2000, an audio interface, head-mounted display and a USB port. This connector organization creates a single cable for each external peripheral that must interface with the embedded computer platform. Each connector is uniquely organized to provide power and signaling to its connected peripheral. Also, each connector is unique in terms of the number of pins and its gender. This prevents accidental attachment of a peripheral cable to an incorrect connector. Also, each connector is labeled. The cable corresponding to that connector also carries the same label.

3.3.3 Enclosure Assembly

The top and bottom covers are secured by four 5 cm [2 in.] Allen head screws. Each screw passes through conduits in the bottom cover and is seated in threads that are part of the top cover.

When ready for assembly, all of the components are attached to the heatsink. All of the connectors for the enclosure are also wired to their respective cable assembly. This heatsink assembly is then placed into the bottom cover by first angling the end with the fans so that the edge of the heatsink is in contact with the edge of the bottom cover. The other end remains away from the bottom cover, while each of the connectors is fed through the bottom cover and retained with a nut. Fig. 42 shows this first step in assembling the enclosure:

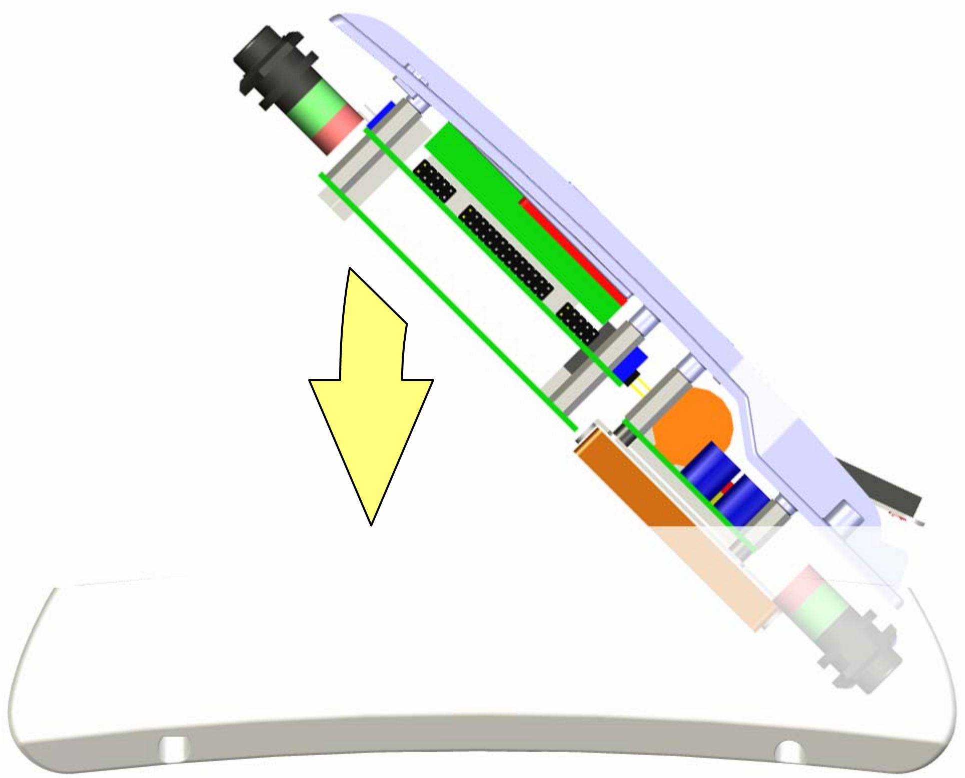


Fig. 42: Step One of Assembling the Enclosure

Once one set of connectors has been inserted, the heatsink assembly can be seated in the bottom cover. Before being fully seated, the connectors on the other side of the enclosure must be fed through the bottom cover and retained with a nut. Fig. 43

shows the results of completing the second step of assembling the enclosure:

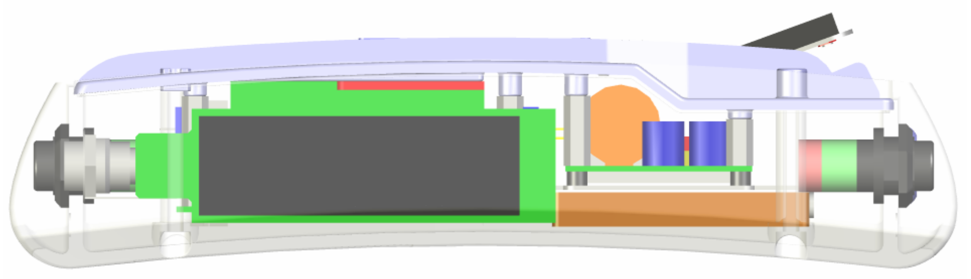


Fig. 43: Step Two of Assembling the Enclosure

Finally, the top cover can be placed over the heatsink, and the four screws tightened to firmly clamp the top and bottom covers together.

A picture of the final enclosure, along with the WUC itself, is shown in Fig. 44:

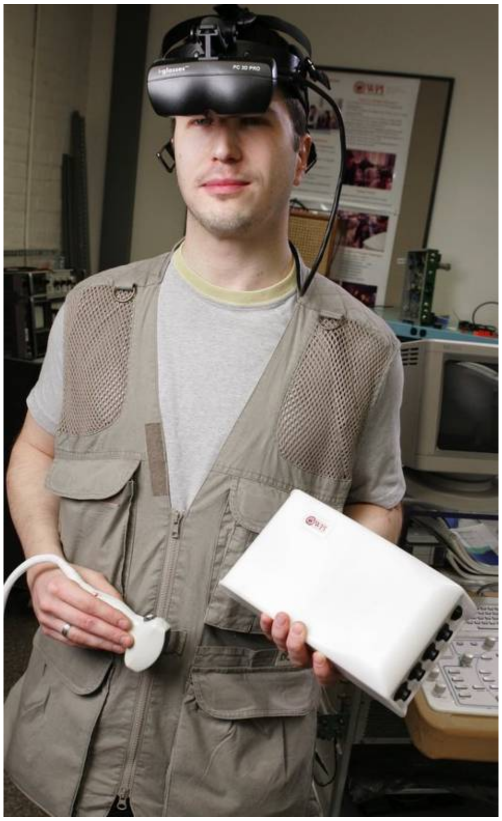


Fig. 44: Enclosure

A key feature of the WUC is its ability to operate for extended periods without a stable power source. To maximize runtime on batteries, and to fit within the tight confines of the enclosure, a small and efficient power supply was designed.

4 Power Supply and Management

Being a portable and battery powered device, the WUC requires comprehensive power management, with consideration given to efficient power conversion, size and weight. This extends beyond various regulated DC voltages and includes other considerations, in order to maximize operating life. These extensions include a requirement for thermally controlled fans that only run when conditions require it, a highly efficient voltage regulator for the embedded computer, monitoring and control by the embedded computer to optimize operation, an efficient battery charger that allows the embedded computer to operate while batteries are charging and ancillary voltage regulators that can accommodate the power requirements of various peripheral devices.

This section explores the design and development of the power supply contained within the embedded computing platform.

4.1 Justification

The first power supply that was considered is a combination battery charger and ATX power supply, in the form of a two board PC/104 stack from a company called *OceanServer*. The complete package, consisting of two identically sized boards, is shown in Fig. 45:

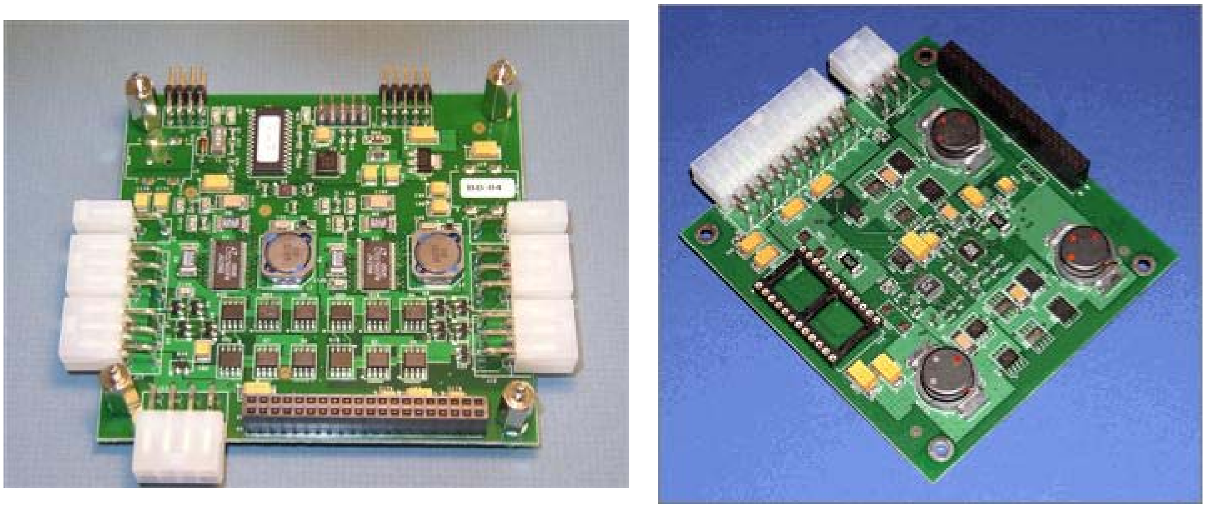


Fig. 45: OceanServer Battery Charger and ATX Power Supply [28,29]

While the OceanServer product met most of the functionality requirements, the size of the enclosure required to contain it, along with the embedded computer, was considered too large for portable use. Specifically, it would have appreciably increased the size of the enclosure relative to previous prototypes, while adding minimal extra functionality. It also lacked some of the regulated voltages to supply power to certain peripherals under consideration.

Another option that was considered was the use of a DC-DC converter brick. These are manufactured by several companies, with Datel being one of the most prominent suppliers. The bricks use standardized package sizes and pinouts. An example of a DC-DC converter is shown in Fig. 46:

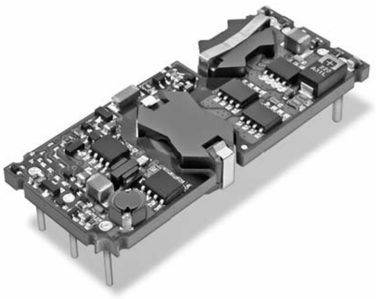


Fig. 46: 1/8 Brick DC-DC Converter [30]

In order to meet the power requirements of the embedded computer, the minimum sized brick is a 1/8 brick measuring 5.64 x 2.26 x 0.91 cm [2.22 x 0.89 x 0.36 in.]. This solution is unsuitable because it lacks a battery charger, as well as any method of monitoring or control. This solution also lacks some of the regulated voltages to supply power to certain peripherals under consideration.

It soon became clear that in order to meet all of the requirements, a custom power supply needed to be designed.

4.2 Introduction

The power supply for the WUC is an entirely custom design performing the following functions:

- Smart Battery System Manager
    - Smart Battery Charger
    - Smart Battery Selector
- 5V Switching Regulator
- 12V Adjustable Linear Regulator (reserved for future use)
- 9V Adjustable Linear Regulator
- SMBus [31] to RS-232 Interface
- Automatic Fan Speed Control
- Thermal Monitoring (local and remote)

All of these functions were implemented on a four layer PCB measuring 4000x2000 mils [10.16x5.08 cm], which is described in Section 4.9. Fig. 47 is a block diagram of the power supply indicating the relative areas of each function:

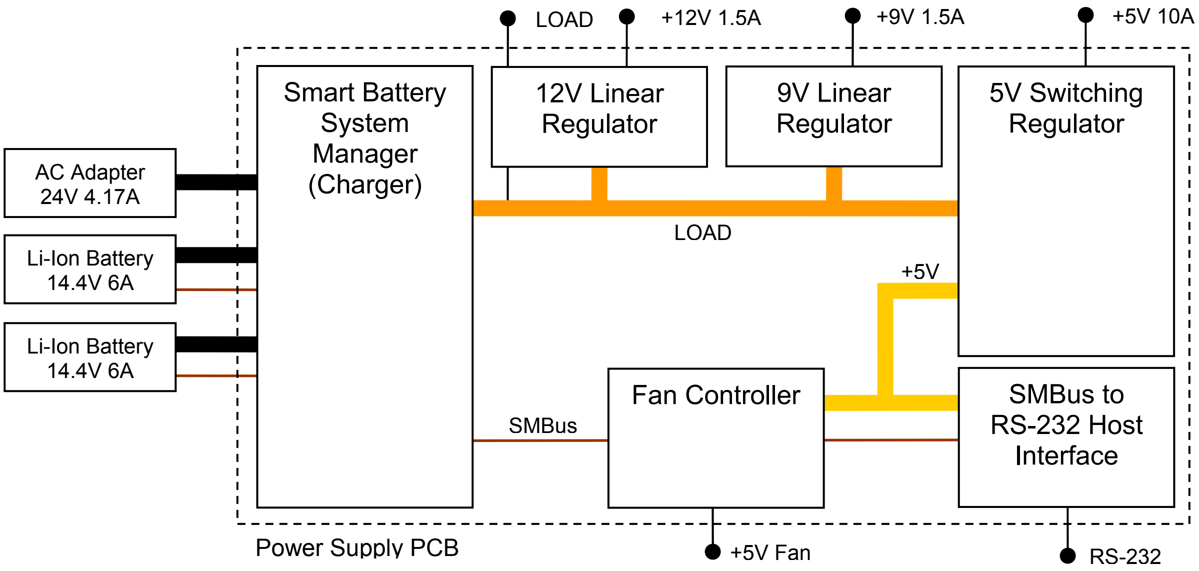


Fig. 47: Block Diagram of Power Supply

The main purpose of the power supply is to provide power for all of the devices in the WUC. The Smart Battery System Manager provides a combination of battery power and AC adapter power (depending on which power sources are currently present) to the various voltage regulators. This unregulated voltage is called the load voltage. Table 4 shows the approximate power requirements for each component in the WUC (please note that the WUC supports multiple HMDs, but only one at a time can be used):

Table 4: Power Requirements for WUC Components

Component	Voltage (V)	Maximum Power (W)	Tolerance (%)
Embedded Computer	5	30	±3
HDD	5	6.5	±5
1394a	5	0.3	±5
DSP/Microphone	5	1.25	
SmartProbe/Transducer	12-30	10	
HMD (eMagin)	5	1.25	
HMD (i-glasses)	9	7	
Fans	5	0.8	
802.11b/g	5	2.36	

Table 5 summarizes the total power required from each power source:

Table 5: Power Requirements by Regulated Voltage

Regulated Power Supply Voltage (V)	Minimum Power Required (W)
5	43
9	7

In addition to supplying power for the entire WUC system, the power supply can also supply information about its current power consumption and thermal conditions via an SMBus interface. This interface can also be used to program certain characteristics of the battery charger and fan controller using the RS-232 host interface. The following sections will show the details for the implementation of each of these functions.

4.3 Smart Battery System Manager

The Smart Battery System Implementers Forum (SBS-IF) has defined a complete system for managing and charging multiple rechargeable batteries. A Smart Battery System Manager [32], as defined by the SBS-IF, consists of a Smart Battery Charger [33], a Smart Battery Selector [34] and Smart Batteries [35].

This system derives its intelligence by adding an SMBus [31] interface to a standard rechargeable battery, making it a Smart Battery. A Smart Battery is a battery that conforms to the Smart Battery Data Specification [35]. This specification defines a model that allows a battery to communicate its internal state and characteristics to external devices. This allows for a mixture of batteries and battery chemistries to be used in a system and still provide accurate information about each battery. This brings along with it several advantages. Total system complexity can be reduced by not duplicating functions such as voltage and current measurements. Battery energy can be maximized and charging times minimized, since the battery can define the best charging scheme for its particular capacity and chemistry. Also, there is extra added safety, with the battery enforcing charging limits on the charger. There is also a thermistor in each Smart Battery that provides thermal protection. An example Smart Battery system is shown in Fig. 48:

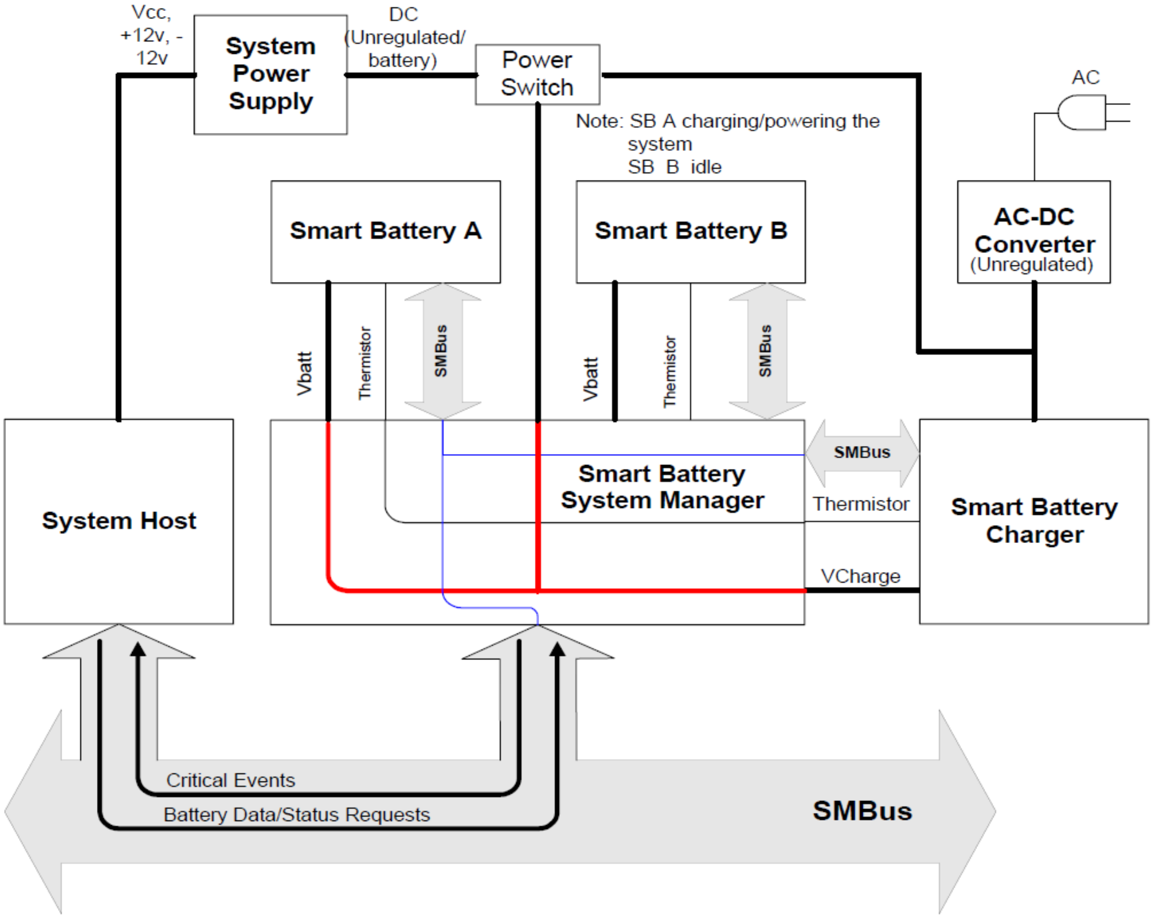


Fig. 48: Example Smart Battery system [32]

Each of the elements represented in Fig. 48 are implemented in the power supply. The key feature of a Smart Battery system is the SMBus that connects all of the major functional components together to bring intelligence to the system. Each block in Fig. 48 that starts with the word "Smart" has a corresponding SBS-IF specification by the same name.

As shown in Fig. 48, a Smart Battery system is designed to accommodate multiple batteries. The Smart Battery Selector specification details how the addition and removal of various batteries should be handled, simplifying the process of maintaining system power.

The charger circuit, developed for the power supply, is designed around a Linear

Technology LTC1760 Smart Battery System Manager, which also integrates Smart Battery Charger functionality. This chip is capable of charging up to two Smart Batteries from an AC power source, while still providing system power.

The major elements, besides the LTC1760 chip, are three power path switches and a switching regulator. The power path switches represent the "Power Switch" functionality described in Fig. 48. Each power path switch uses a pair of P-channel MOSFETs to diode connect and switch the various power sources to the system power bus. A single switching regulator is used to provide the requested charging voltage for both Smart Batteries.

The charger design is adapted from the reference design provided by Linear Technology. All equations in this section were described in the Applications Information section of the datasheet. Some component changes were required to adapt the design to the DC power supply used for charging, as well as a hardware enforced limit on charging voltage and current as an added safety measure. These limits were defined by the actual Smart Battery being used in the WUC system (described in Section 4.4). Also, some filtering capacitors must be properly sized to have a time constant that adequately filters switching noise. The reference design parameters that influence these values were not changed, so no variation from the reference design was required.

The LTC1760 will adjust the charging current, so as to not overload the DC power source. This limit is set by a resistor, whose value is determined by Eq. 1:

$$R_{CL} = \frac{100mV}{I_{LIM}} \quad (1)$$

Through experimental observation, it was determined that a DC power source of at least 22 V was required for proper operation of the Smart Battery Charger. The closest commercially available AC adapters operate at 24 V. The highest power AC adapters available are rated for 100 W, or a maximum current rating of 4.17 A.

Therefore, using Eq. 1, the value for R_{CL} was determined to be 24 mΩ. This value was rounded up to the standard value of 25 mΩ, giving a final input current limit of 4 A.

Since the entire current being drawn from the DC power supply must flow through the current limiting resistor, the maximum power dissipation possible is shown in Eq. 2:

$$R_{CL\_Power} = I_{LIM}{}^{2} R_{CL} = 4^{2} \cdot 0.025 = 0.4W \qquad (2)$$

The full specification for R_{CL} is therefore: 25 mΩ, 1 %, 0.5 W.

The rest of the design involves inductor selection for the switching power supply and the selection of two resistors to enforce charging limits. This is an additional safety measure, should there be some sort of failure in communication between the charger and the Smart Battery, which would normally set the charging limits.

The battery being charged requires a constant voltage of 16.8 V and maximally draws 4 A during charging. Since the maximum charging current of the LTC1760 is 4 A total, no charge current limiting is required.

The data sheet for the LTC1760 lists the value of the charging voltage limit resistor for setting a limit of 16.8 V as 33 kΩ.

The inductor value is determined from the desired ripple voltage in the inductor. The recommended value for the ripple current is 40 % of I_{MAX}, which is 4 A in this case. The ripple current, from the LTC1760 datasheet, is defined in Eq. 3 as:

$$\Delta I_L \geq \frac{1}{f \cdot L} V_{OUT} \left(1 - \frac{V_{OUT}}{V_{IN}} \right) \qquad (3)$$

Where:
f - switching regulator minimum switching frequency
V_{in} - supply voltage
V_{out} - charging voltage.

The minimum value for the inductor can then be determined by solving for the inductor value in Eq. 3 and substituting in a desired ripple current of 1.6 A (or 40 % of the maximum 4 A charging current):

$$L \geq \frac{1}{f \cdot \Delta I_L} V_{OUT}\left(1-\frac{V_{OUT}}{V_{IN}}\right) \geq \frac{1}{255\times 10^3 \cdot 1.6} 16.8\left(1-\frac{16.8}{24}\right) \geq 12.4\times 10^{-6} H \qquad (4)$$

Therefore, the full specification for L is: 10 μH, 4 A. It is also important to minimize the power loss in the inductor by selecting an inductor with the lowest DC resistance (DCR) possible. The specifications for the selected inductor are: 15 μH, 5 A and 25 mΩ.

The power path multiplexer uses three pairs of P-channel MOSFETs connected in series to switch the DC power supply and each Smart Battery in as power sources for the load. Each pair of PMOS devices have their sources connected together, with one drain connected to a power source and the other drain connected to the load, as shown in Fig. 49:

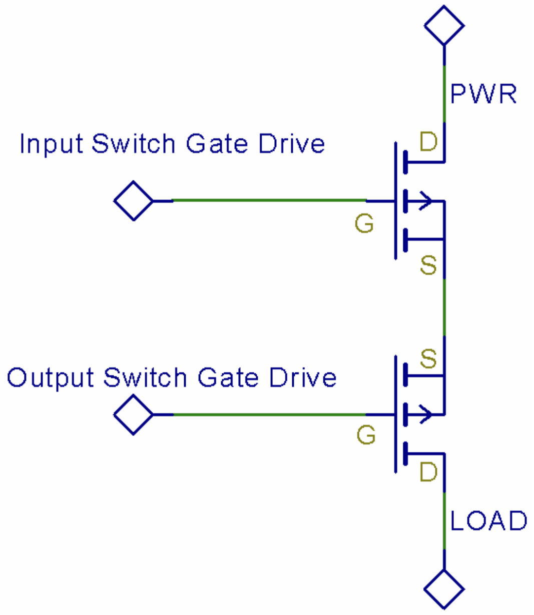


Fig. 49: Power Path Switch

This allows the LTC1760 to switch Smart Batteries between charging and powering the load, if a DC power supply is present. This also allows both Smart Batteries and the DC power supply to power the load simultaneously, or to be completely disconnected if a low-voltage or over-current condition is present.

4.4 Li-Ion Rechargeable Batteries

The WUC is designed to operate using any two rechargeable (secondary) batteries that conform to version 1.1 of the Smart Battery System Manager specification. The reasons for using two batteries are twofold. First, having two batteries doubles the available capacity and second, it allows for the hot-swapping of batteries. By hot-swapping a battery that is nearly empty, and replacing it with a fully charged battery, the system is able to continue operation without interruption.

There are many different types of rechargeable batteries available. Being a wearable system, a battery chemistry that minimizes weight and maximizes capacity is the ideal candidate. Also, in order to derive the required system voltages, a battery exceeding 12 V was required. Table 6 contains an overview of various rechargeable battery chemistry characteristics:

Table 6: Characteristics of Commonly Used Rechargeable Batteries [36]

	NiCd	NiMH	Lead Acid	Li-ion	Li-ion polymer	Reusable Alkaline
Gravimetric Energy Density (Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits) in mW	100 to 200[1] 6V pack	200 to 300[1] 6V pack	<100[1] 12V pack	150 to 250[1] 7.2V pack	200 to 300[1] 7.2V pack	200 to 2000[1] 6V pack
Cycle Life (to 80% of initial capacity)	1500[2]	300 to 500[2,3]	200 to 300[2]	500 to 1000[3]	300 to 500	50[3] (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Self-discharge / Month (room temperature)	20%[4]	30%[4]	5%	10%[5]	~10%[5]	0.3%
Cell Voltage (nominal)	1.25V[6]	1.25V[6]	2V	3.6V	3.6V	1.5V

Load Current - peak - best result	20C 1C	5C 0.5C or lower	5C[7] 0.2C	>2C 1C or lower	>2C 1C or lower	0.5C 0.2C or lower
Operating Temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months[9]	not req.	not req.	not req.
Typical Battery Cost (US$, reference only)	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per Cycle (US$)[11]	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10-0.50
Commercial use since	1950	1990	1970	1991	1999	1992

The C-rate is a unit by which charge and discharge currents are scaled. A charge current of 1000 mAh, or 1 C, will charge a 1000 mAh battery in slightly more than one hour. A 1 C discharge lasts one hour.

From Table 6, it can easily be seen that Li-Ion batteries have the highest gravimetric energy density available (measured in Wh/kg). However, Li-Ion batteries also have the most stringent charging requirements and do not tolerate over-charging or over-discharging. The use of a Smart Battery Charger helps to mitigate this issue and provide a safe and reliable power source.

Based on the requirements in Table 4 and Table 5, a rechargeable battery that maintains at least 12V is required to power the system. *Inspired Energy* is the only manufacturer that sells Li-Ion battery packs commercially. The largest capacity battery they carry is nominally rated for 6.6 Ah. With a nominal voltage of 14.4 V, this capacity can also be expressed as 95.04 Wh. With two packs in use, the total capacity is as much as 190 Wh.

Each battery, model NL2024A22, uses a constant voltage charging algorithm and draws a maximum of 4A while charging. The battery pack is arranged as a 4 series/3 parallel (4S 3P) combination of individual Li-Ion cells. Each individual cell has a nominal voltage of 3.6V and a nominal capacity of 2.2 Ah [7.9 Wh]. The battery pack weighs 0.647 kg [1.43 Lbs.] and measures 16.751 x 10.287 x 2.093 cm [6.595 x 4.050 x 0.824 in.]. The NL2024A22 battery is pictured in Fig. 50:

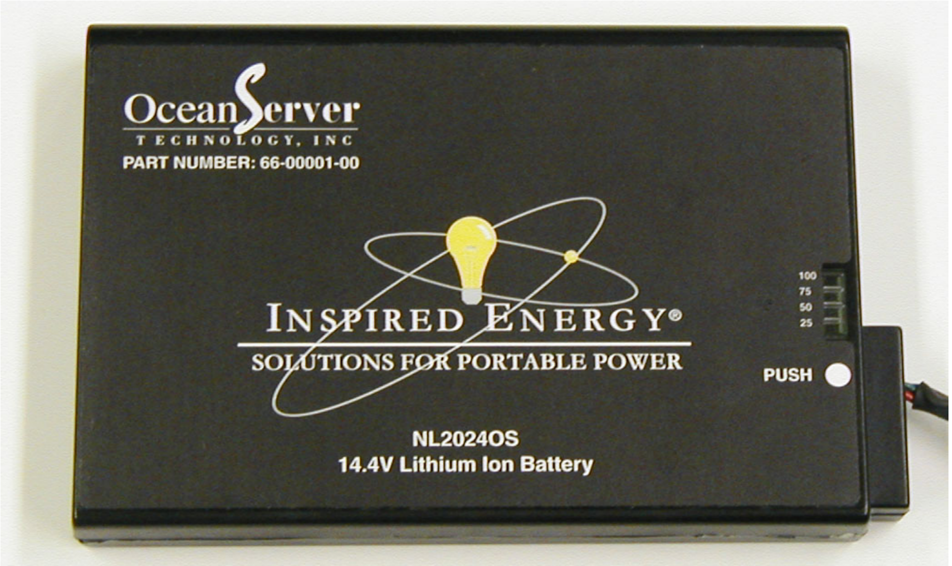


Fig. 50: Inspired Energy NL2024A22 Rechargeable Li-Ion Battery

Since the NL2024A22 is a Smart Battery, it implements the Smart Battery interface and requires a Smart Battery Charger to properly charge it. It also includes a fuel-gauge and protection circuitry to prevent an over-charge or over-discharge condition. Fig. 51 shows a block diagram of the battery pack:

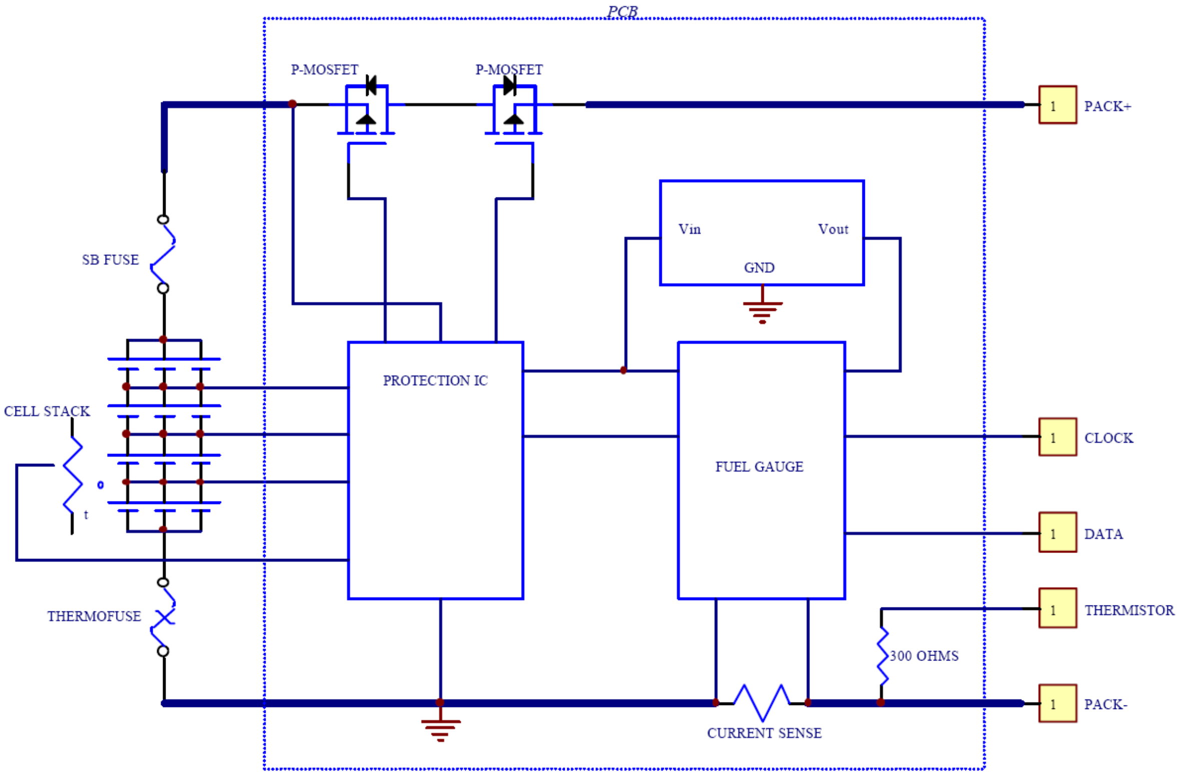


Fig. 51: Block Diagram of Smart Battery Pack [37]

The three extra signals: clock, data and thermistor, are part of the SMBus interface, used by the Smart Battery to communicate with the Smart Battery Charger. More details on this interface are provided in Section 4.7.

4.5 5V Switching Regulator

There are two distinct categories of voltage regulators suitable for providing a lower regulated voltage from a higher unregulated voltage. There are linear regulators, which regulate the output voltage using an internal network of transistors and generally have few pins, and there are also switching regulators, which generally control external circuitry to provide a regulated voltage. While both classes of regulators perform the same function, each has different attributes, as summarized in Table 7:

Table 7: Attributes of Linear and Switching Regulators [38]

	Linear	Switching
Function	**Only steps down**; input voltage must be greater than output.	**Steps up, steps down, or inverts**
Efficiency	**Low to medium,** but actual battery life depends on load current and battery voltage over time; **high** if V_{IN}-V_{OUT} difference is small.	**High,** except at very low load currents (μA), where switch-mode quiescent current is usually higher.
Waste Heat	**High** if average load and/or input/output voltage difference are high	**Low** as components usually run cool for power levels below 10W
Complexity	**Low**, which usually requires only the regulator and low-value bypass capacitors	**Medium to high** which usually requires inductor, diode, and filter caps in addition to the IC; for high-power circuits, add external FETs
Size	**Small to medium** in portable designs, but may be larger if heatsink is needed	Larger than linear at low power, but smaller at power levels for which linear requires a heat sink
Total Cost	**Low**	**Medium to high** largely due to external components
Ripple/Noise	**Low**; no ripple, low noise; better noise rejection.	**Medium to high** due to ripple at switching rate

In the case of the power supply, an unregulated 12-24 V input voltage (depending on whether the system is powered from a 24 V AC adapter or the Li-Ion batteries in varying states of discharge) must be regulated to 5 V. Since the regulated voltage is not more than 42 % of the input voltage, a switching regulator will provide superior efficiency. Also, a switching regulator often provides better load regulation when current requirements change dramatically. Modern CPUs can quickly draw several Amperes of current when switching from a power-conservation mode to a more active mode. In light of the amount of power being drawn from the regulated 5 V supply (> 43 W, from Table 5) and the nature of the load (rapidly changing current requirements), the efficiency gains offered by using a switching regulator over a linear regulator justify the added complexity.

The 5 V power supply is a switching regulator designed around a Linear Technology LTC1775 controller chip. This chip is a synchronous step-down switching regulator operating at 150 kHz that, when used with the appropriate components, provides up to 20 A of current at 5 V, or 100 W. It can respond to severe load changes in hundreds of micro-seconds and is >90 % efficient throughout the loads that the system will present.

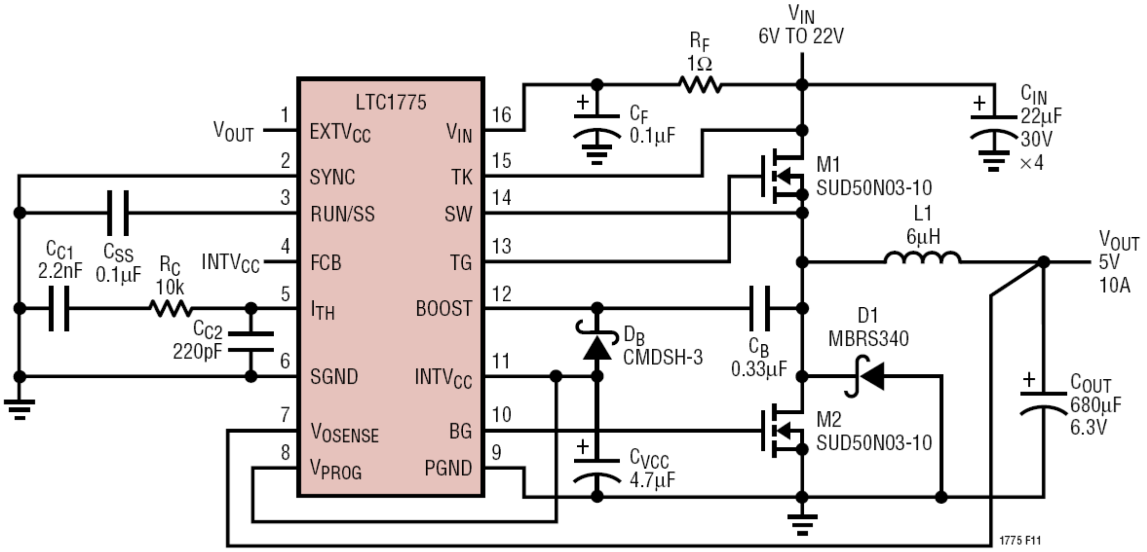
The input voltage to the switching regulator can be as high as 30 V, although it is expected that a range of 12–24 V will be present. The performance of the final design is presented in Section 9.2.

The LTC1775 has a soft start feature that enables the output current to ramp up, which reduces the inrush current to the load. An external capacitor is charged by an internal 3 μA current source. As the voltage on this capacitor increases, the output current limit is increased. This relationship is given in Eq. 5:

$$t_{DELAY} = \left(\frac{1s}{1\mu F}\right) C_{SS} \tag{5}$$

In the case of the reference design used to implement the power supply, the delay time is 100 ms.

The implemented design was mostly taken from a reference design provided by Linear Technology. Fig. 52 shows the reference design used:



C_{IN}: SANYO 30SC22M
C_{OUT}: SANYO 6SP680M
L1: MAGENTICS 55380-A2, 8 TURNS, 15 GAUGE

Fig. 52: Power Supply Reference Design [39]

Switching regulators operate by rapidly switching transistors on or off to manipulate the charge flowing into an inductor. A full duty cycle involves turning on the M1 MOSFET, then turning off the M1 MOSFET and turning the M2 MOSFET on and then off. The period of a full cycle is the switching frequency, which is 6.7μs in this case.

As the M1 MOSFET turns on, current flows into the output capacitor and the load. Once a current threshold is reached (measured by the V_{DS} of M1 exceeding 300 mV), the M1 MOSFET turns off and the M2 MOSFET turns on. The cycle will repeat once the switching period has passed. By varying the duty cycle, a constant voltage is maintained for varying load currents.

The potential output current is dependent on the MOSFETs and the inductor. For the MOSFETs, there are two main parameters to be concerned with: R_{DS} and I_D. The I_D parameter can be read directly from the datasheet for the MOSFET. The R_{DS} parameter, or the on-state resistance, must be low enough so that V_{DS} does not exceed 300 mV. Since the LTC1775 uses the R_{DS} of the MOSFET to determine the current through the inductor, the MOSFET should have a maximum R_{DS}, given by Eq. 6:

$$R_{DS(ON)(MAX)} \cong \frac{240mV}{I_{O(MAX)}\rho_T} \qquad (6)$$

The ρ_T term is used to normalize the equation for the wide variations in R_{DS} that occur with temperature changes. Ignoring this term (by setting it to 1) yields a maximum R_{DS} of 24 mΩ. The MOSFET used in the reference design exceeds this requirement with a worst case R_{DS} of 19 mΩ.

The inductor is required to carry all of the output current, and must be properly rated to handle the expected 10 A saturation current. The actual value of the inductor can be found by reusing Eq. 4 and substituting in a desired ripple current of 4 A (or 40 % of the maximum 10 A current). The final equation is shown in Eq. 7:

$$L \geq \frac{1}{f \cdot \Delta I_L} V_{OUT}\left(1-\frac{V_{OUT}}{V_{IN}}\right) \geq \frac{1}{135\times 10^3 \cdot 4} 5\left(1-\frac{5}{24}\right) \geq 7.33\times 10^{-6} H \qquad (7)$$

Therefore, the full specification for the inductor is: 7.3 μH, 10 A. It is also important to minimize the power loss in the inductor by selecting an inductor with the lowest DCR possible.

There are two variations from the reference design that were required to achieve reliable operation. These were the disabling of burst mode, and a change in the value of the boost capacitor (C_B).

Burst mode is an operational mode whereby both MOSFETs are off for some period of time during the switching cycle. This is meant to provide better efficiency during low-current operation where the capacitor charge can supply the load current. Burst mode is slower to respond to abrupt load changes, as are often found in modern microprocessors. Starving a microprocessor of required current can result in latch-up of the internal transistors and lead to unreliable operation. Therefore, this operational mode was disabled.

Another change that was required was a modification to the value of the boost capacitor (C_B). This capacitor provides the gate drive voltage for the M1 MOSFET. It is charged through the Schottky diode D_B from an internal voltage regulator when the M2 MOSFET is conducting. When the M1 MOSFET is conducting, the boost capacitor floats between the gate and the source of M1. The reference value of .33 μF was found to be too low to carry enough charge for driving the gate long enough. This value was doubled to .66μF.

4.6 Linear Regulators

In order to have various peripheral devices integrated into the system, several other regulated voltages are required. To fulfill this need, two adjustable linear voltage regulators have also been included.

Each regulator is capable of providing up to 1.5 A of current at output voltages ranging from 1.2-37 V with a maximum dropout voltage of 2 V. The same unregulated 12-24 V input voltage used to power the 5 V switching regulator is also used to provide power to each of the linear regulators.

The voltage is adjusted by means of a 1.25 V reference voltage provided by a voltage divider. The voltage divider is connected to the output voltage to provided feedback to the device for load regulation, as shown in Fig. 53:

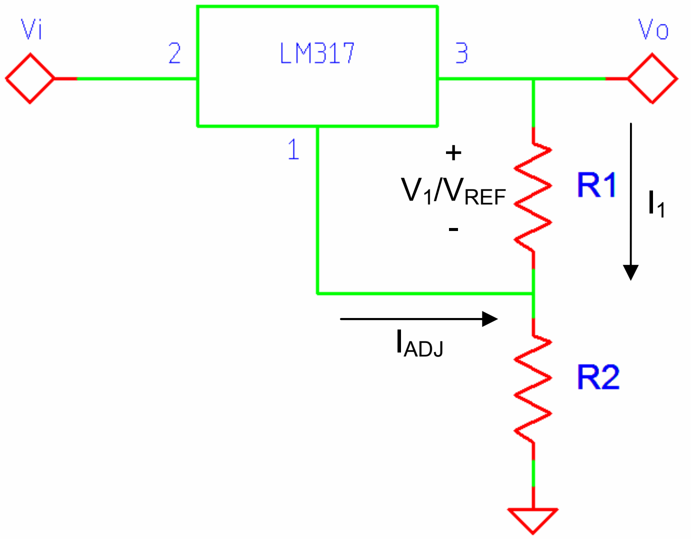


Fig. 53: Output Voltage Adjustment of Linear Voltage Regulator

Eq. 8 shows how to determine the output voltage by using two external resistors. Note that since $I_1 >> I_{ADJ}$, the I_{ADJ} current can safely be ignored.

$$V_O = V_{REF}\left(1+\frac{R_2}{R_1}\right) \tag{8}$$

By assuming R_1 is connected between the output and the reference terminals, and is kept constant at 237 Ω (an example value in the data sheet), we can derive an exact representation for R_2:

$$R_2 = R_1\left(\frac{V_O}{V_{REF}} - 1\right) \qquad (9)$$

One peripheral device that requires a regulated voltage other than 5V is the HMD. It requires up to 7 W of power at 9 V. By substituting into Eq. 9 the desired output voltage of 9 V, R_2 is found to be 1.469 kΩ. This is rounded to the closest available value of 1.47 kΩ in the design. At 9 V, the linear regulator can supply up to 13.5 W of power, which is more than adequate to power the HMD.

4.7 SMBus to RS-232 Host Interface

The SMBus [31] was originally designed by the Intel Corporation in 1995. It is found in personal computers and utilized for system-management communication. In a personal computer, the SMBus is used for system management by connecting temperature sensors, microprocessors, memory and other peripherals to an SMBus controller. The SMBus is a 2-wire serial bus using a master/slave architecture and a maximum data rate of 100 kb/s. It supports two physical layer types, a low-power and a high-power mode. The main difference is in the pull-up resistors used and the currents that the bus can be driven with. The signaling voltage can be between 2.7 V and 5.5 V, allowing a wide range of device to be directly connected.

The Smart Battery System Manager (LTC1760) has three SMBus connections. Two are used for connections to each of the Smart Batteries, while the third can be used to connect to a host SMBus. It is important to note that the Smart Battery charger does not require a host to operate. However, providing this connection will allow the host to directly access the data provided by each Smart Battery, as well as the Smart Charger. In this instance, the host is the embedded computer.

Since there is no SMBus interface available on the selected embedded computer, an interface was designed using a microcontroller and an RS-232 transceiver. The selected microcontroller was from *PICmicro* (PIC16LF767), and it integrates a master capable Inter-Integrated Circuit (I^2C) [40] controller and a UART. A UART is hardware device that converts between serial and parallel data, accessed from disjoint clock domains. This reduced the complexity of the accompanying software, since the microcontroller has a hardware peripheral for each bus that was to be interconnected. This device was selected due to it being the smallest device currently available from Microchip that support a master capable I^2C controller and a UART. While the device is capable of operating with a clock as fast as 20 MHz, only a 3.68 MHz clock was used. This clock speed results in convenient operation of the UART, as well as reduced power consumption while still achieving adequate performance.

The I^2C bus has a similar physical layer to the SMBus. It is physically compatible, with the only major difference being the I^2C clock rate is reduced from 400 kHz to 100 kHz for SMBus. The data link layer, however, is significantly different. The embedded I^2C controller in the microcontroller is master capable, but requires software for controlling the data link layer. By providing software to make the I^2C master act as an SMBus master, the I^2C can be made to act as an SMBus master.

The microcontroller also integrates an asynchronous UART that is appropriate for use with many serial data protocols. RS-232 was chosen due to its availability on the embedded computer and its ubiquity in standard desktop computers. The use of this UART in an RS-232 signaling environment requires the use of a transceiver to level shift the incoming 5V signal to ±15 V. This function was provided by a Maxim RS-232 transceiver (MAX3221CAE+) with auto shutdown. This device uses two charge-pumped power supplies to provide the ±15 V required for RS-232 signaling. The auto shutdown feature allows the chip's onboard power supply and drivers to shut-down and draw only 1 µA of current when no valid signal is sensed on any receiver inputs.

In addition to the microcontroller and the Smart Battery charger, there is also a fan controller on the SMBus. The specifics of the fan controller are discussed in Section 4.8. A complete diagram of the SMBus is shown in Fig. 54:

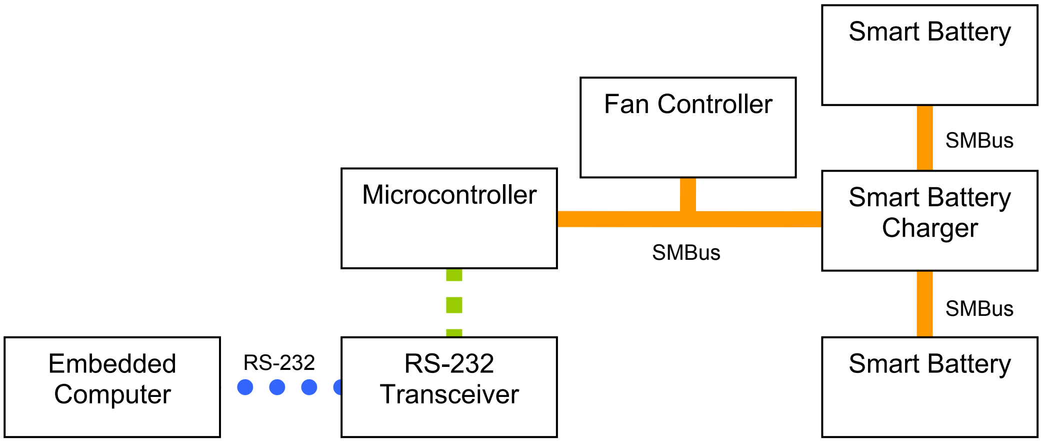


Fig. 54: Power Supply SMBus Block Diagram

Each device on an SMBus has a 7-bit address. The Smart Battery Charger provides an SMBus multiplexer to select either Smart Battery for direct communications. Table 8 summarizes the SMBus memory map:

Table 8: SMBus Memory Map

Device	Address
Smart Battery Charger (LTC1760)	0x14 [0001 010X]
Smart Battery	0x15 [0001 011X]
Fan Controller (ADM1030)	0x5C [0101 110X]

There are two signals used in the SMBus: SMBDAT and SMBCLK. Each SMBus device drives each signal using an open collector driver. Fig. 55 shows a generic SMBus topology that uses mixed supply voltage devices:

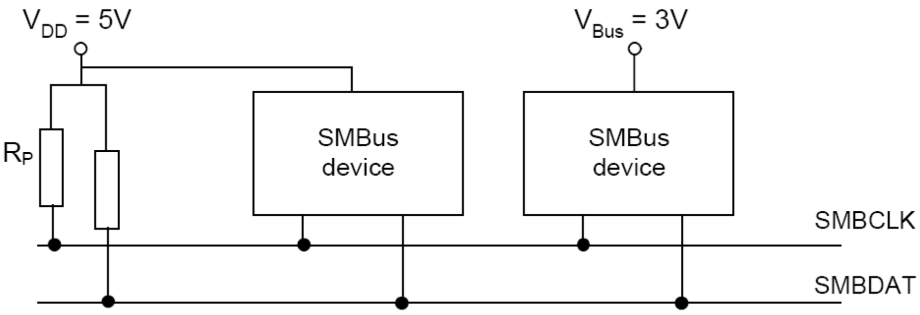


Fig. 55: Generic SMBus Topology [40]

All protocols start with the assertion of START condition on the bus. The START condition is defined as SMBDAT transitioning from HIGH to LOW, while SMBCLK is HIGH. After the generation of a START condition, the bus is considered to be busy.

A STOP condition is used to signal the end of a bus cycle, either by normal or abnormal conditions. It is defined as SMBDAT transitioning from LOW to HIGH, while SMBCLK is HIGH. The bus is considered idle after the generation of a STOP condition.

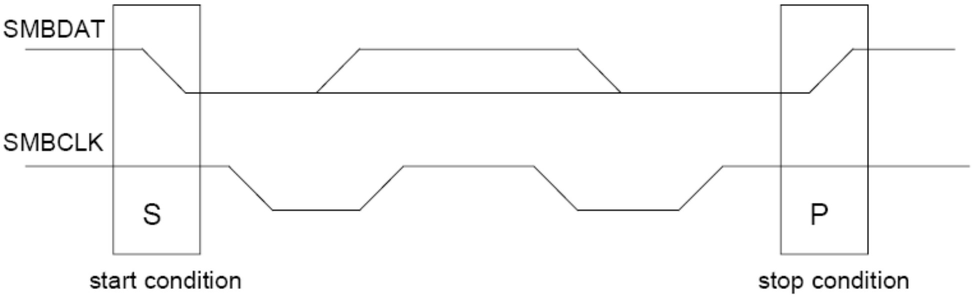


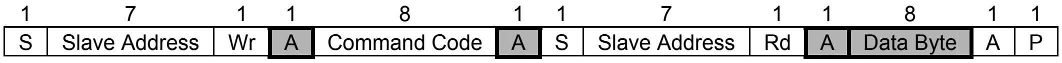
Fig. 56: SMBus START and STOP Conditions [40]

Note that the state of SMBDAT, between the START and STOP conditions, will vary depending on the data being transferred.

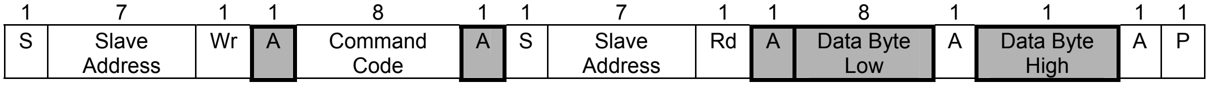
The SMBus defines several bus protocols. The four implemented protocols are:

- Read Byte
- Write Byte
- Read Word
- Write Word

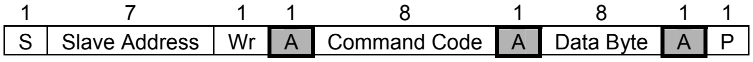
Each of these protocols has a slightly different set of bus cycles associated with it, and each is summarized in the following tables. Note that the number above each bus cycle is the bit length of each protocol segment.



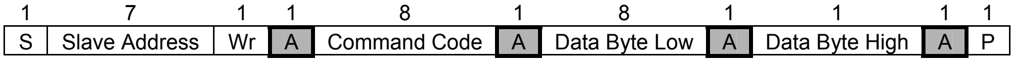
(a) SMBus Read Byte Protocol



(b) SMBus Read Word Protocol



(c) SMBus Write Byte Protocol



(d) SMBus Write Word Protocol

Fig. 57: SMBus Protocols

Table 9: SMBus Protocol Mnemonics

Mnemonic	Definition
S	START condition
Rd	Read (bit value of 1)
Wr	Write (bit value of 0)
x	Don't care value
A	Acknowledge (0 for ACK, 1 for NACK)
P	STOP condition
☐	Master-to-Slave

▨	Slave-to-Master
…	Continuation

Data is transferred on the falling edge of SMBCLK. There are further provisions in the specification for arbitration between multiple bus masters, collision detection, device timeouts and clock stretching to allow slower slaves to successfully communicate with a faster bus master.

The host communicates with the SMBus master by using a 4-Byte command packet. The packet has the following format:

7	1	8	8	8
SMBus Address	Rd/Wr	Command Code	Data Byte Low	Data Byte High

Fig. 58: Host SMBus Command Packet

Regardless of the size of the desired protocol, the same command packet format is always used. After receiving an entire 4-Byte packet, the microcontroller will determine the proper bus cycle to execute, based on the SMBus address and the Rd/Wr bit. Accesses to the fan controller are always Byte sized, while accesses to the Smart Battery Charger or a Smart Battery are always Word sized. Bit 5 of the SMBus Address (bit 6 of the first Byte in the command packet) determines the access size by uniquely identifying which device will be accessed. This is due to the unique memory map of the SMBus devices on the power supply.

Once a full command packet has been received, the microcontroller will index into a jump table and execute the specified bus protocol. Whether reading or writing, the microcontroller will always return one or two Bytes back to the host (depending on the access size) for synchronization purposes. If a write protocol was performed, the returned data is discarded. This synchronization is important, in order to avoid issuing a new command while a bus protocol is executing. Each command packet is stored on the microcontroller and referenced during the bus operation. Sending a new command packet, before the previous bus protocol had completed, could lead to unexpected behavior and possibly lock up the microcontroller.

It has been observed that the Windows operating system can occasionally write spurious data out of the serial port. To manage this, the microcontroller includes a watchdog timer with a timeout of 8.39 s. Therefore, if the microcontroller locks up, it will return to normal operation within 8.39 s. The timeout value is specified as a certain number of periods of a local 31.25 kHz oscillator. In this instance, the multiple is 262,144, or $2x10^{18}$. The timeout value is long enough to not interrupt normal execution, but short enough to reset the microcontroller within a reasonable time period.

4.8 Fan Controller

The embedded computer uses a pair of fans to provide active cooling. Each fan is a 40x6 mm box fan, capable of pushing 5.5 CFM of air per fan, for a total of 11 CFM of air flow. Also, at the full rotational speed of 6000 RPM, each fan draws as much as 400 mW, for a total of 800 mW. A temperature controlled fan controller, provided by an Analog Devices ADM1030, was used to vary the fan speed, based on the current thermal conditions. This allows for reduced power consumption by not always running both fans at full speed.

During periods of low processor utilization, the CPU within the embedded computer can reduce its power consumption dramatically. At peak load, the CPU consumes as much as 12.96 W of power, running at 1.4 GHz and a core voltage of 1.116 V. When idle, the CPU runs at 600 MHz, consuming as little as 2 W of power, with a core voltage of 0.988 V. Depending on the environmental conditions, passive cooling may be all that is required.

The ADM1030 uses two temperature sensors, in conjunction with several registers on the device, to determine the proper fan speed. One temperature sensor is located within the ADM1030 itself and measures the ambient temperature within the enclosure. The remote temperature sensor is located on the heatsink, near the

CPU, and attached with a thermally conductive epoxy. This temperature sensor is created by measuring the change in V_{BE} of a general purpose 2N3906 PNP transistor, when operated at two different currents. This temperature measurement technique is described in Eq. 10:

$$\Delta V_{BE} = \frac{KT}{q} \ln(N) \tag{10}$$

Where:
K - Boltzmann's constant
q - charge on the carrier
T - temperature in Kelvins
N - ratio of the two currents

By using the ratio of two currents, the device to device variation in V_{BE} can be nullified.

The registers on the ADM1030 are accessed using the same SMBus used for host communication, with the Smart Battery Charger and Smart Batteries. In turn, the temperatures and fan speed are also available to the host.

The fans are controlled together, as if they were a single fan. The fan speed is controlled by pulse width modulation (PWM). This is a technique to provide different amounts of power to a device, by varying the duty cycle of a square wave. The amplitude of the square wave is constant and set to the supply voltage of the fans. In this case, the fans are designed to operate with a 5V supply. By running at less than 100% duty cycle, the fans can effectively be operated at lower speeds and power levels.

Fig. 59 and Fig. 60 show the control loops programmed into the ADM1030:

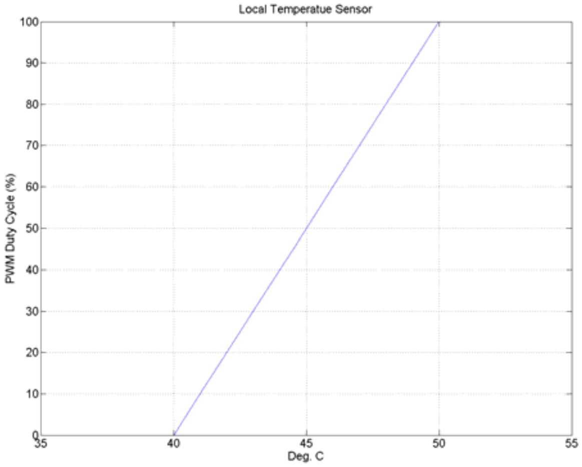


Fig. 59: Local Temperature Sensor Control Loop

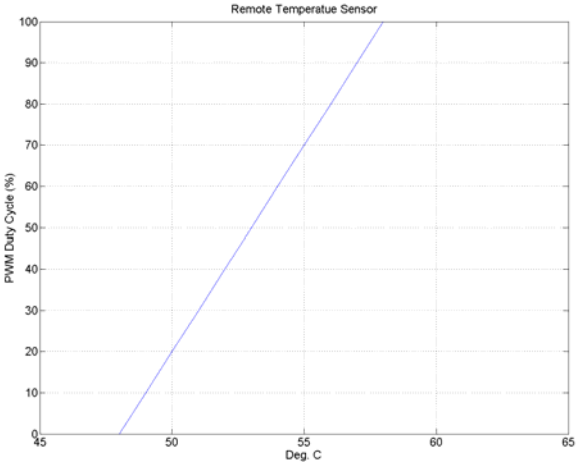


Fig. 60: Remote Temperate Sensor Control Loop

The control loops are arranged so that the highest duty cycle determined, by either control loop, is the actual duty cycle used.

4.9 Power Supply PCB Design

A custom board was designed for the power supply, in order to fit all the required functionality into the available space. No combination of off-the-shelf components met both the space and functionality requirements. The entire board was designed and populated in-house, using available software tools and labor resources.

The power supply was design using tools from *Mentor Graphics*. The DesignView-Expedition tool flow was used. The board has a total of four layers, three of which are used for signal routing and two of which are used for power planes (one layer is split, with one-half being a power plane and the other half used for signal routing). The finished board is made of FR-4 material and finished in a green soldermask with tin-plated land pads and a white silkscreen. The dimension of the board is 10.16 x 5.08 cm [4000 mils x 2000 mils], with an area of 51.62 cm^2 [8 in.^{2}]. Appendix V – PCB Layout contains shows the complete stackup for the board. The finished board is shown in Fig. 61:

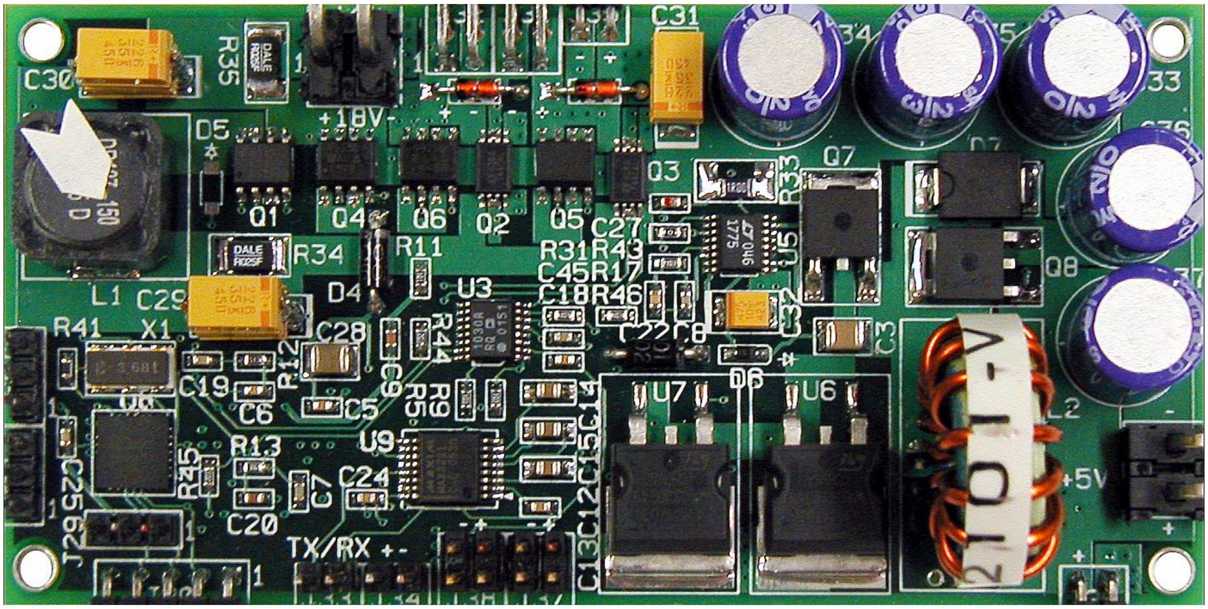


Fig. 61: Populated Power Supply PCB

The design rules were defined by the board-house and are summarized in Table 10:

Table 10: PCB Design Rules

Design Rule	Description
Inner Layer Clearances	A minimum of 0.010" inner layer clearance.
Copper to Edge of Printed Circuit Board	Minimum of 0.010" (outer layers) and 0.014" for inner layers (0.020" preferred for inner layers). For scoring, minimum of .015 for outer layers and .020 for inner layers.
Pad Size/Annular Ring	Pad size should be at least + 0.010" over finished hole size for vias and + 0.014" over finished hole size for component holes. This means the annular ring (radius of the pad) should be at least .005" for vias and a minimum of 0.007" for component holes.
Hole Size	+/- 0.005" Prototype +/- 0.005" Production default +/- 0.003" Production upon request 1 oz and 2 oz finished copper weight only Minimum finished hole size; 0.010".
Printed Circuit Board Thickness	Overall may vary +/- 10% (Minimum +/- 0.005") • Minimum finished thickness for 2-layer: 0.005" • Minimum finished thickness for 4-layers: 0.020" • Minimum finished thickness for 6-layers: 0.031" • Minimum finished thickness for 8-layers: 0.047" Minimum finished thickness for 10-layers: 0.062"
Inner Layer Thickness	Tolerances do not apply to the inner layers of prototypes.
Rout (Board Outline)	+/- 0.010"

Design Rule	Description
Copper Trace Width/Spacing	This is the minimum air gap between any two adjacent copper features. Trace width is the minimum width of a copper feature, usually traces. • For trace width/spacing, we require a minimum of 0.005" for 1 oz. finished copper weight on outer layers. Premiums are added for trace/space specs less than 0.008" • For 1 oz. finished copper weight (inner layers), minimum trace width/space is 0.005" • For 2 oz. finished copper weight (inner & outer), minimum trace width/space is 0.007" • For 3 oz. finished copper weight (inner & outer), minimum trace width/space is 0.010" • For 4 oz. finished copper weight (inner & outer), minimum trace width/space is 0.012"
Trace Width/Air Gap	The greater of +/- 20% or +/- 0.002"
Soldermask Swell	This is the expansion of mask relief over pad area. Our minimum is 0.005" over pad dimension or 0.0025" each side. Advanced Circuits will modify files to meet the minimum dimension.
Slot Width	Minimum 0.031" in width.
Tab Rout Spacing	Please allow 0.100" spacing between your individual PCBs for tab rout spacing. When scoring there should be no spacing between boards.
Silkscreen (Legend)	0.008" minimum line width.

In general, the manufacturer’s suggested layout guidelines were followed for each individual integrated circuit. The addition of two capacitors to the output of the 5 V switching regulator was required to limit the coupling of the switching noise to other parts of the board. This also reduced the switching noise present on the 5 V output.

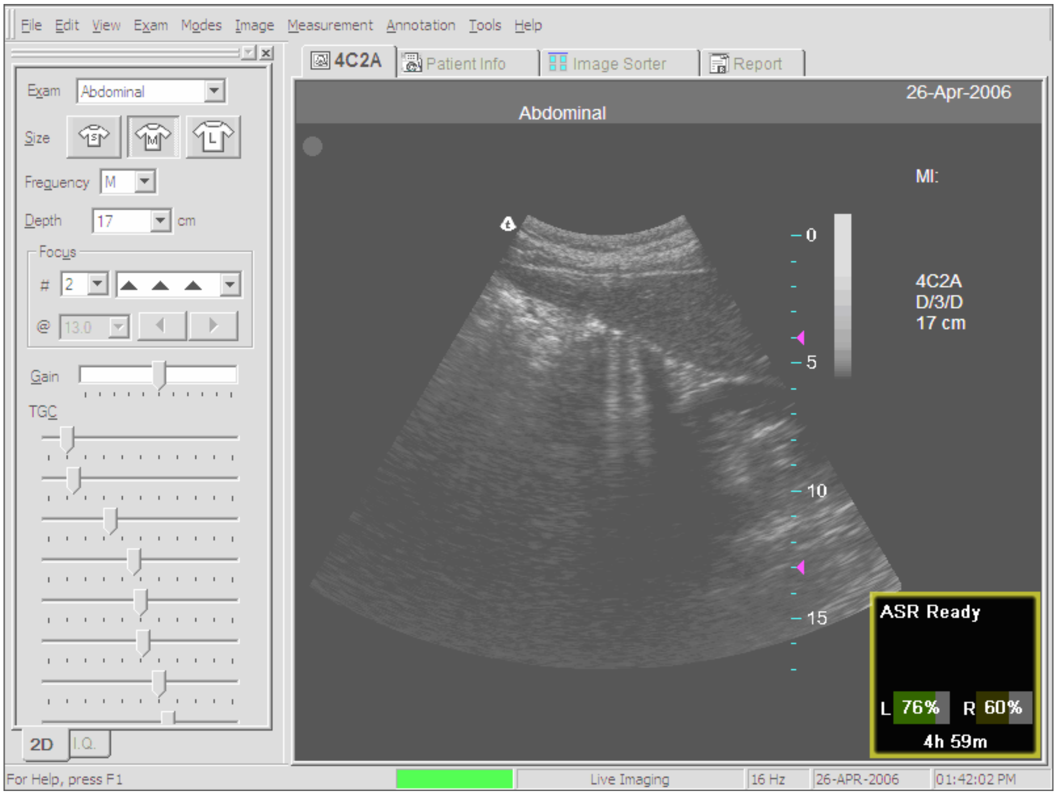
4.10 IEEE 1394a Power Supply

The typical bus power used on IEEE 1394a links is 12 V. In the case of the WUC, only the Terason SmartProbe is being supplied with 1394a bus power. The SmartProbe has an input voltage range of between 12 and 30 V. Using this range, the SmartProbe can be directly powered from either the Smart Batteries or the AC adapter. This results in a range of voltages, between 12 and 24 V, appearing for 1394a bus power. However, the 1394a interface board cannot withstand 1394a bus voltage in excess of 22 V. Also, it has been observed that the SmartProbe will draw as much as 5 W of power when the host system is off, but the SmartProbe is still connected to 1394a bus power. Therefore, some modifications to the 1394a interface board were required.

To reduce the power consumption of the SmartProbe, when the system is off, an optically coupled relay circuit was introduced. This relay circuit is controlled using the parallel port on the host computer and allows 1394a bus power to be switched on and off via software. Also, the interface board was modified so the 1394a bus voltage would not appear anywhere on the board. This was achieved by removing some components on the 1394a interface board to isolate 1394a bus power being supplied by the relay. A schematic for the relay appears in Appendix IV – Schematics.

4.11 User Interface

The power supply provides information to the user of the WUC by means of a small window inserted over the Terason application. This overlay is called the Dashboard, and is made to appear as if it is part of the normal Terason application interface. In reality, it is a separate window, located in the lower right-hand corner of the display. The window is decorated to blend in with the Terason application. It has no title bar or border, and uses a similar background and foreground color. Fig. 62 highlights the location of the Dashboard within the Terason application:



Exam Abdominal

Frequency M

Depth 17 cm

Focus # 2

@ 13.0

26-Apr-2006

Abdominal

4C2A
D/3/D
17 cm

ASR Ready

L 76% R 60%

4h 59m

For Help, press F1

Live Imaging

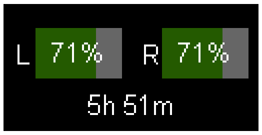
16 Hz

26-APR-2006

01:42:02 PM

Fig. 62: Dashboard

The dashboard contains several pieces of information, some of which is explained in later sections. The information pertaining to the power supply is contained in the bottom half of the Dashboard and is highlighted in Fig. 63:



L 71% R 71%

5h 51m

Fig. 63: Power supply area of the Dashboard

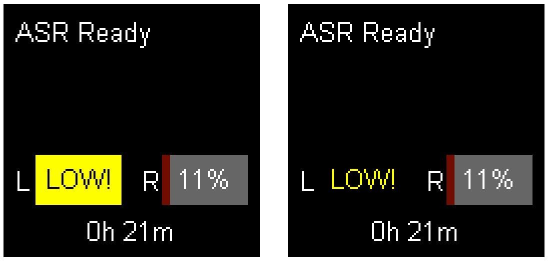
The WUC can accommodate up to two batteries. Information about the remaining capacity for each battery is displayed separately in the Dashboard. The *L* and the *R* are intended to show whether the battery is in the left or right breast pocket respectively. This information is reported directly from the Smart Battery, using the SMBus to RS-232 Host Interface.

The remaining capacity is indicated through three different display methods. The first method is a textual representation of the remaining capacity as a percentage of the total capacity of the battery. For example, each battery in the WUC has an initial capacity of 95 Wh. At 71 %, approximately 61 Wh of energy remain. The second method uses the color of the background to indicate the relative remaining capacity. The colored portion of the background will change from green to red as the capacity decreases from 100 to 11 %. The third method is the amount of colored area versus the amount of gray area. This area is also drawn relative to the remaining capacity of the battery.

The total capacity of Li-Ion batteries will slowly diminish over the course of thousands of charge and discharge cycles. This translates into less and less total actual capacity for the same displayed remaining capacity. The electronics, in the Smart Battery, constantly monitor the charge going into and out of the battery and uses this to determine the actual capacity of the battery, as opposed to the original rated capacity. This information, along with a two minute average of the current being drawn from the Smart Battery, allows for directly predicting the remaining battery time until empty. The empty condition, as defined by the batteries used in the WUC, is indicated when any individual Li-Ion cell has a voltage of < 2.9 V.

The remaining time until empty, as reported by each Smart Battery, is displayed at the bottom of the Dashboard, in hours and minutes. The displayed remaining time until empty is determined by averaging the remaining time reported by each Smart Battery. This time represents the predicted total remaining runtime of the WUC.

The Dashboard also displays a warning when any individual Smart Battery is either below 11 % remaining capacity, or reports a remaining time until empty as less than 21 minutes. The warning is displayed by changing the battery indicator to a blinking yellow/black box with the text “LOW!” displayed in a reverse color. The indicator will reverse colors every second.


ASR Ready

L LOW! R 11%

0h 21m

ASR Ready

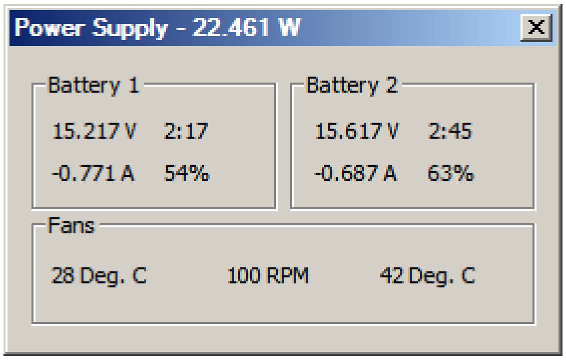
L LOW! R 11%

0h 21m

Fig. 64: Low Battery Warning Indicator

In addition to displaying a warning for each individual Smart Battery, a warning will also be displayed if the total remaining time is less than 21 minutes. This is displayed by changing the color of the remaining time indication to yellow.

Further information about the status of the power supply is also provided by a dialog box. This dialog box, among others, is accessible via a pop-up menu. The pop-up menu is displayed by clicking with the right mouse button on the Dashboard. Selecting the "Power Supply…" option will display the Power Supply dialog box shown in Fig. 65:


Power Supply - 22.461 W

Battery 1
15.217 V 2:17
-0.771 A 54%

Battery 2
15.617 V 2:45
-0.687 A 63%

Fans
28 Deg. C 100 RPM 42 Deg. C

Fig. 65: Power Supply Dialog Box

The power supply dialog box displays all of the remaining information that is routinely gathered using the SMBus to RS-232 Host Interface. When the dialog box is displayed, the information it contains is updated every 10 seconds. For each Smart Battery, voltage, current, remaining time until empty, and relative capacity are displayed. The current is displayed as negative when it is flowing out of the battery.

If the battery was recharging, the value would be displayed as positive. This information is all acquired from the Smart Battery System Manager. The lower portion displays information gathered from the fan controller. This includes the temperature sensor read from an on-die thermistor, the current fan speed and the temperature from the remote temperature sensor.

In conclusion, a complete custom power supply was designed and built. In total, ten boards were built for use within the embedded computing platform. The power supply provides power for the embedded computer, as well as every other peripheral in the WUC. It integrates a Smart Battery Charger, and a host interface provided by a microcontroller and small assembly language program.

The following three sections discuss the main aspects of the software that was written during this thesis.

5 Speech Recognition

Speech recognition is an important element in making the WUC a portable device. It allows for the replacement of a traditional keyboard interface, with a more natural voice interface. It also frees up one of the sonographer's hands for other tasks, such as scanning with the ultrasound transducer, interacting with the patient or steadying themselves during transport.

The speech recognition engine and microphone were selected during prior thesis work [18], and adapted for use with the WUC.

5.1 Background

There are two major types of speech recognition, sometimes called Automated Speech Recognition (ASR), engines available. The first type is called speaker-dependent. This type of ASR engine requires training by individual users before it can be used effectively, but has an unrestricted vocabulary. The second type is called speaker-independent. It does not require training by individual users before use, but has a restricted vocabulary. The different types of ASR engines are summarized in Table 11:

Table 11: Speech Recognition Engine Types

ASR Engine Variant	Speaker Dependent	Vocabulary
Speaker-Dependent	Yes	Unrestricted
Speaker-Independent	No	Restricted

The speech engine selected for use in the WUC is speaker-independent and provided by a company called *ScanSoft*. The ASR engine is version 2.0 of their VoCon 3200 product. It was originally developed by *Lernout and Hauspie* (L&H) for automotive use.

A speaker-independent ASR engine is well suited for use in the WUC, where a limited set of commands need to be recognized. These commands are defined by a grammar, written in a format called “ScanSoft BNF+” form. The “BNF”, in “ScanSoft BNF+”, stands for Backus-Naur Form and is a metasyntax that describes context-free grammars. This grammar uniquely and unambiguously defines the language that the ASR engine can understand.

The individual sounds in a language are called phonemes. The English language consists of 44 phonemes and each phoneme has a representative symbol. Other languages may have more or less. The utterances, or recognizable speech phrases in the grammar file, are converted into their phonetic transcription during initialization of the recognition engine. The actual phonemes are what is recognized by the recognition engine.

The conversion from written form to phonetic representation is called phonetic transcription. The VoCon 3200 includes a phonetic transcription component; however, pronunciation of a particular word can vary with geography and language dialects. To account for this, a word in the grammar file may be “spelled” using the phonetic alphabet, or different pronunciations of the word may be provided. This feature allows the grammar file to be fine tuned where appropriate.

A language can be formally described as a set of strings over an alphabet. The alphabet is composed of symbols from the language, and a string is a finite sequence of symbols from the alphabet. There are two general methods that can be used to fully define a language. One method, used by the VoCon 3200, is to use a grammar to describe a language. Another method uses a computational model that has the minimal complexity required to fully describe a language.

Languages are classified into a hierarchy according to their complexity. Each language classification has a corresponding grammar and equivalent minimal computational model that is required to fully describe the language. This hierarchy, called the Chomsky hierarchy, contains four types of languages. Each level in the hierarchy is a proper subset of any lower levels, and is detailed in Table 12:

Table 12: Chomsky Hierarchy

Chomsky Hierarchy	Grammar	Language	Minimal Automaton
Level 0	Unrestricted	Recursively Enumerable	Turing machine
Level 1	Context-sensitive	Context-sensitive	Linear Bounded automata
Level 2	Context-free	Context-free	Pushdown automata
Level 3	Regular	Regular	Finite automata

A minimal automaton is analogous to a minimal computational model. A Turing machine describes a computational model equivalent to a modern computer with infinite memory.

BNF was specifically developed by John Backus and Peter Naur to represent the programming language ALGOL in 1960 [41]. This was the first use of a grammar to formally define a programming language. BNF describes context-free languages, and is therefore, a context-free grammar.

A context-free grammar, G, takes the form of a 4-tuple, described by Eq. 11:

$$G = (V, \Sigma, P, S) \tag{11}$$

where:
V - finite set of variables (non-terminal symbols)
Σ - finite set of terminal symbols
P - finite set of rules
S - start symbol

The sets *V* and *Σ* are disjoint ($V \bigcup \Sigma = \varnothing$), so no variables may appear in any strings in the language.

A simple context-free grammar, in ScanSoft BNF+, may look like the following [42]:

```
!start <Speech>;

<Speech>: <Drinks> | <Food>;
<Drinks>: lemonade | milkshake | “orange juice”;
```

```
<Food>: hamburger | “french fries”;
```

In this example, the start symbol is identified by the `!start` directive and is represented as `<Speech>`. All variables (or non-terminal symbols) are enclosed in angle brackets: `<>`. All grammar rules end in a ‘`;`’, and a ‘`|`’ means that any of the following variables or terminal symbols can be substituted. Using the above example, and the definition of a context-free grammar, we can see the following sets defined:

V = { <Speech>, <Drinks>, <Food> }
Σ = { English alphabet $\cup$ English phonetic alphabet }
P = { <Speech>: <Drinks> | <Food>,
    <Drinks>: lemonade | milkshake | “orange juice”,
    <Food>: hamburger | “french fries” }
S = { <Speech> }

To see how the grammar *G* describes a language, a derivation can be performed to produce a string in the language. A derivation starts with the start symbol, *S*, and continues substituting variables with terminal symbols and variables, according to the rules of the grammar, until a string consisting of only terminal symbols is produced. For example:

```
<Speech> → <Drink> → milkshake
```

Therefore, “milkshake” is part of the language described by the grammar *G*.

The grammar used in the WUC is extremely simple and only contains six rules. There are also three possible start symbols that must be selected before any recognition can take place. This is done to limit the number of strings in the language to improve recognition accuracy. The selection of the appropriate start symbol is made automatically. The particular phrases in the grammar were chosen to maximize phonetic diversity among the phrases to get the highest possible recognition rates. The complete listing of the grammar file appears in Appendix VI – Speech Recognition Grammar.

5.2 Implementation

The VoCon 3200 Application Programming Interface is implemented as three separate Dynamic Link Libraries (DLL) and a single import library. These files, along with a language model for the particular language being used, make up the files supplied by ScanSoft to use the speech recognition system. The programmer must also supply a grammar file to be used in building a context that is used by the actual ASR engine.

There are three distinct phases to a speech recognition application. The first phase is to assemble and initialize the various elements that comprise the speech recognition system into the runtime system. This is performed during application initialization. The runtime system is the actual combination of objects and application code that performs the work while the application is running. The work is performed in a separate pop-up thread. A pop-up thread is a thread that is created only when needed, performs some work, and is then destroyed. This is different from a regular thread, which is normally present during the entire lifetime of a process. The final phase involves freeing any resources used by the runtime system.

5.2.1 Speech Recognition Initialization

Several objects are combined together by the programmer to create a complete speech recognition system. Most of these objects are supplied by the VoCon 3200 application programming interface (API). It is up to the programmer using the API to provide audio data to the VoCon 3200. Each object must be created and initialized with a set of parameters to create a complete speech recognition system.

The first step in creating the speech recognition system is to convert the grammar file, using the language model, into a form that is usable by the ASR engine. This form is called a context.

To create a context, several objects must be combined into a lexicon. The lexicon encapsulates the grammar file, language model, and a grammar to phoneme module. The grammar file is created by the programmer to indicate exactly what words or phrases are to be recognized by the ASR engine, and how to interpret the recognized results. The grammar to phoneme module translates the text in the grammar file into its phonetic representation. The language model, along with the grammar to phoneme module, is used to translate the grammar file into a context that will be run on the ASR engine. Fig. 66 shows how each of these objects interacts to create a context:

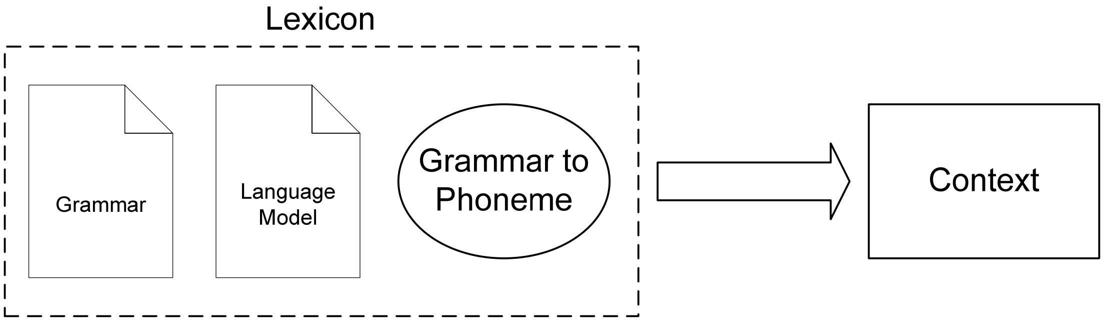


Fig. 66: Context Creation

Once a context is created, the rest of the supporting objects can be created to finish initializing a complete speech recognition system. These objects are an audio source, feature extractor, jump-back buffer and the recognizer.

The audio source object is used to supply speech data to the ASR engine. The ASR engine expects 16 bit linear pulse-code modulated (PCM) data, sampled at 16 kHz. This data is organized into frames containing 384 samples, making each frame 768 Bytes in size. The data is supplied to the ASR engine by a thread that records incoming audio data into a 16 entry circular buffer where each entry in the buffer contains 32 frames of data. Therefore, each entry is 24,576 Bytes in size and the entire circular buffer is 393,216 Bytes. A circular buffer is a memory model that implements a queue, of a predetermined size, that can be simultaneously written to by one thread and read from another. Each entry written into the buffer is written to a successive position in a circle or ring. Data is read from the oldest entry to the current write position. This reduces the chance that a sample may be lost if the reader does not remove a sample before another sample is ready to be written. This is often the case when a time-dependent data stream must be processed by a non real-time OS, such as Windows.

The feature extractor object performs basic signal analysis and processing. It computes the signal to noise ratio (SNR) and energy level for each frame of audio data. This data is used to make any adjustments to the input gain for the audio data, otherwise known as automatic gain control (AGC). Additionally, it can also determine if the frame contains the beginning of speech, also known as a voice activity detector (VAD), or if the frame contains the end of speech, indicated as trailing silence.

A jump back buffer is used by the ASR engine to buffer some amount of the incoming speech samples. This is required for situations when the ASR engine detects some characterization about the incoming speech samples and needs to “jump back” to the beginning of the samples and process it again in some other manner.

An entire segment of speech, comprised of separate frames of audio data, is called an utterance. A complete utterance, in the case of the WUC, is a command to be carried out by the WUC. The recognizer object does the actual work of creating a recognition result from an utterance.

A recognition result contains many pieces of information, but only three are used by the WUC. These three pieces of information are: a string representation of the recognized utterance, an id value and a confidence score. The next section will describe what the id value and confidence score are used for.

5.2.2 Speech Recognition Runtime

The end result of initializing the speech recognition system is the creation of the runtime system. The runtime system exists for the duration of the application and performs the actual work of speech recognition. The combination of context, feature extractor and recognizer is called the ASR engine. The ASR engine, along with the audio source and a jump back buffer, comprise a complete speech recognition system. Fig. 67 shows a representation of the speech recognition system during runtime:

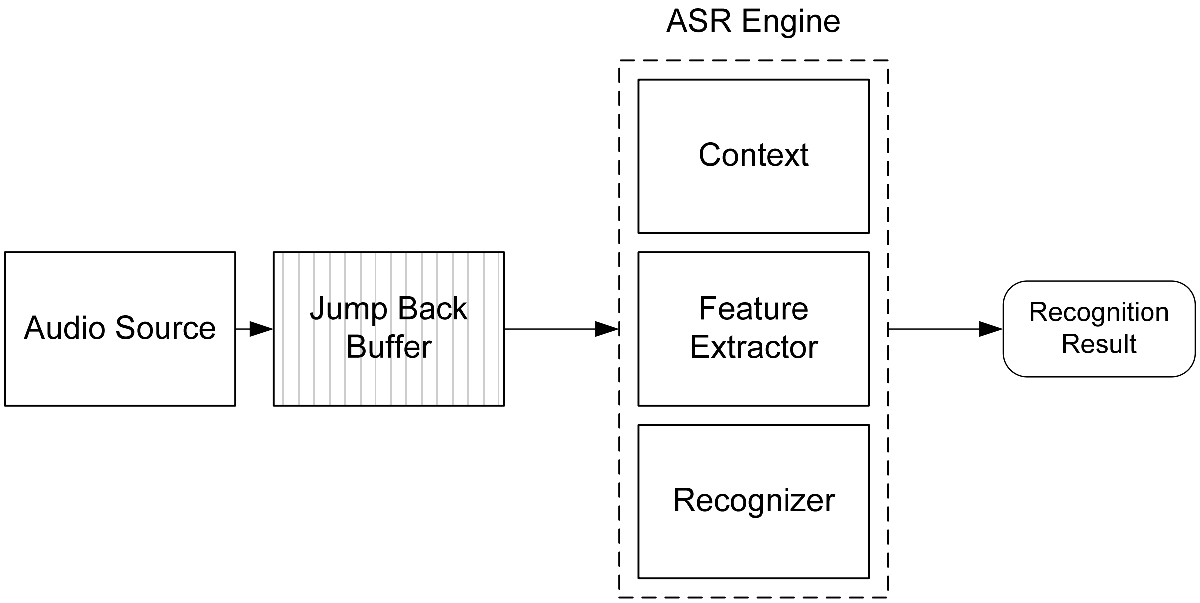


Fig. 67: Speech Recognition System Runtime

Each of these components is provided by the VoCon 3200. The audio source is used by the VoCon 3200 to receive audio samples from the application. The jump back buffer is shown with vertical lines to represent a line of samples waiting for processing by the ASR engine.

The audio source is supplied with frames of audio data by the application. A separate set of threads within the application are used to supply this data to the audio source. These threads exchange frames of audio data with the pop-up thread that contains the speech recognition system by using a circular buffer. Fig. 68 shows how speech data is buffered in a circular buffer for consumption by the ASR engine:

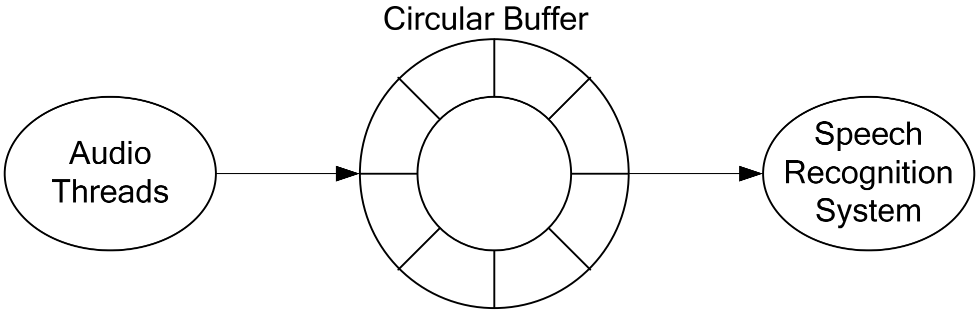


Fig. 68: Circular Buffer

There are two main methods used to determine what portion of incoming audio data should be submitted to the ASR engine for recognition. The first method is an automated method that attempts to analyze incoming speech and select the beginning and end of an utterance. To accomplish this, the VAD in the feature extractor is used to determine the beginning of speech. The end of speech is determined by waiting for the feature extractor to indicate that trailing silence was detected. It was found, however, that trailing silence detection was unreliable in most environments. Often, ambient noise would fool the feature extractor into thinking that the utterance was continuing, when it had already ended. This method was soon abandoned, in favor of the second method.

The second method is called push-to-talk (PTT). This entails the user to determine when an utterance begins and ends, thus bypassing the feature extractor entirely. Using this approach, the feature extractor is used solely for AGC.

A recognition event refers to the entire process of beginning an utterance, gathering frames of audio data, completing the utterance, and then processing the entire utterance to create a recognition result. The ultimate goal of a recognition event is to obtain a recognition result.

One piece of information that is returned with each recognition result is a confidence score. If the utterance is not pure silence, the ASR engine will always return a recognition result, whether a correct match for the current grammar is found or not. The confidence score can have a value of between 0 and 10,000 and directly relates to how closely an utterance matched an entry in the current grammar.

The confidence score is also dependent on the number of phonemes in the utterance. Less phonetically rich utterances (the number of phonemes in the utterance) will have relatively lower confidence scores, since there are fewer phonemes to match. Typically, the confidence score is used to determine whether a recognition result should be accepted or rejected. An acceptance threshold is established, where anything lower than the acceptance value is rejected. Through laboratory testing, and analysis of field trials, a confidence score of 3,700 was selected as the acceptance threshold.

During a recognition event, different messages are generated by the ASR engine and must be handled by the application. There are three types of messages that are processed: recognition result available, AGC request and abnormal condition detected. Fig. 69 shows a complete overview of the application that integrates speech recognition with the Terason application:

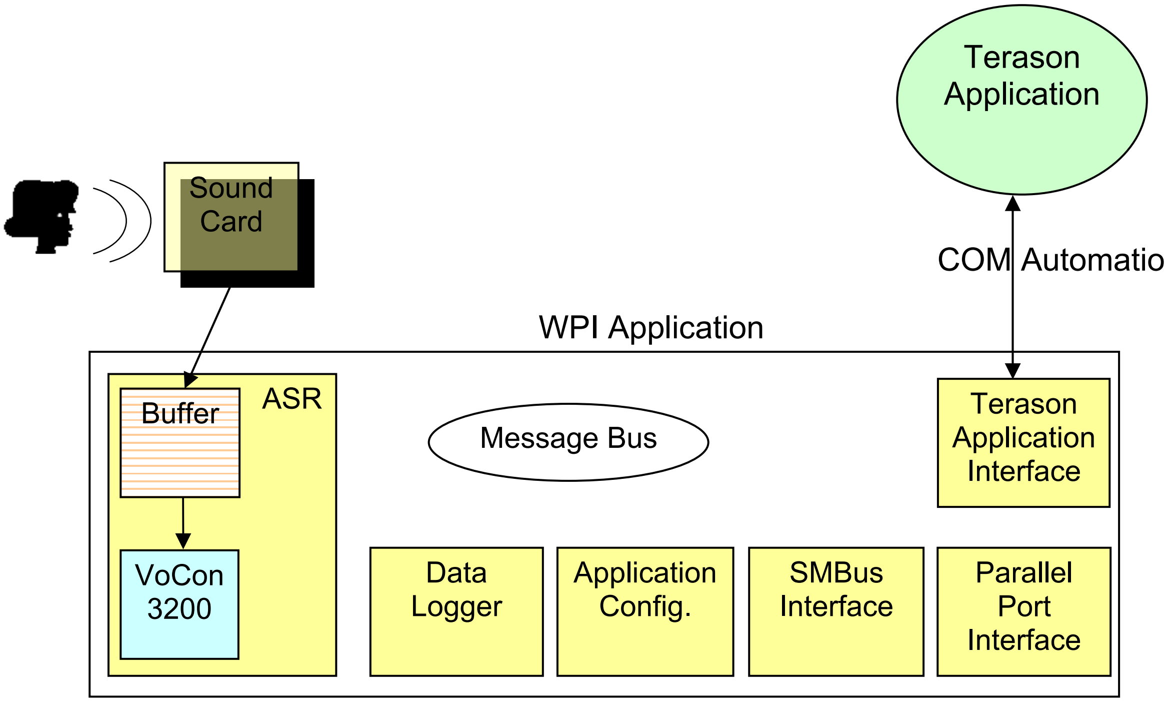


Fig. 69: WPI Application Overview

When a message indicating that a recognition result is available, the application retrieves the result and executes some action based on this result. The action may be to display an alphanumeric character on the screen, change a parameter pertaining to the current exam, or to shut down the machine.

AGC requests are sent when the feature extractor determines a need to change the input gain. The application must retrieve the requested gain and set it before processing any more data.

Finally, several abnormal conditions may be indicated by the ASR engine. These include:

- Signal to noise ratio is too low
- Signal is too loud (clipped)
- Signal is too quiet
- AGC cannot adjust the gain on the input signal to get it into the proper range

These abnormal conditions are logged by the application, but are otherwise ignored. If the current recognition event results in a successful recognition, and an abnormal condition was indicated, the confidence score will be negatively impacted. Therefore, continuing to solely use the confidence score as the criterion to accept or reject a recognition result is still appropriate.

5.3 User Interface

The speech recognition system has a user interface with two separate aspects. The first aspect is a control interface while the second is used to provide user feedback about the current state of the speech recognition system.

The control interface consists of two pieces. The normal means of control is by using the PTT button on the transducer. Depressing the PTT button begins the recognition sequence, and releasing the PTT button signals the end of an utterance. Fig. 70 shows the PTT button on a linear array transducer:

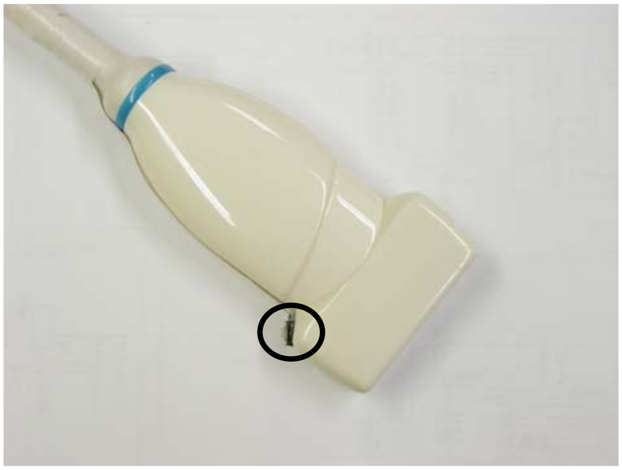


Fig. 70: Push-To-Talk Button

The second piece of the control interface is the right mouse button. It performs the same functions as the PTT button when the mouse pointer is over the Dashboard.

User feedback is provided through two mechanisms. The first and primary interface is the Dashboard. The upper area of the Dashboard contains two lines of text. The first line of text indicates one of four possible states for the speech recognition engine, by displaying a corresponding notification message. The notification message can be one of the following:

- Initializing…
- ASR Ready
- Listening…
- Processing…

Any text that is followed by an ellipsis indicates an ongoing operation. Each notification message indicates the current state of the speech recognition system. The start state for the speech recognition system displays the text "*Initializing…*" This state will transition to "*ASR Ready*" once the speech recognition system has been fully initialized. The operator is then ready to issue commands. The PTT button is used to enter the "*Listening…*" state, where the speech recognition system is actively processing user speech. By releasing the PTT button, the speech recognition system begins processing the acquired speech and the notification message "*Processing…*" is displayed. Once speech processing is complete, a command is issued and the speech recognition system returns to the "*ASR Ready*" state. Fig. 71 shows a graphical representation of the speech recognition system state machine and its transitions:

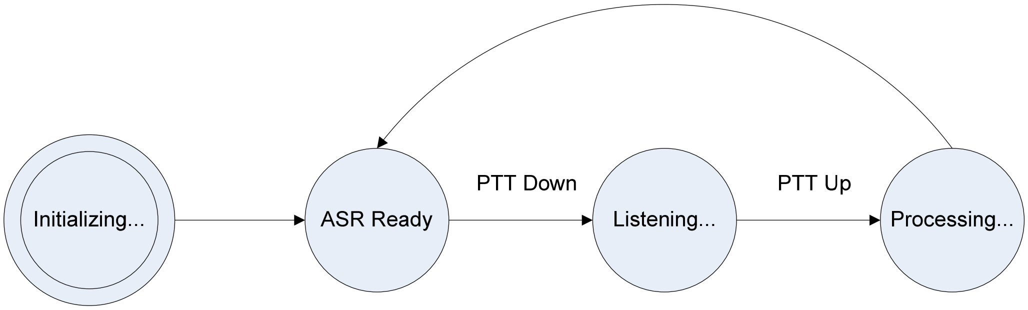


Fig. 71: Speech Recognition States

Fig. 72 and Fig. 73 show the upper area of the Dashboard after two separate recognition events. Fig. 72 shows a successful recognition of “*live image*” while Fig. 73 shows a poor recognition of “*power doppler*”.

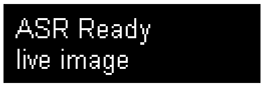

ASR Ready
live image

Fig. 72: Successful Recogntion of “live image”

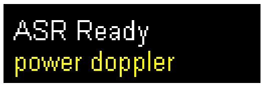
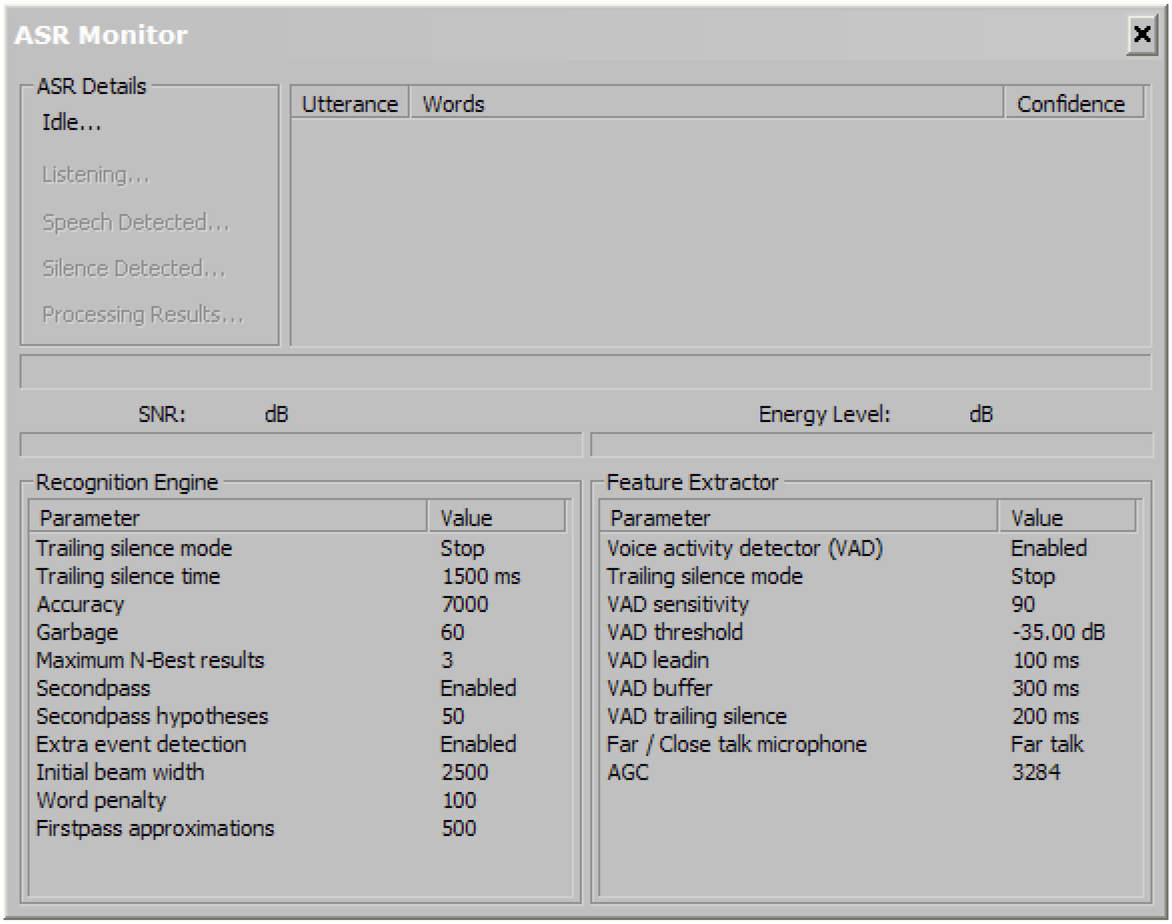

ASR Ready
power doppler

Fig. 73: Poor Recognition of “power doppler”

Note that the poor recognition event is displayed in yellow. This is because the confidence score, reported by the ASR engine, is below 3,700. In this instance, the command is not carried out and the user must repeat the command.

The secondary mechanism for providing user feedback about the speech recognition engine is a dialog box accessible via a pop-up menu. The pop-up menu is displayed by clicking with the right mouse button on the Dashboard. Selecting the “*ASR Details…*” option will display the ASR details dialog box shown in Fig. 74:



Recognition Engine

Parameter	Value
Trailing silence mode	Stop
Trailing silence time	1500 ms
Accuracy	7000
Garbage	60
Maximum N-Best results	3
Secondpass	Enabled
Secondpass hypotheses	50
Extra event detection	Enabled
Initial beam width	2500
Word penalty	100
Firstpass approximations	500

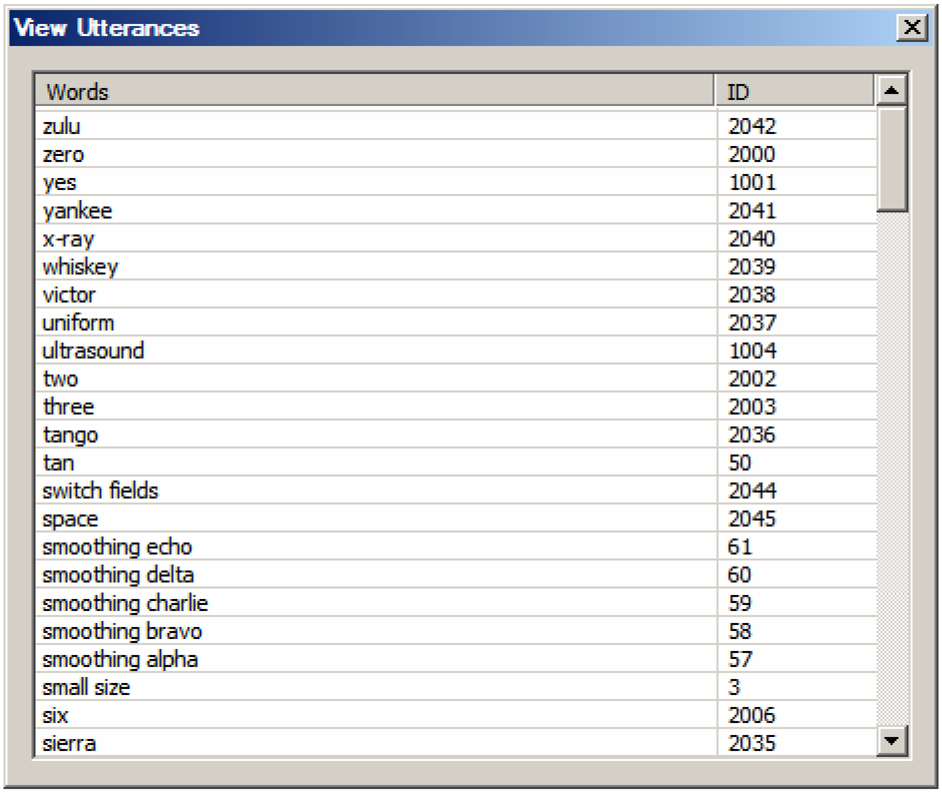
Feature Extractor

Parameter	Value
Voice activity detector (VAD)	Enabled
Trailing silence mode	Stop
VAD sensitivity	90
VAD threshold	-35.00 dB
VAD leadin	100 ms
VAD buffer	300 ms
VAD trailing silence	200 ms
Far / Close talk microphone	Far talk
AGC	3284

Fig. 74: ASR Details Dialog Box

This dialog box contains a detailed display showing the current state of the speech recognition engine and accepts no user input. It is updated whenever any speech recognition event occurs. The upper left portion of the dialog box indicates the current state of the speech recognition system. The upper right portion will display any results that are returned after processing user speech. Below this is an area that can display various warning and error messages that may be generated by the speech recognition system. Below this are two progress bars that show, in real-time, the currently reported values for the SNR and the energy level, both in Decibels (dB). At the bottom of the dialog box are two lists showing the exact parameters currently in use by the speech recognition system. An exact description of each parameter and its possible values is contained in the manual for the speech recognition system.

In addition to displaying the current state of the recognition system, the user can also display a dialog box containing all utterances for all grammars:



Words	ID
zulu	2042
zero	2000
yes	1001
yankee	2041
x-ray	2040
whiskey	2039
victor	2038
uniform	2037
ultrasound	1004
two	2002
three	2003
tango	2036
tan	50
switch fields	2044
space	2045
smoothing echo	61
smoothing delta	60
smoothing charlie	59
smoothing bravo	58
smoothing alpha	57
small size	3
six	2006
sierra	2035

Fig. 75: View Utterances Dialog Box

The view utterances dialog box always displays all of the possible utterances, regardless of which grammar is active. Therefore, some of the displayed utterances may not be valid.

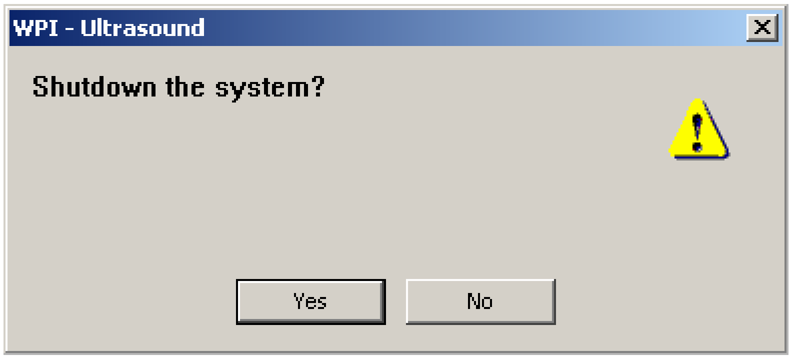
5.4 Terason Application Integration

The earlier generations of the WUC interfaced the speech recognition system with the Terason application using keyboard commands. This method had several drawbacks, prompting a new method to be employed. Sending keyboard commands to the Terason application would cause the menus to activate during command execution, causing distraction. Subsequent Terason application releases often altered the menu structure, which would break the interface. Also, the interface was limited to only sending commands to the Terason application, and could not query the Terason application to obtain any information. Therefore, the interface was rewritten to use a COM Automation interface to interact with and control the Terason application.

COM stands for *Component Object Model* and is a mature Microsoft technology that allows COM objects to be exposed by applications for manipulation by other applications. A COM object is an instance of a COM class, which is registered by the application exposing the class. Another program wishing to use an instance of that class can use the Windows registry to locate an instance of that class, and use that instance to control the exposing application. For instance, the Terason application exposes a COM class with methods for every control present in the Terason application. Through this interface, third parties can interact with the Terason application by sending commands, as if the user clicked a button within the application, or even replace the graphical user interface (GUI) entirely.

The WPI ultrasound application, discussed in detail in Chapter 7, uses the Terason COM interface to carry out speech commands. An integer value is associated with every recognizable utterance specified by the grammar. This integer value is returned as the id portion of a recognition result. These integer values are interpreted as commands that are then issued through the Terason COM interface to the Terason application. By using an integer value assigned to an utterance, and not the utterance itself, the actual utterance used to evoke a command can be changed without changing the WPI Ultrasound application. It is even possible to have multiple utterances that carry out the same command, though this has not been done.

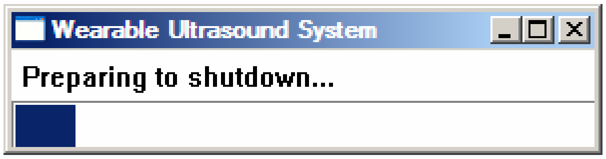
Not all commands are necessarily meant for the Terason application. Some commands are used directly by the WPI ultrasound application. An example of this is the "*shutdown*" command, which is used to shutdown the entire WUC via voice-command. The "*shutdown*" command will display a dialog box, shown in Fig. 76, asking the user to respond with "*yes*" or "*no*" to verify that they indeed would like to shut down the WUC.



Shutdown the system?

Fig. 76: Shutdown Dialog Box

If a "*no*" command is issued, the dialog box will be destroyed and imaging can continue. If a "*yes*" command is issued, another dialog box, shown in Fig. 77, will be displayed.



Preparing to shutdown...

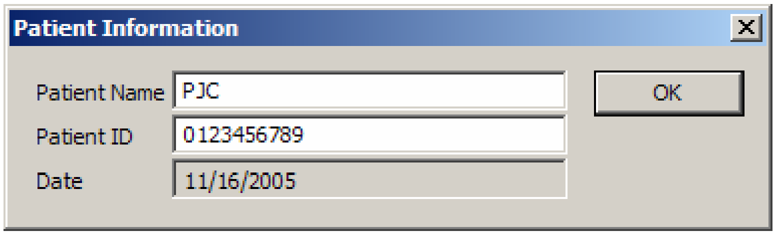
Fig. 77: Shutdown Progress Dialog Box

The dialog box has a progress bar at the bottom that will indicate the progress of shutting down the WUC as it progresses. This dialog box was implemented because there is a fairly long delay of up to 10 seconds before the Terason application disappears from the screen.

5.5 Patient Information

The speech recognition system is also used to enter patient information. Since there is no keyboard, a system was developed to enter alphanumeric information using the NATO phonetic alphabet. A phonetic alphabet uses strings to represent letters and sometimes numbers. For example, the letter ‘a’ is represented as “*alpha*” and the letter ‘*r*’ is represented as “*romeo*”. The numbers zero through eight are represented with their normal English names, but nine is represented as “*niner*”. A complete listing of the NATO phonetic alphabet appears in the listing of the grammar file in Appendix VI – Speech Recognition Grammar. A phonetic alphabet is used to improve recognition accuracy by providing greater phonetic diversity for each letter.

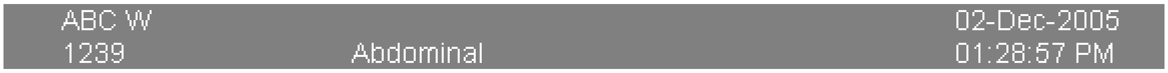
This data is used to associate metadata about a patient with captured ultrasound images or clips. Currently, only the patient’s name, patient id and current date are saved. Rudimentary commands for deleting a character and moving between fields in a dialog box are also implemented. Fig. 78 shows the dialog box used to enter patient information:



Patient Name: PJC
Patient ID: 0123456789
Date: 11/16/2005

Fig. 78: Patient Information Dialog Box

This dialog box can easily be extended to include other data. This data is used in two separate places. The first place is as a header at the top of any saved ultrasound images or video clips, as shown in Fig. 79:



ABC W 02-Dec-2005
1239 Abdominal 01:28:57 PM

Fig. 79: Patient Information Header

The second place that the patient information is used is for remote viewing of saved images. This is further detailed in Section 6.

5.6 Array Microphone

One of the most important elements of a speech recognition system is the microphone. The WUC makes use of a four element linear array microphone, connected to a digital signal processor (DSP) contained in a small box. The DSP implements algorithms to make the microphone more sensitive along the long axis. When in use, the microphone is pointed in the direction of the user's mouth. This helps to reject directional noise sources, such as other people talking, which could interfere with the accuracy of the voice recognition system. The array microphone is shown in Fig. 80, while Fig. 81 shows the directional sensitivity of the array microphone:

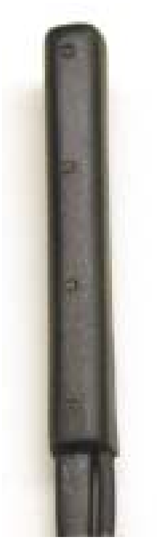


Fig. 80: Linear Array Microphone

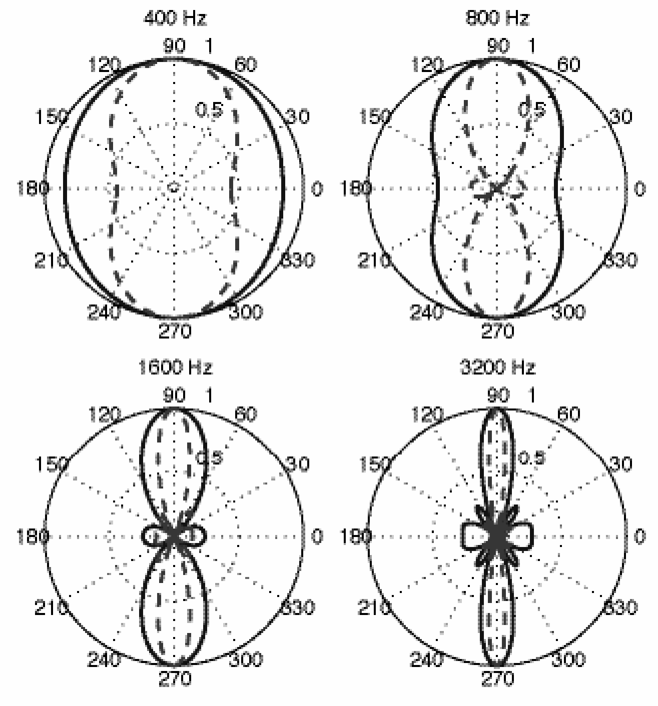


Fig. 81: Linear Array Microphone Directional Sensitivity

The array microphone is not the only microphone that can be used with the WUC. The eMagin HMD has a built in microphone that can also be used for speech recognition. Testing (not performed by this author) has proven it to provide comparable speech recognition performance to the array microphone.

6 Remote Data Facilities

In continuing with the desire to have a fully untethered ultrasound device, the WUC integrates a wireless data interface that allows for remote administrative access, as well as access to any data stored on the device. This data includes web pages, manuals, databases, static and real-time ultrasound images, voice communications and stored ultrasound image clips. The data interface, as well as most of the protocols used for data transmission, is based on open standards to promote the widest interoperability possible. The following sections will discuss the various remote data facilities, organized according to the *Open Systems Interconnection* (OSI) reference network model. For reference, the OSI model is shown in Fig. 82:

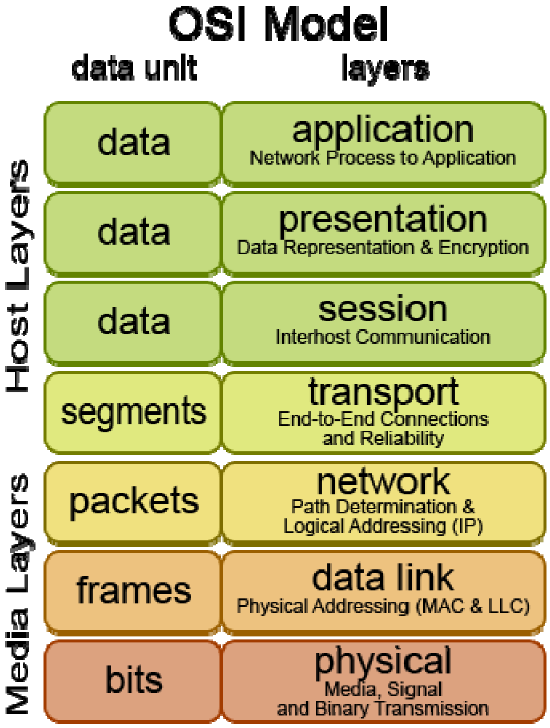

OSI Model
data unit
layers
Host Layers
Media Layers
data
application
Network Process to Application
data
presentation
Data Representation & Encryption
data
session
Interhost Communication
segments
transport
End-to-End Connections and Reliability
packets
network
Path Determination & Logical Addressing (IP)
frames
data link
Physical Addressing (MAC & LLC)
bits
physical
Media, Signal and Binary Transmission

Fig. 82: OSI Reference Model [43]

6.1 Physical Layer

The physical layer, as defined in the OSI model, represents the physical device and the electrical characteristics of the transmission medium being employed. In the case of the WUC, the IEEE standard 802.11 [44] is used for the physical layer. There are several variants within this standard, identified with letters, which indicate which variant is being used. Specifically, the 802.11b and 802.11g variants are available on the WUC.

IEEE 802.11b [45] and IEEE 802.11g [46] are often written as 802.11b/g to indicate their inherent interoperability. Each standard operates in the same Industrial, Scientific and Medical (ISM) frequency band of 2.4 GHz. The band limits in North America are 2.402 GHz to 2.480 GHz. Within this band, as defined in North America, are 11 channels allowing for multiple networks to operate in geographically overlapping areas by using frequency division multiplexing. Within each channel, network nodes access the medium using time division multiple access (TDMA) methods and transmit data in timeslots.

The 802.11b standard defines a maximum physical layer data rate of 11 Mb/s. However, due to protocol overhead, the actual throughput for application data will be somewhat less and will vary depending on the number of nodes and the condition of the transmission channel.

The 802.11g standard enhances the 802.11b standard with a higher physical data rate of 54 Mb/s. This is accomplished by using a different modulation standard for the application data being transferred, but is otherwise similar to the 802.11b specification. It will also have a throughput that is somewhat less than the maximum rate due to the same reasons that affect the maximum data throughput for 802.11b.

6.2 Transport Layer

The Transport Layer, as defined in the OSI model, defines a method for transferring data between two endpoints in a network. It sits on top of the Data Link and Network Layer. The Data Link layer specifies an addressing and data format scheme for transmitting data between two network nodes and generally includes methods for error detection and correction for the Physical Layer. The Data Link layer is part of the 802.11 specifications. The Network layer defines an addressing and data format for sending data to a particular network node. All of the Transport Layer protocols defined here will use Internet Protocol (IP) for the Network Layer.

There are two Transport Layer protocols in use on the WUC. The first is called Transmission Control Protocol (TCP) and the second is called User Datagram Protocol (UDP). They are often written as TCP/IP or UDP/IP to indicate that IP is used to locate a particular network node. Also, both protocols use the concept of a port to locate a specific network endpoint.

A network endpoint is an actual application running on a network node, and a single node can have multiple endpoints. Each endpoint may be used with the TCP or UDP protocol to actually transmit user data.

TCP defines a reliable method of transport that is connection oriented. Before data may be transferred, a connection must be set up between the two network endpoints. When a session is complete, this connection must be torn down. While a session is active, TCP ensures that any data sent from one endpoint to another is received properly. There are facilities within the protocol to verify that the data was transmitted properly. If an error was detected, the data is retransmitted.

UDP differs from TCP in that it is not connection oriented and is not reliable. There are no facilities to detect errors in data transmission. However, UDP does not require a connection to be set up and has less protocol overhead. This results in lower latency and higher throughput, but at the cost of reliability.

Each protocol is suited to a particular set of applications. TCP is used when reliable delivery is important, and the increased latency and reduced throughput can be tolerated. On the WUC, TCP is used for all data transfers, except for real-time ultrasound images and voice communications. UDP is better suited for applications where lower latency is more important and the occasional dropped packet can be tolerated. These applications are often called streaming, since a stream of data is sent between endpoints. UDP is used to stream real-time ultrasound images and for voice communications.

6.3 Real-Time Transport Protocol

The WUC has the ability to transmit live ultrasound images in real-time to a single network endpoint using real-time transport protocol (RTP). RTP is defined by the Internet Engineering Task Force (IETF) in RFC3550 [47]. real-time control protocol (RTCP) is also defined in RFC3550.

As stated in RFC3550, “RTP provides end-to-end network transport functions suitable for applications transmitting real-time data, such as audio, video or simulation data, over multicast or unicast network services.” A custom software stack was written to implement RTP and used to deliver real-time ultrasound images and voice communications services. The details of the protocol are contained in the specification, but the implementation specific details are presented in the remainder of this section.

RTP makes use of UDP for the actual transfer of data between endpoints. Two channels are defined: RTP Data Transfer protocol is used to deliver the actual data while Real-Time Control protocol (RTCP) is used as a control channel. Each channel is defined as a network endpoint having a sequential port number. Port numbers in UDP are defined as unsigned 16 bit data types and therefore have a range of 0 – 65,535. This means that any network node may have up to 65,536 UDP endpoints. When RTP is used, one port is used for data transfer, and the next sequential port is used for RTCP. For example, an RTP connection on port 1000 will use port 1000 for RTP data transfer and port 1001 for RTCP. Fig. 83 shows the RTP network stack as it appears in the WUC. Note that the dashed lines represent virtual connections that are made using the underlying protocols for the actual transport.

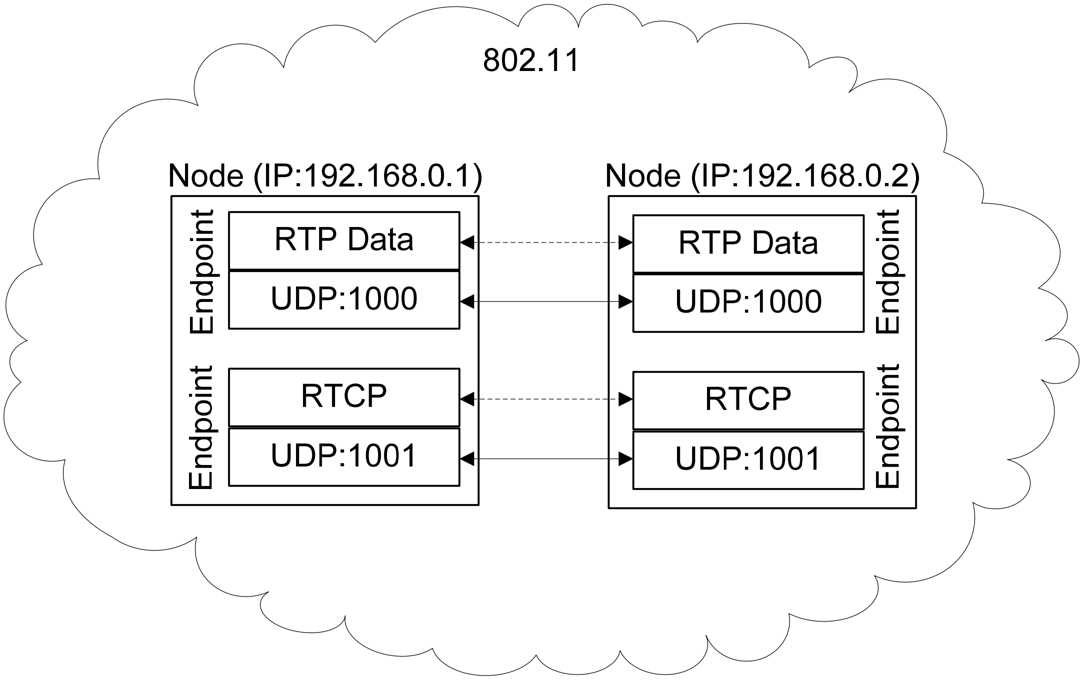


Fig. 83: RTP Network Stack

In this example, there are two network nodes using RTP to transfer data. Each network node has a distinct network address. An IP address is made up four Bytes and in the example above, one node has an IP address of 192.168.0.1 and the other node has an address of 192.168.0.2. The physical layer, upon which all data is transferred, is 802.11.

An RTP session is an association among a set of participants using RTP for communication. A session can potentially contain multiple participants, such as in the case of audio conferencing. Each participant is identified by a unique 32 bit identifier called a Synchronization Source (SSRC). If a participant is only receiving data, it is labeled a receiver, while a participant that both sends and receives data is labeled a sender. Session control and reporting mechanisms occur using RTCP, while the actual transfer of data occurs with RTP data transfer.

Each RTP data transfer includes a packet header containing the following relevant information:

- RTP Version
- Payload Type
- Sequence Number
- RTP Timestamp
- SSRC

Each packet of data transferred by a session participant includes all of the above information. The RTP version is the version of the RTP protocol being used. The payload type identifies what sort of data is in the packet, such as video or audio data. The sequence number is incremented by 1 for every packet that is sent, allowing for the identification of dropped or out-of-order packets. The RTP timestamp is used to indicate the sampling instance of the data within the packet. The SSRC uniquely indicates the participant that sent this packet.

RTCP is used for periodically reporting statistical data to all of the session participants, gathering information on session participants, session initiation and session tear-down.

The statistical data takes the form of sender or receiver reports, depending on the type of participant, and is periodically sent by every participant in the session. This primary purpose of this statistical data is to inform session participants about the quality of the data distribution. This can be used to diagnose network problems, provide for congestion and flow control algorithms, or as input to adaptive encoding algorithms. A receiver report, sent by receiver participants, contains the following information for each sender that the receiver has received data from:

- Sender SSRC
- Fraction of packets lost
- Total number of lost packets

- Interarrival jitter
- Timestamp relating to the last sender report receiver from this sender
- Relative delay since receiving the last sender report receiver from this sender

The sender SSRC uniquely identifies which sender in this session this report is about. The fraction of packets lost indicates the fraction of RTP data transfers that were dropped. The total number of lost packets is the cumulative number of lost packets. Interarrival jitter is an estimate of the statistical variance of RTP data transfer packet arrival times. The timestamp is the wallclock time of the last time a sender report was received from this sender. Wallclock time is an absolute time, such as might be found on a clock on a wall. The relative delay indicates the relative delay since the last time a sender report was received from this sender.

A sender report is only sent by sender participants and contains the same information as a receiver report, but also includes the following information pertaining to the sender:

- NTP Timestamp
- RTP Timestamp
- Sender's packet count
- Sender's octet count

The NTP timestamp defines the current wallclock time according to the sender. The RTP timestamp is the same as defined in an RTP data transfer. The sender's packet count is the cumulative number of RTP data packets sent by this sender. The sender's octet count is the cumulative number of Bytes sent in the payloads of each RTP data packet.

RTCP is also used by participants to join a session or leave a session. Also, there are facilities in the RTCP protocol to allow a participant to disseminate information, such as the participant's name, phone number, email address, geographical location, etc. RTCP can also be extended in an application specific manner to send custom information.

6.4 Real-Time Ultrasound Imaging

The WUC has the ability to send real-time ultrasound images to a remote viewer using RTP as transport mechanism. This section will describe the entire process of acquiring an ultrasound image and displaying it on a remote computer or laptop for viewing.

The Terason COM interface provides methods for setting up the Terason application as a frame server. Access to these image frames is accomplished with a shared memory interface, allowing a separate process on the same computer to consume the image frames.

The frames can be accessed in one of three modes: “LIO”, “FIFO” or “LIFO”. The “LIO” mode, which stands for Last-In-Out, delivers only the last frame to the receiving process. This mode has the lowest latency, but can result in lost frames. “FIFO” mode, which stands for First-In-First-Out, improves upon “LIO” mode by storing frames in a circular buffer. This greatly reduces the chances of losing a frame, but results in greater latency. The final mode, “LIFO”, stands for Last-In-First-Out and approximates a fixed size stack. This mode also greatly reduces the chances for losing a frame, but also has the advantage of low latency. However, the frames may not always be delivered in order and may need to be sorted by the process consuming the frames produced by the Terason application frame server. The WUC uses “LIO” mode to acquire ultrasound images for transmission.

The individual ultrasound images are transferred using RTP to a remote viewer. The use of “LIO” mode for acquiring the images is the most appropriate, since the underlying transport protocol can lose packets, and no attempt is made to recover the lost packets. Since the person viewing the remote images is interested only in the current image, attempting to perfectly transfer every image could eventually lead to the displayed image lagging behind the real-time image. This lagging situation will occur if the time to transmit the frame to the remote viewer is longer than the time it takes for a frame to be produced by the ultrasound system. By simply dropping frames that cannot be transmitted in time, the remote image remains real-time, although the frame rate may be reduced in certain situations.

Each image frame is acquired from the shared memory interface in a device independent bitmap (DIB) format. A DIB image contains a header, a color palette and pixel data. A DIB image is an indexed color image. An indexed color image uses a color palette to describe the color of each individual pixel in the image. The images produced by the Terason application contain a color palette with 256 colors. Each entry in the color palette is 32 bits in length with 8 bits used for the colors red, green and blue for a total of 24 bits. The remaining 8 bits are unused. By summing the various intensities of red, green and blue, any color can be reproduced. The color of each pixel in the image is represented as an index into the color palette. Since there are 256 colors, each pixel only 8 bits to fully represent its color.

In order to reduce the time required to transmit an image frame to a remote viewer, compression is used to reduce that data that must be transferred. Many compression algorithms specifically targeted at video applications make use of the fact that, in general, individual video frames do not vary much in their content from frame to frame. Put another way, the video frames are highly correlated. For example, a scene showing a person talking will probably have a static background that does not change often and does not need to be transmitted with each frame. These video compression algorithms take advantage of this and only transmit the differences between frames. The initial reference frame is called a key-frame, and some number of intervening differential frames are encoded for transmission until the coding algorithm decides to send another key frame. A popular example of a video compression algorithm using this technique, along with others, is the MPEG 2 algorithm used on DVDs.

Unfortunately, ultrasound images contain speckle noise that greatly reduces the correlation in image data between frames. Also, the extreme compression achieved by many video compression algorithms is computationally intensive and potentially unsuitable for resource constrained systems. Therefore, a generic and readily available data compression algorithm is employed to compress the ultrasound image frames.

The freely available compression library zlib [48] was used for lossless data compression. zlib implements IETF standard RFC1950 [49] for compression and the IETF standard RFC1951 [50] for decompression. It is important to use lossless data compression to avoid degrading the ultrasound image, and possibly leading to diagnosis errors. The actual compression and decompression routines are implemented in assembly for the highest speed possible.

In order to recover the original data from its compressed representation, the entire compressed representation must be available. RTP is not a reliable transmission method, so it is expected that some packets will be lost. If the entire image was compressed as a whole, and segmented into packets for transmission, then the loss of a single packet would corrupt the entire image and the receiving computer would be unable to reconstruct the image. Therefore, the image is split into a number of tiles whose maximum compressed size will fit into a single RTP data packet.

The WUC uses a resolution of 800x600 pixels for the ultrasound images. This limit is bounded by the maximum resolution that can be displayed using the head-mounted display. By observation, this image can be compressed to a size of no greater than 14 kB. The lower limit for the compressed image sizes is unknown. The default maximum size for a UDP packet in Windows is 1280 Bytes. The RTP data transfer header is 12 Bytes long, leaving a maximum payload size of 1268 Bytes. When using UDP, it is important to not send messages that exceed the maximum allowable size, or they will be most likely be dropped at some point along the transmission path.

To address the limitations in packet size, the 14 kB image is split into 16 separate tiles. These tiles are then individually compressed to create 16 RTP packets of a small enough size that they can be transmitted over UDP. The DIB header and color palette are less than 1 kB, but they are also compressed to shorten transmission time and transmitted together in a single RTP message. In total, 17 RTP messages are transmitted for each ultrasound image frame. Because each message has been compressed independent of any of the other messages, the loss of any number of RTP packets does not corrupt any of the other RTP packets that carry the data for the image. The RTP message that is sent contains the compressed DIB header and color palette, followed by 16 RTP messages containing the compressed image tiles.

The receiving computer simply needs to acquire the 17 messages and reconstruct the sent image. This process begins whenever a new RTP message containing the DIB header and color palette arrives at the receiver. Upon arrival, a new blank image containing all black pixels is created in an off-screen buffer. The sequence number of this message is noted and used to determine where the subsequent image tiles should be placed in the image. Each subsequently received image tile is the uncompressed and placed into the image. Finally, when another RTP message containing a new DIB header and color palette is received, completed image is displayed on the screen. The process then starts anew with another blank image created in an off-screen buffer. This method of displaying an image on the screen, while creating the next image to be displayed off of the screen, is called a buffer backed GUI and is shown in Fig. 84:

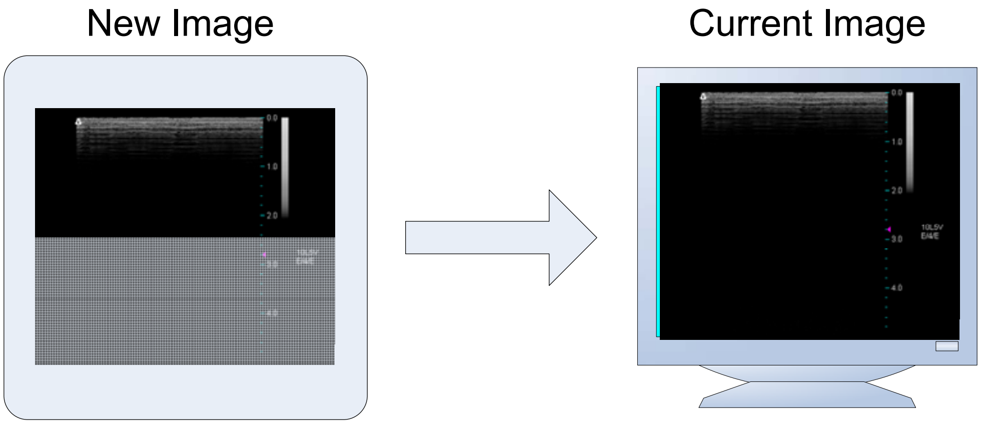
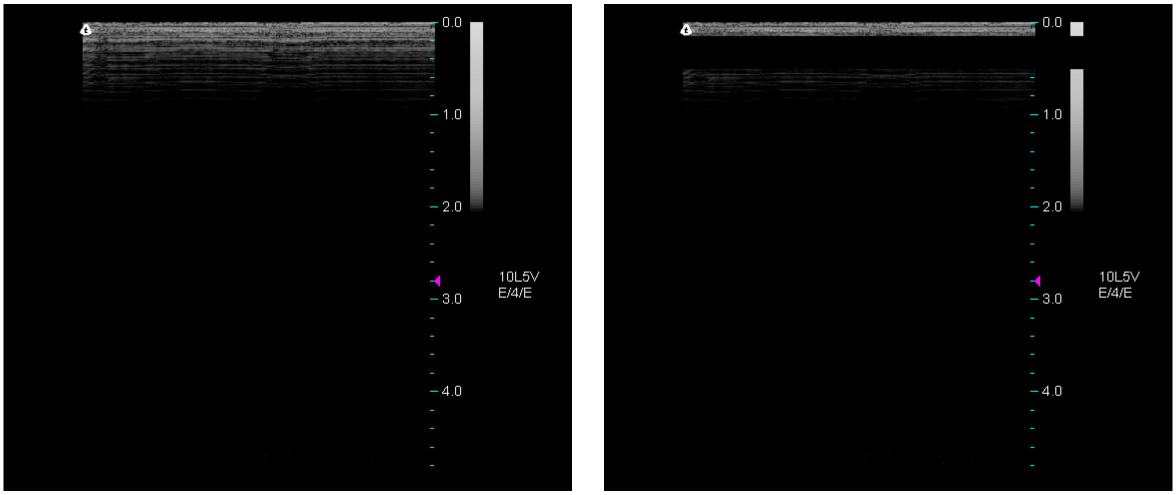


Fig. 84: Buffer Backed GUI

There are two scenarios that can occur with RTP packet loss. The first scenario is that the packet containing the DIB header is lost. When this occurs, the prior header is reused. This results in the old color palette being used to display the image tiles until an updated DIB header is received. Since the color palette is rarely changed, this will most likely go unnoticed. In the case where an image tile is lost, it is replaced with an all black tile, as shown in Fig. 85:



(a) Original Ultrasound Image

(b) Ultrasound Image with Lost Tile

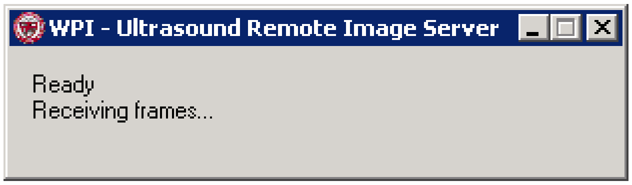
Fig. 85: Lost Image Tile

There are several ways to write applications for Windows, and each approach uses a different programming model and API. The WPI ultrasound application is written using the lowest level API, called Win32. This was chosen because it offers the lowest overhead and fewer resource requirements than other APIs. In fact, many of the other APIs are written using Win32 and are attempts at making writing programs for Windows simpler and faster for the programmer. However, this ease of use brings a penalty by requiring more memory, resources, and sometimes slower execution and reliability. None of which is desirable in an embedded computing system.

The API to access the shared memory interface containing the ultrasound images is only provided by Terason as an ActiveX object. An ActiveX object is a special type of COM object that must be run within a container. In this instance, a container is a software construct that provides certain services to software designed to run within the container. Containers for ActiveX objects are only available using technologies other than the Win32 API. Terason uses the *Microsoft Foundation Class* (MFC) API to implement the majority of their software, as well as to write the ActiveX object used to access the shared memory interface. Therefore, a separate process was required to implement the server portion of the real-time ultrasound imaging, and it was written using MFC.

This separate process, called the remote imaging daemon (RID) is created by the WPI ultrasound application and only interacts with the Terason application to retrieve ultrasound image frames from the shared memory interface. A daemon describes a process that provides some sort of service and is not intended to interact with the user. All control and setup of the shared memory interface is performed in the WPI ultrasound application to avoid synchronization issues.

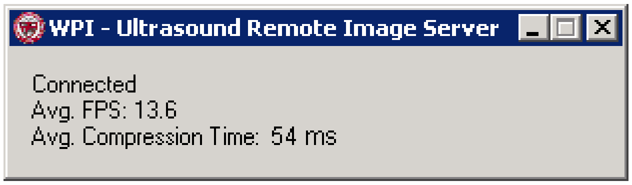
The RID includes a complete RTP server, listening for connections on UDP port 1038. Whenever a client application connects to the RID, it begins transmitting the ultrasound images to the client as described above. The interface to the application is a small dialog box. When the RID is running, and no client is connected, it appears as shown in Fig. 86:



Ready
Receiving frames...

Fig. 86: RID Without Client

When a client is connected to the RID, the RID will display the number of frames per second (FPS) that are being sent to the client, as well as the number of milliseconds it took to compress the entire frame, averaged over the last 16 frames. Fig. 87 shows the RID with a connected client:



Connected
Avg. FPS: 13.6
Avg. Compression Time: 54 ms

Fig. 87: RID With Client Connected

In Fig. 87, the RID is averaging 13.6 frames transmitted to the client, with an average compression time of 54 ms for an entire image frame.

The RID client software, for viewing real-time images, is a very simple program. When it is first run, the user is presented with a small dialog box requesting the IP address of the WUC system to connect to. The dialog box contains a list of any prior successful connections to make selection of a connection target more convenient. Fig. 88 shows the RID client connection dialog box:

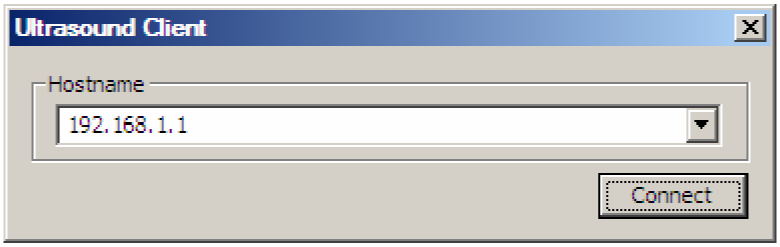


Fig. 88: RID Client Connection Dialog Box

Once pressing the connect button, the user is presented with the main window for the RID client application, as shown in Fig. 89:

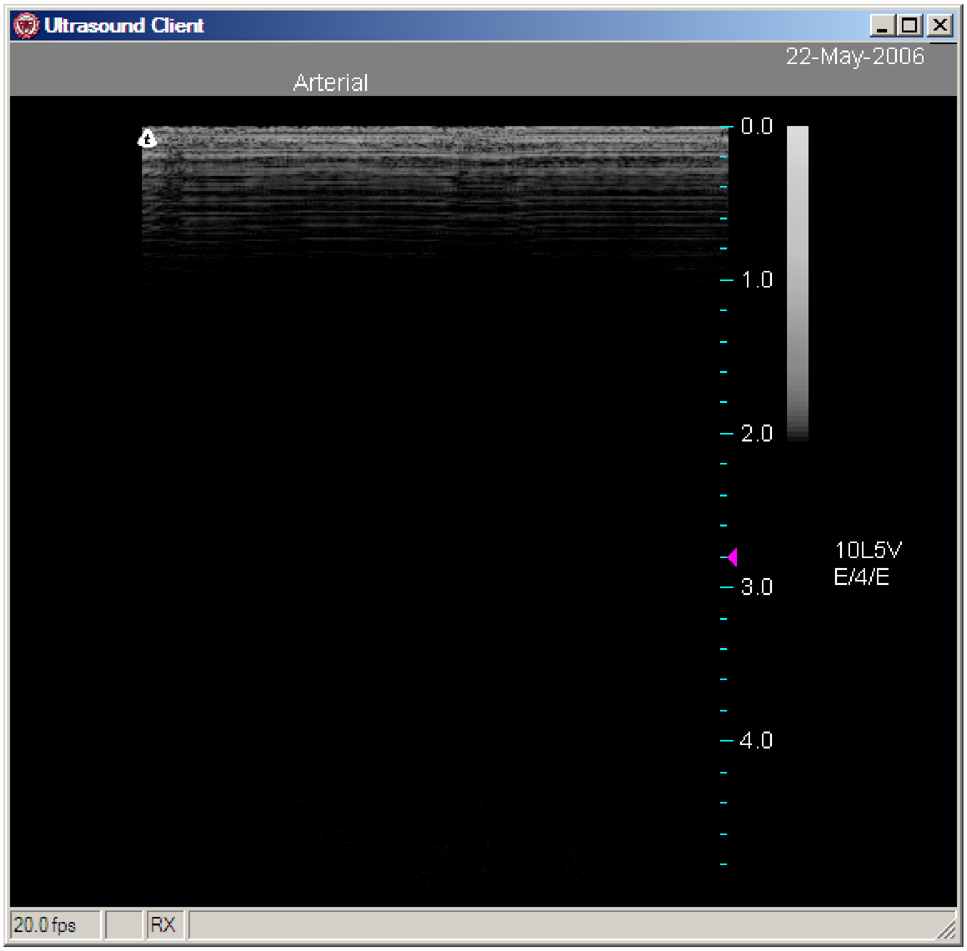


Fig. 89: RID Client Application

The window displays the current stream of ultrasound images from the WUC. Below the image is a status bar control that displays three items. The leftmost indication is the number of FPS that are being displayed by the application. The next two fields to the right are used for indications relating to voice transmission, which is further covered in the next section.

The RID client will always display a main window, whether it was able to connect to a running instance of a RID or not. If no image data is available, either because a connection was made to the wrong address, or if the WUC is currently not acquiring ultrasound images, the window will display the text "*Image Unavailable…*"

6.5 Voice Communications

In addition to real-time remote imaging, the WUC also supports full-duplex voice communications between the WUC operator and the RID client application.

There are many standards for providing voice communications over IP networks. These are collectively referred to as voice over IP (VoIP) standards. However, most of these standards deal with replacing the functionality currently provided by the regular public switched telephone network (PSTN). This functionality includes call setup, call teardown, billing and call routing. Only a small portion of the standards actually addresses the transmission of voice. Since the functionality required by the WUC does not include billing, call routing or call setup/teardown, only the voice transmission aspects of the standards were used.

The VoIP standards include a wide variety of speech codecs for voice transmission. Incidentally, the transmission protocol of choice is RTP, which is the same protocol used to transmit real-time ultrasound images. The most widely used speech codecs are the family of International Telecommunication Union (ITU) standards. These vary in data rates from 5.3 to 64 kb/s. However, no software could be freely acquired that supports any of these codecs. Therefore, the second most popular choice, the GSM 6.10 codec, was used. This codec is included with Windows and required no extra software to use.

The GSM 6.10 codec is commonly used in GSM cellular telephone networks. This type of cellular telephone network uses TDMA methods for transmission of voice and data on any one of 125 possible channels (frequencies) [51]. The bandwidth of a standard GSM channel is 22.8 kb/s.

The GSM codec uses a Regular Pulse Excited – Linear Predictive Coder (RPELPC) algorithm to encode speech. This method encodes the differences between the current speech samples and the previous speech samples. It also includes a long-term predictor to estimate speech samples that may be lost during transmission. This allows for the loss of several speech packets in a row before voice quality degrades. This makes the GSM codec well suited for packet based communications on bandwidth constrained networks.

RFC 3551 [52] provides a profile for transporting GSM encoded speech using RTP. GSM encodes speech into 20 ms frames of 260 bits (32.5 Bytes) in length. RFC 3551 describes a method of packing each of these frames into a 33 Byte packet for transmission. This results in an effective data rate of 13.2 kb/s for the encoded speech. The RTP header for each packet is 12 Bytes, resulting in a protocol overhead of 4.8 kb/s. Therefore, the total data rate is 18 kb/s.

When the RID client application is connected to the WUC, a voice connection is automatically established along with the real-time imaging stream. There are two indicators in the bottom of the window showing the RID client application. One shows “TX” when the application is actively transmitting, and the other shows “RX” when the application is receiving. An “RX” indication only means that the application is connected and capable of playing received speech. No speech is actually sent until the user signals to do so.

To transmit speech from the RID client application to the WUC, the user holds down the left mouse button anywhere within the window. This causes the “TX” indicator to be displayed while the voice is being actively transmitted. Releasing the left mouse button causes the speech transmission to stop. Much like the PTT button on the transducer handle, which is used for issuing voice commands to the WUC, the left mouse button acts as a PTT button for the RID client application.

If the WUC operator wishes to speak to a connected RID client application, speech transmission is enabled through a pop-up menu accessed via the Dashboard. The WUC operator must right-click within the Dashboard to display the pop-up menu and select then select the *"Start Audio"* option. Once the menu item has been selected, speech is continuously transmitted to the RID client application. Voice commands may still be issued to the WUC in the normal manner, but they will also be transmitted simultaneously to the RID client application. Voice transmission is stopped by selecting the *"Stop Audio"* option in the pop-up menu.

6.6 Remote Administration

The WUC also makes use of the web server that is supplied as part of Windows. The web-site hosted on the WUC can be used to:

- View the User's Guide
- Retrieve stored images
- Download the RID client application
- Retrieve logs

The home page for the WUC is shown in Fig. 90:

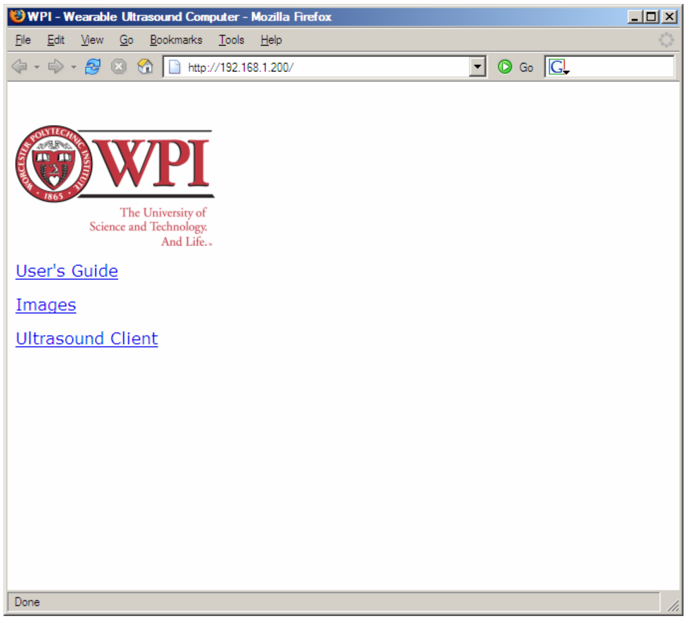

WPI - Wearable Ultrasound Computer - Mozilla Firefox
File Edit View Go Bookmarks Tools Help
http://192.168.1.200/
Go
WPI
The University of Science and Technology. And Life.
User's Guide
Images
Ultrasound Client
Done

Fig. 90: Web Server Home Page

The web pages are organized as two separate frames. In the left frame is a navigation menu that does not change. Selecting options in the navigation menu displays different content in the right frame. For example, selecting *"User's Guide"* in the navigation menu will bring up the User's Guide, as shown in Fig. 91:

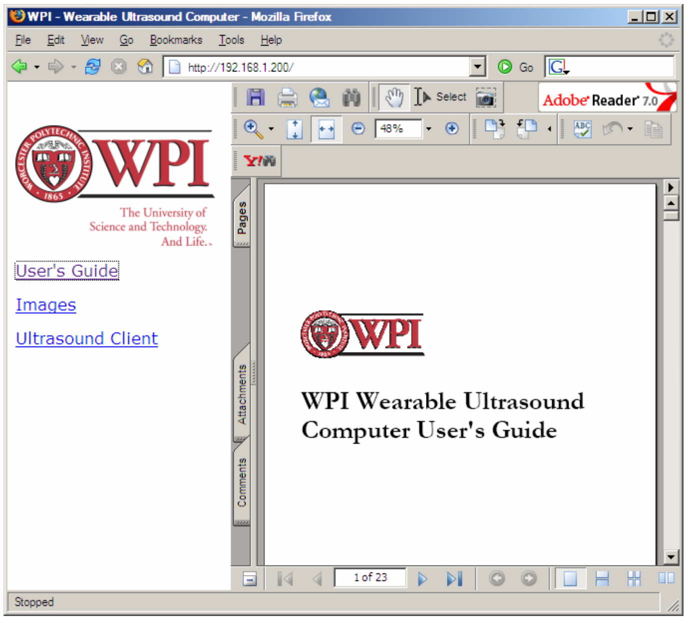
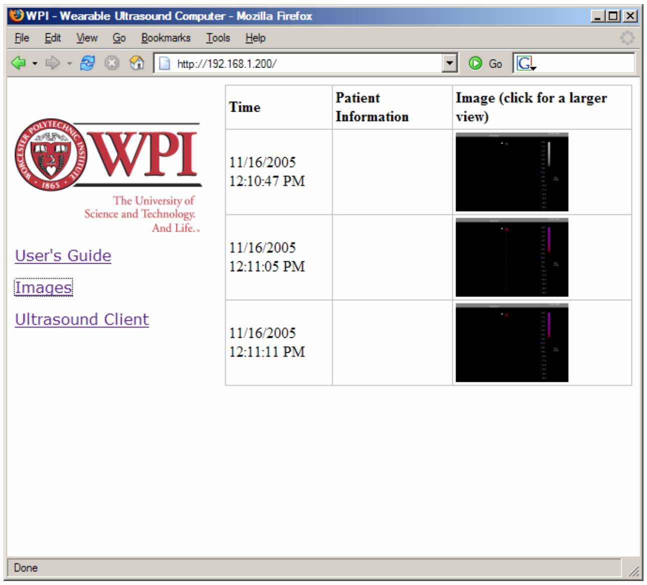

WPI - Wearable Ultrasound Computer - Mozilla Firefox
File Edit View Go Bookmarks Tools Help
http://192.168.1.200/
Go
Select
Adobe Reader 7.0
48%
WPI
The University of Science and Technology. And Life.
User's Guide
Images
Ultrasound Client
Pages
Attachments
Comments
WPI
WPI Wearable Ultrasound Computer User's Guide
1 of 23
Stopped

Fig. 91: User's Guide on Web Server

Selecting the *"Images"* option will display a table containing all of the images that are currently stored on the WUC. An example display, showing three stored images, is shown in Fig. 92:


WPI - Wearable Ultrasound Computer - Mozilla Firefox
File Edit View Go Bookmarks Tools Help
http://192.168.1.200/
Go
WPI
The University of Science and Technology. And Life.
User's Guide
Images
Ultrasound Client
Done

Time	Patient Information	Image (click for a larger view)
11/16/2005 12:10:47 PM		
11/16/2005 12:11:05 PM		
11/16/2005 12:11:11 PM		

Fig. 92: Saved Images on Web Server

The saved images are displayed in ascending order according to the time that the image was saved. The first column in the table shows the time that the image was saved. The second column would display any patient information that may have been stored with the image. In the previous example, there is no patient information associated with any of the images. The third column shows a thumbnail view of the saved image. By clicking on any of the thumbnail images, a full-size version of the image is displayed in the right frame. If there are more images available than can be displayed in a single frame, the frame will become scrollable.

The table is created using an auto-generated *VBScript*. *VBScript* is a scripting language that the Microsoft web server uses to generate dynamic content. In this case, the content is gathered from a database on the WUC. The script was generated using the Microsoft Office FrontPage program. More details on the database are presented in Section 7.

The last option shown in the navigation menu is *“Ultrasound Client”*. Clicking this option will begin a download of the RID client application. This ensures that only a web browser is ever required to access the full remote functionality of the WUC remote data facilities.

A final option, not pictured in any of the preceding figures, is used solely for clinical evaluation. The option is called *“Administrative”*, and is a link to a database dump that must be manually created by a WUC user. The database dump is created by running a small script on the WUC and the link is included for ease of use in transferring the actual data off of the WUC.

7 Logging

Logging functionality is an important piece of any large and complex project, and the WUC is no exception. The prototype evaluations systems were delivered into clinical settings and left to operate without administrative attention for weeks to several months at a time. In order to gather meaningful data and statistics about the many facets of the WUC, a comprehensive and pervasive logging system was developed.

7.1 Logging Method

The Windows operating system uses a message passing scheme to communicate events to programs. Each message is identified with a 32 bit number and two additional 32 bit parameters, whose contents depend on the message. The additional parameters are called *lParam* and *wParam*. A Windows program contains a main message loop that receives messages and processes them. Most of the messages are defined by Windows; however, some messages may be defined by the application. For example, when a program initially requests to have its main window displayed, a message called *WM_CREATE* is sent to the program's main message loop. One of the additional 32 bit parameters is the memory address (pointer) of a structure (a data type comprising a set of primitive data types) that contains information about the new window, such as the size and position of the window.

Windows also provides a mechanism for programs to define their own messages. The WUC application defines 35 messages that are used to coordinate between the various elements of the software. There is a main message loop that receives all of these messages and takes varying actions depending on the message and the current program state. Some of these messages use one of the additional two parameters, specifically *lParam*, to pass additional information concerning the message. This information is referred to as the payload of the message. For example, when an ASR result is generated by the speech recognition system, an application defined message called *CASR_RESULT* is sent to the main message loop in which one of the additional parameters contains a pointer to a structure that contains information about the recognition result. In this instance, the recognition result is the payload for the *CASR_RESULT* message.

At the entry point into the main messaging loop, every message that is defined by the application is first passed to a logger. This piece of software logs every message into a persistent data store. In the case of the WUC, the persistent data store is a relational database. Each message is parsed and stored into the database for later retrieval and analysis. The 32 bit number that defines each message is given a mnemonic, which is a short string that is interpreted synonymously with 32 bit number. Table 13 contains a list of every application defined message:

Table 13: WUC Application Defined Messages

Mnemonic	Description
CASR_ERROR	ASR error (lParam -> *error message)
CASR_READY	ASR engine is ready
CASR_PARAMS	ASR parameters (lParam -> *CASR_PARAMS_PAYLOAD)
CASR_START	ASR start
CASR_STOP	ASR stop
CASR_FRAME_AVAILABLE	ASR frame available
CASR_SNR	ASR SNR available (lParam -> *snr)
CASR_ENERGY_LEVEL	ASR SNR available (lParam -> *energy level)
CASR_VAD	ASR VAD event
CASR_TS_FX	ASR trailing silence from feature extractor
CASR_TS_REC	ASR trailing silence from recognition engine
CASR_RESULT	ASR result (lParam -> *CASR_RESULT_PAYLOAD)
CASR_CMD	ASR command to execute (lParam -> *command)
CASR_REJECT	ASR utterance had poor confidence score (lParam -> *wave_buffer)
CASR_GAIN	ASR requested a new gain (lParam -> *new gain)
CASR_ABNORMAL	ASR abnormal condition (lParam -> *CASR_ABNORMAL_PAYLOAD)
CASR_DONE	ASR done
CASR_EXIT	ASR exited
PTT_BUTTON_DOWN	Push-to-talk button down

PTT_BUTTON_UP	Push-to-talk button up
ASR_MON_EXIT	ASR Monitor dialog box exited
VIEW_UTTERANCES_EXIT	View utterances dialog box exited
POWERSUPPLY_EXIT	Power supply dialog box exited
YESNO_EXIT	Yes/No dialog exited
YESNO_YES	Yes/No dialog 'yes'
YESNO_NO	Yes/No dialog 'no'
CPU_TEMP	CPU Temperature sensor measurement (lParam -> *TEMPERATURES)
BAT_STATUS	Updated battery status measurement is available (lParam -> *BATTERY_STATUS)
EXCEPTION	An exception was thrown
RADIO_BUTTON_DOWN	Radio button down
RADIO_BUTTON_UP	Radio button up
US_IMAGE_SAVED	An ultrasound image was saved (lParam -> *US_IMAGE)
PATIENTINFO_EXIT	Patient Info dialog exited
PATIENTINFO_SAVEDLAST_MESSAGE	Patient information was saved

The messages described above are generated in different parts of the application, but are all sent to the main message loop. They are all first logged, and then processed according to the message type and any additional information that the message may carry.

7.2 Logging Data Store

The WUC uses a relational database to store information gathered during usage. The choice of a relational database was made to take advantage of the search and data analysis capabilities they offer. This will be further discussed in Section 7.3.

A relational database consists of a set of tables. Each table has a set of columns of a predefined data type. The data types are generally specific to the particular database being used. Information is stored in rows in the tables of the database. Each row is called a record and contains fields that correspond to the column definitions for a table. The entire definition of tables and columns is called a schema. For the WUC, the open-source database MySQL was used.

The database is made relational by storing information in certain columns that correspond to the same column in other tables. For instance, a customer ID in one table containing orders placed at a store may correspond to an entry in another table that contains information about that customer, such as their address.

The goal of designing a schema for a relational database is to not replicate any information. This ensures that no space is wasted by having multiple copies of the same data and also ensures error free updates to the database. For example, if a customer's address is contained in two tables, an update to one table and not the other would leave the database in an inconsistent state.

Every record in a table must also be uniquely identifiable. This uniqueness is generally accomplished by designating one of the columns in a table as a primary key. Sometimes multiple columns may be combined to create a primary key. Using these principles, the database schema defined in Appendix VII – Database Schema was developed. While a full explanation of the design process for relational databases will not be provided, the WUC database schema will be detailed.

The database schema was developed to support statistical analysis of various aspects of the WUC, in addition to generic logging. These aspects include speech recognition, power supply monitoring, internal temperatures and errors. Additionally, the database supports the remote viewing of stored images functionality provided by the web server.

A set of tables was developed to store information pertinent to each of the aspects noted above. The tables use data types defined by MySQL and are detailed in the following tables:

Table 14: MySQL Numeric Data Types

Type	Signed Range	Unsigned Range	Storage Size	C Data Type
TINYINT	-128 to 127	0 to 255	1 Byte	(unsigned) char
SMALLINT	-32,768 to 32,767	0 to 65,535	2 Bytes	(unsigned) short

INT	-2,147,483,648 to 2,147,483,647	0 to 4,294,967,295	4 Bytes	(unsigned) int

Table 15: MySQL Binary Data Types

Type	Maximum Range	Storage Size	C Data Type
TINYBLOB	255 (2^8-1) Bytes	n+1 Bytes	void *, unsigned long n
BLOB	65,535 (2^{16}-1) Bytes	n+2 Bytes	void *, unsigned long n
MEDIUMBLOB	16,777,215 (2^{24}-1) Bytes	n+3 Bytes	void *, unsigned long n

Table 16: MySQL String Data Types

Type	Maximum Range	Storage Size	C Data Type
VARCHAR(M)	M Characters	M+1 Bytes	char *
TEXT	65,536 Characters	string length+2 Bytes	char *

There are additional data types defined by MySQL that are not detailed in the above tables, however, they are not used.

Every application defined message that is logged is assigned a timestamp that is accurate to the ms.

Generic logging uses a single table in the database, called *tblPackets*, and is defined in Table 17:

Table 17: tblPackets Definition

Column Name	Not Null	Unsigned	Data Type	Description
packet	✓	✓	INTEGER	Primary Key
tstamp			TIMESTAMP	Timestamp
tstampms	✓	✓	SMALLINT	Millisecond portion of timestamp
msg	✓	✓	TINYINT	Message identifier, Foreign Key
payload			TINYBLOB	Message payload

Any generic messages, which are messages that do not undergo any further processing such as *PTT_BUTTON_DOWN*, are logged into this table. The table logs the arrival of each message by noting its arrival time, the message identifier and the contents of the message payload if there is one.

The message identifier relates to another table in the database called *tblMessages*. This table relates the message identifier to its mnemonic and description and is detailed in Table 18:

Table 18: tblIMessages Definition

Column Name	Not Null	Unsigned	Data Type	Description
msg	✓	✓	TINYINT	Primary Key (related to Windows msg number)
mnemonic	✓		VARCHAR(45)	Mnemonic for message
description	✓		VARCHAR(255)	Full description of message

The relationship between the two tables is provided by the common *msg* column. The *msg* column in table *tblPackets* is a foreign key for the *msg* column in table *tblMessages*, and the *msg* column in table *tblMessages* is a primary key uniquely identifying each record in table *tblMessages*.

Speech recognition information spans three different tables. The primary table is called *tblUtterance*, and is detailed in Table 19:

Table 19: tblUtterance Definition

Column Name	Not Null	Unsigned	Data Type	Description
utterance	✓	✓	INTEGER	Primary Key
tstamp			TIMESTAMP	Timestamp
tstampms	✓	✓	SMALLINT	Millisecond portion of timestamp
words	✓	✓	INTEGER	Foreign Key, pk field from tblWords
end	✓	✓	SMALLINT	Elapsed time that PTT button was depressed (ms)
rec	✓	✓	SMALLINT	Elapsed time that PTT button was depressed plus processing time to return a recognition result (ms)
confidence	✓	✓	SMALLINT	Confidence score (0-10,000)
snr	✓		BLOB	Array of SNR values from ASR engine (dB/100)
el	✓		BLOB	Array of energy level values from ASR engine (dB/100)
abnormal			TINYBLOB	Structure containing information about any reported abnormal conditions that may have occurred during this utterance

This table stores a multitude of information about each and every recognition event that occurs. The timestamp for each utterance is the time that a recognition results was returned from the ASR engine.

The *words* column is a foreign key for table *tblWords*, which contains information about every possible utterance and is detailed in Table 20:

Table 20: tblWords Definition

Column Name	**Not Null**	**Unsigned**	**Data Type**	**Description**
pk	✓	✓	INTEGER	Primary Key
words	✓		VARCHAR(45)	String defined in the grammar
id	✓	✓	INTEGER	ID value assigned to the string

The *words* column contains the string for a particular utterance and the *id* column contains a number assigned to every utterance. The *id* value for a string is the actual value assigned to a particular command. The *id* column cannot be used as a primary key since multiple utterances may have the same id, allowing for more than one utterance to correspond to a single command.

The final table involved in logging ASR specific event is the *tblAudio* table, which is detailed in Table 21:

Table 21: tblAudio Definition

Column Name	**Not Null**	**Unsigned**	**Data Type**	**Description**
utterance	✓	✓	INTEGER	Primary Key, Foreign Key
audio	✓		MEDIUMBLOB	Wave file containing a recorded utterance

This is a very simple table whose primary key, *utterance*, is also a foreign key for the *utterance* column in table *tblUtterance*. The *audio* column contains complete WAVE file recordings of utterances that had poor confidence scores. This allows for later review by listening to utterances with low confidence scores to determine what may have caused the poor performance.

It would also have been correct to include *audio* column in the *tblUtterances* table. However, the frequency of needing to store this data was expected to be low. Also, a record that has blank fields still requires some data in the blank fields to indicate that they are blank. Having a mostly empty column in a table justified moving the data to a separate table.

The next two tables are used for periodically logging the current status of the power supply and the internal temperatures of the WUC. This data was logged once every minute into two separate tables. The battery information was logged into table *tblBattery*, and is detailed in Table 22:

Table 22: tblBattery Definition

Column Name	Not Null	Unsigned	Data Type	Description
pk	✓	✓	INTEGER	Primary Key
tstamp			TIMESTAMP	Timestamp
tstampms	✓	✓	SMALLINT	Millisecond portion of timestamp
bat1_tte	✓	✓	SMALLINT	Battery 1 estimated minutes until empty (0 – 65,535 min.)
bat2_tte	✓	✓	SMALLINT	Battery 2 estimated minutes until empty (0 – 65,535 min.)
bat1_rc	✓	✓	TINYINT	Battery 1 relative charge (0 – 100%)
bat2_rc	✓	✓	TINYINT	Battery 2 relative charge (0 – 100%)
bat1_v	✓	✓	SMALLINT	Battery 1 Voltage (0 – 65,535 mV)
bat2_v	✓	✓	SMALLINT	Battery 2 Voltage (0 – 65,535 mV)
bat1_i	✓		SMALLINT	Battery 1 Current (-32,768 – 32,767 mA)
bat2_i	✓		SMALLINT	Battery 2 Current (-32,768 – 32,767 mA)

The internal temperatures were logged into table *tblCPUTemp*, which is detailed in Table 23:

Table 23: tblCPUTemp Definition

Column Name	Not Null	Unsigned	Data Type	Description
pk	✓	✓	INTEGER	Primary Key
tstamp			TIMESTAMP	Timestamp
tstampms	✓	✓	SMALLINT	Millisecond portion of timestamp
cpu_temp	✓	✓	TINYINT	CPU on-die temperature sensor (0 – 255 °C)

local_temp	✓		TINYINT	Fan controller on-die temperature sensor (0 – 124 °C)
remote_temp	✓		TINYINT	Heatsink temperature sensor (0 – 124 °C)

Any error messages that occurred were logged into the table *tblErrors*, which is detailed in Table 24:

Table 24: tblErrors Definition

Column Name	Not Null	Unsigned	Data Type	Description
pk	✓	✓	INTEGER	Primary Key
tstamp			TIMESTAMP	Timestamp
tstampms	✓	✓	SMALLINT	Millisecond portion of timestamp
msg	✓		TEXT	Error message text

The final database table, detailed in Table 25, is called *tblImages*:

Table 25: tblImages Definition

Column Name	Not Null	Unsigned	Data Type	Description
pk	✓	✓	INTEGER	Primary Key
tstamp			TIMESTAMP	Timestamp
patient_name			VARCHAR(255)	Patient name (from patient information dialog)
patient_id			VARCHAR(255)	Patient id (from patient information dialog)
url	✓		VARCHAR(255)	URL for web interface

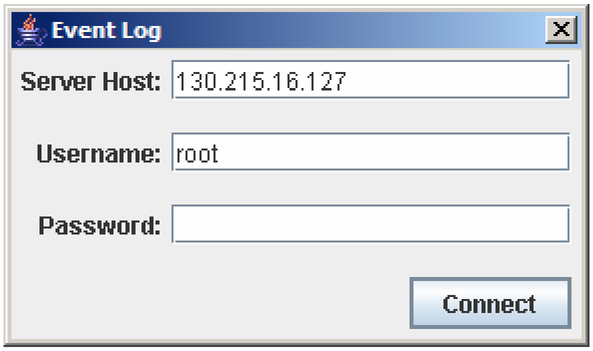
This table was used to store information that is presented by the web server when the user wishes to view saved images. The web page that is presented is derived from this database table. The URL column contains a URL that can display a thumbnail preview of the image and contains a hyperlink to the full-size image.

7.3 Data Analysis

Once the logging data has been stored in the relational database, it can be analyzed at a later time. To facilitate this analysis, a program was written using the Java programming language. The name of the program is JEventLog. It was developed using the Sun NetBeans 5.0 Development environment and the Java 1.5.0 update 6 software development kit (SDK).

The Java programming language is an interpreted language that can run on many different operating systems. A Java program is hosted within a virtual machine that is designed to run Java applications on a particular operating system. This allows the same program to be run on different operating systems without the need for recompilation and without changes. In addition to OS independence, the Java language has a rich set of built-in APIs to create graphical programs. In particular, many database vendors include software tools to allow access to their database products from Java programs. The particular database vendor chosen for the WUC, MySQL, also includes this software.

Before a database can be used, a connection to the database server must be established. Upon starting the JEventLog program, the user is presented with the dialog box shown in Fig. 93:



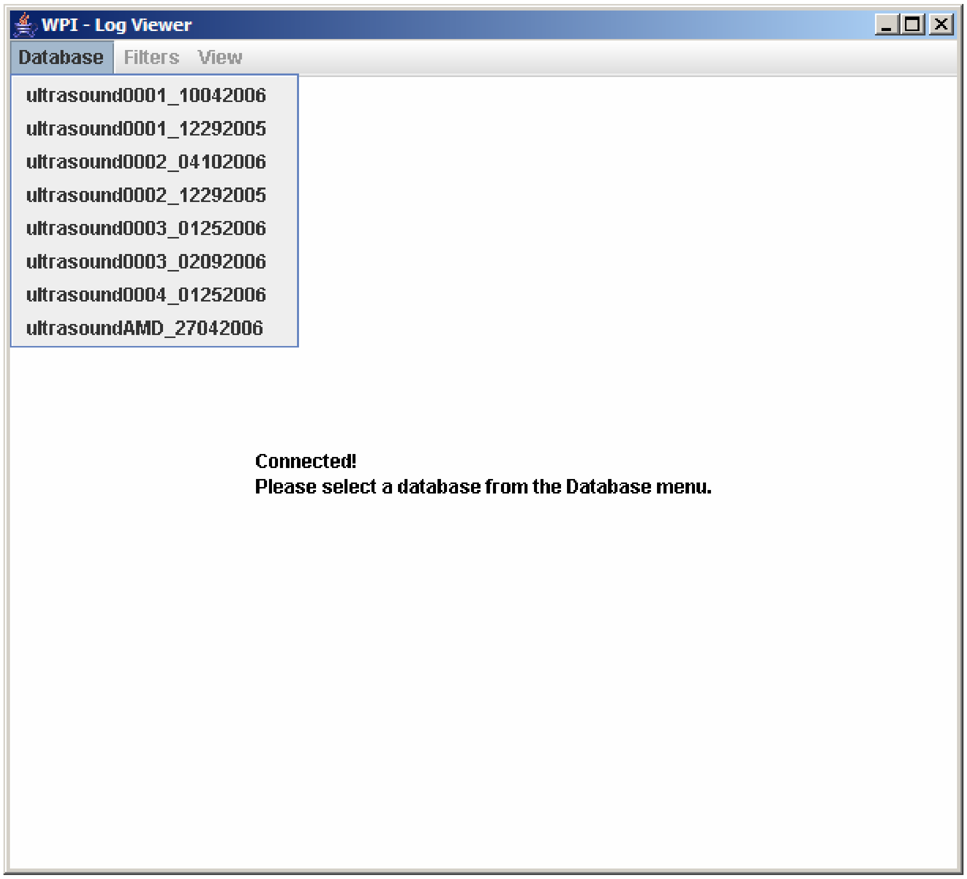
Server Host: 130.215.16.127

Username: root

Password:

Fig. 93: Data Analysis Application Connection Dialog

Databases use username/password authentication mechanism. Different users can be assigned different privileges, restricting what they can read or change. Upon logging in, a database on the database server must be selected. Fig. 94 shows the JEventLog program after a successful login.

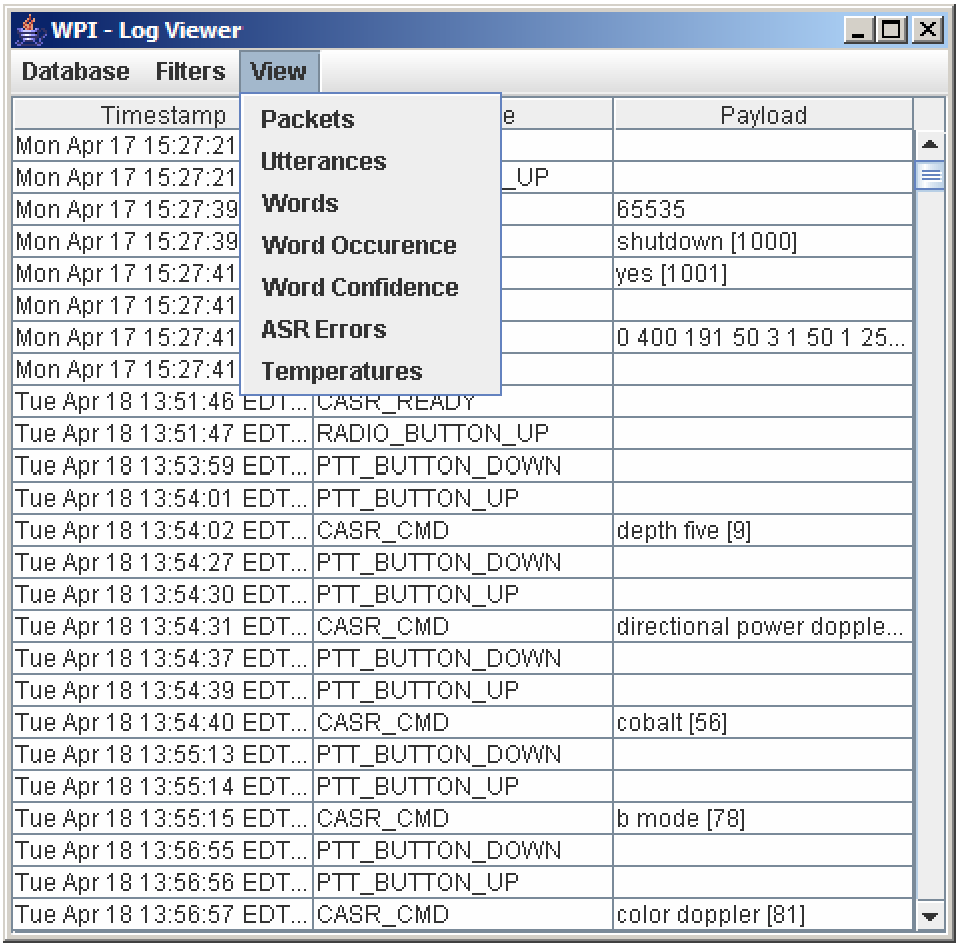


Connected!
Please select a database from the Database menu.

Fig. 94: Database Analysis Application Database Menu

All of the menus are unavailable, except for the Database menu. Using this menu, a particular database can be selected. In this instance, there are eight separate databases on this particular server. Specifically, each of these databases is a snapshot from a WUC prototype after it was received in from a clinical trial.

Once the user has logged in and selected a database, there are seven views that can be selected for the database. Each view focuses on a particular set of data and presents it in a conveniently readable manner. Fig. 95 shows the default view that is presented after a database is selected. This figure also shows the *View* menu items.



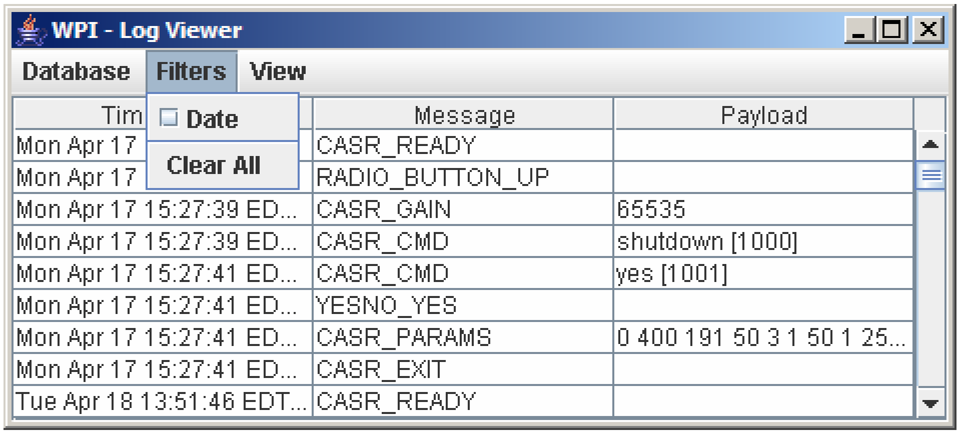
Timestamp	e	Payload
Mon Apr 17 15:27:21		
Mon Apr 17 15:27:21	_UP	
Mon Apr 17 15:27:39		65535
Mon Apr 17 15:27:39		shutdown [1000]
Mon Apr 17 15:27:41		yes [1001]
Mon Apr 17 15:27:41		
Mon Apr 17 15:27:41		0 400 191 50 3 1 50 1 25...
Mon Apr 17 15:27:41		
Tue Apr 18 13:51:46 EDT...	CASR_READY	
Tue Apr 18 13:51:47 EDT...	RADIO_BUTTON_UP	
Tue Apr 18 13:53:59 EDT...	PTT_BUTTON_DOWN	
Tue Apr 18 13:54:01 EDT...	PTT_BUTTON_UP	
Tue Apr 18 13:54:02 EDT...	CASR_CMD	depth five [9]
Tue Apr 18 13:54:27 EDT...	PTT_BUTTON_DOWN	
Tue Apr 18 13:54:30 EDT...	PTT_BUTTON_UP	
Tue Apr 18 13:54:31 EDT...	CASR_CMD	directional power dopple...
Tue Apr 18 13:54:37 EDT...	PTT_BUTTON_DOWN	
Tue Apr 18 13:54:39 EDT...	PTT_BUTTON_UP	
Tue Apr 18 13:54:40 EDT...	CASR_CMD	cobalt [56]
Tue Apr 18 13:55:13 EDT...	PTT_BUTTON_DOWN	
Tue Apr 18 13:55:14 EDT...	PTT_BUTTON_UP	
Tue Apr 18 13:55:15 EDT...	CASR_CMD	b mode [78]
Tue Apr 18 13:56:55 EDT...	PTT_BUTTON_DOWN	
Tue Apr 18 13:56:56 EDT...	PTT_BUTTON_UP	
Tue Apr 18 13:56:57 EDT...	CASR_CMD	color doppler [81]

Fig. 95: Database Analysis Application View Menu

The *Packets* view shows the interpreted contents of the *tblPackets* table in the database. For the messages that contain a payload, the payload is parsed and displayed in a user readable manner. For instance, the *CASR_CMD* message has a payload that is the id value of a command to be executed. The *Packets* view uses the contents of the *tblWords* table to display the utterance string that led to that command.

Databases are manipulated using a language called structured query language (SQL). The JEventLog program uses SQL to define queries that retrieve or update information stored in the database. The previous example shows the utility of SQL to manipulate and parse data.

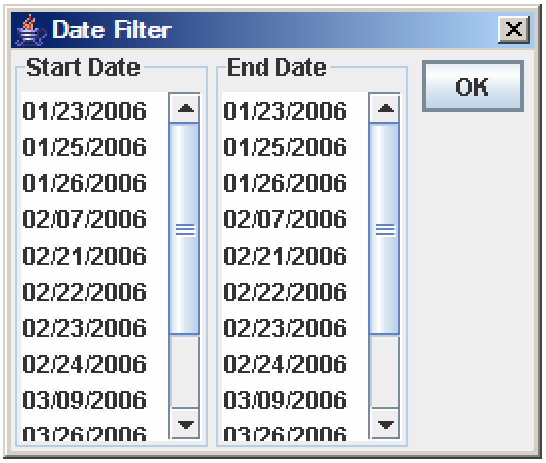
Another feature of the JEventLog program is the ability to add filters to the data being viewed. Using the *Filters* menu, a Date filter can be added. The *Filters* menu is shown in Fig. 96:



Tim	Message	Payload
Mon Apr 17	CASR_READY	
Mon Apr 17	RADIO_BUTTON_UP	
Mon Apr 17 15:27:39 ED...	CASR_GAIN	65535
Mon Apr 17 15:27:39 ED...	CASR_CMD	shutdown [1000]
Mon Apr 17 15:27:41 ED...	CASR_CMD	yes [1001]
Mon Apr 17 15:27:41 ED...	YESNO_YES	
Mon Apr 17 15:27:41 ED...	CASR_PARAMS	0 400 191 50 3 1 50 1 25...
Mon Apr 17 15:27:41 ED...	CASR_EXIT	
Tue Apr 18 13:51:46 EDT...	CASR_READY	

Fig. 96: Database Analysis Application Filters Menu

Selecting the *Date* menu item in the *Filters* menu brings up the dialog box shown in Fig. 97:

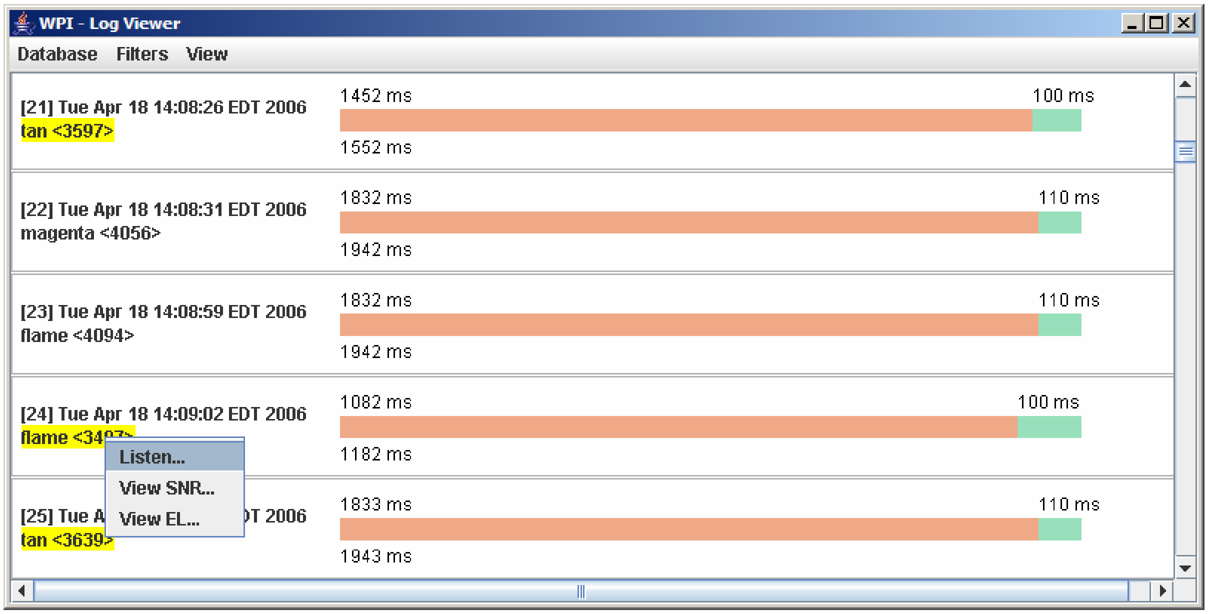


Start Date	End Date
01/23/2006	01/23/2006
01/25/2006	01/25/2006
01/26/2006	01/26/2006
02/07/2006	02/07/2006
02/21/2006	02/21/2006
02/22/2006	02/22/2006
02/23/2006	02/23/2006
02/24/2006	02/24/2006
03/09/2006	03/09/2006
03/26/2006	03/26/2006

Fig. 97: Date Filter Dialog Box

The Date filter dialog box contains a list of dates that have log events associated with them in the database. By selecting a start and end date, only events that occurred within the specified date range will be presented when selecting the various views. Again, SQL is used to add a filter to the query to only retrieve data within a specific data range. Currently, only the Date filter has been defined.

The view that contains the most information is the Utterance view, shown in Fig. 98:



[21] Tue Apr 18 14:08:26 EDT 2006
tan <3597>
1452 ms 100 ms
1552 ms

[22] Tue Apr 18 14:08:31 EDT 2006
magenta <4056>
1832 ms 110 ms
1942 ms

[23] Tue Apr 18 14:08:59 EDT 2006
flame <4094>
1832 ms 110 ms
1942 ms

[24] Tue Apr 18 14:09:02 EDT 2006
flame <34
1082 ms 100 ms
1182 ms

[25] Tue A DT 2006
tan <3639>
1833 ms 110 ms
1943 ms

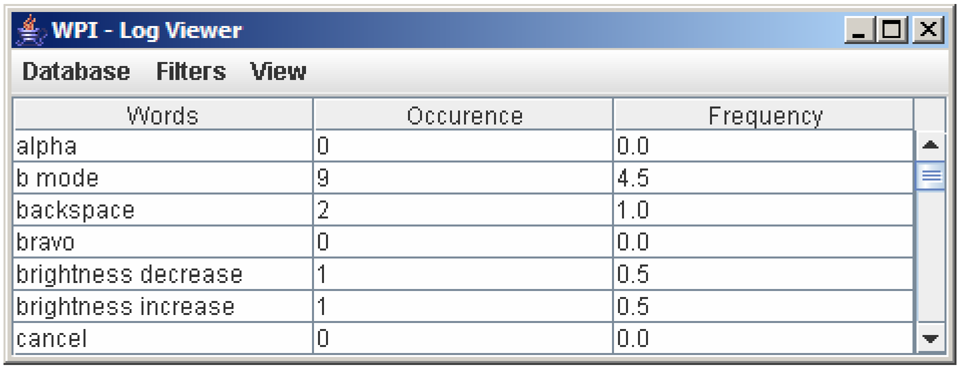
Fig. 98: Database Analysis Program Utterance View

The Utterance view presents a list of the utterances in the database. On the left side of each entry is the utterance number in brackets (which is the primary key for the table *tblUtterance*), timestamp, utterance string and a confidence score in angle brackets. On the right side is a bar the represents the duration of the utterance. The red portion is proportional to the time between depressing and releasing the PTT button, and the green portion is proportional to the processing time used by the ASR engine to generate a recognition result. The number above the bar correspond to the duration of these two sequences in ms, while the number below the bar is the overall duration of the recognition event.

Each item in the Utterance view also has a pop-up menu. From this menu, a graph can be displayed that shows the SNR and EL over time for the entire utterance, as reported by the feature extractor. If the utterance had a poor confidence score, it will be highlighted in yellow. In this case, the actual sound of the utterance was stored in the database and can be replayed using the JEventLog program.

The next view is the Words view. This view just shows a table displaying every utterance string in the grammar and the associated id value. Essentially, this is table *tblWords* without the primary key column.

The next two views shows statistics for the various utterance strings in the grammar. The first view is the Word Occurrence view and it is shown in Fig. 99:



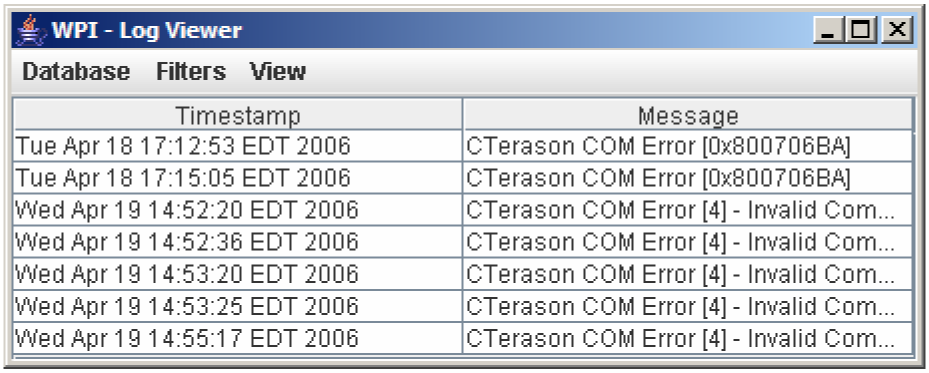
Words	Occurence	Frequency
alpha	0	0.0
b mode	9	4.5
backspace	2	1.0
bravo	0	0.0
brightness decrease	1	0.5
brightness increase	1	0.5
cancel	0	0.0

Fig. 99: Database Analysis Program Word Occurrence View

This view shows the overall occurrence and frequency of each utterance string. When selecting this view, the user is also presented with the option of saving these results as a comma separated values (CSV) file. This type of file is easily imported into programs such as Excel or MATLAB for further analysis.

The other statistical view is Word Confidence. This is very similar to the Word Occurrence view, but instead shows the average confidence score, as generated by the ASR engine, for each utterance string. It also has the option of saving the results into a CSV file.

The ASR Errors view is shown in Fig. 100:



Timestamp	Message
Tue Apr 18 17:12:53 EDT 2006	CTerason COM Error [0x800706BA]
Tue Apr 18 17:15:05 EDT 2006	CTerason COM Error [0x800706BA]
Wed Apr 19 14:52:20 EDT 2006	CTerason COM Error [4] - Invalid Com...
Wed Apr 19 14:52:36 EDT 2006	CTerason COM Error [4] - Invalid Com...
Wed Apr 19 14:53:20 EDT 2006	CTerason COM Error [4] - Invalid Com...
Wed Apr 19 14:53:25 EDT 2006	CTerason COM Error [4] - Invalid Com...
Wed Apr 19 14:55:17 EDT 2006	CTerason COM Error [4] - Invalid Com...

Fig. 100: Database Analysis Program ASR Errors View

This view is a summary of the errors that occurred while the WUC was operating. These errors may be transient in nature, or they may indicate a bug in the software. This view is useful in improving the reliability and robustness of the WUC software.

The final view is the Temperatures view. This view displays a table that shows temperatures read from the CPU, as well as the two temperatures available from the fan controller. The option to save the information into a CSV file is also given. In addition, another window displays the temperatures as a line plot of degrees Celsius over time, as shown in Fig. 101:

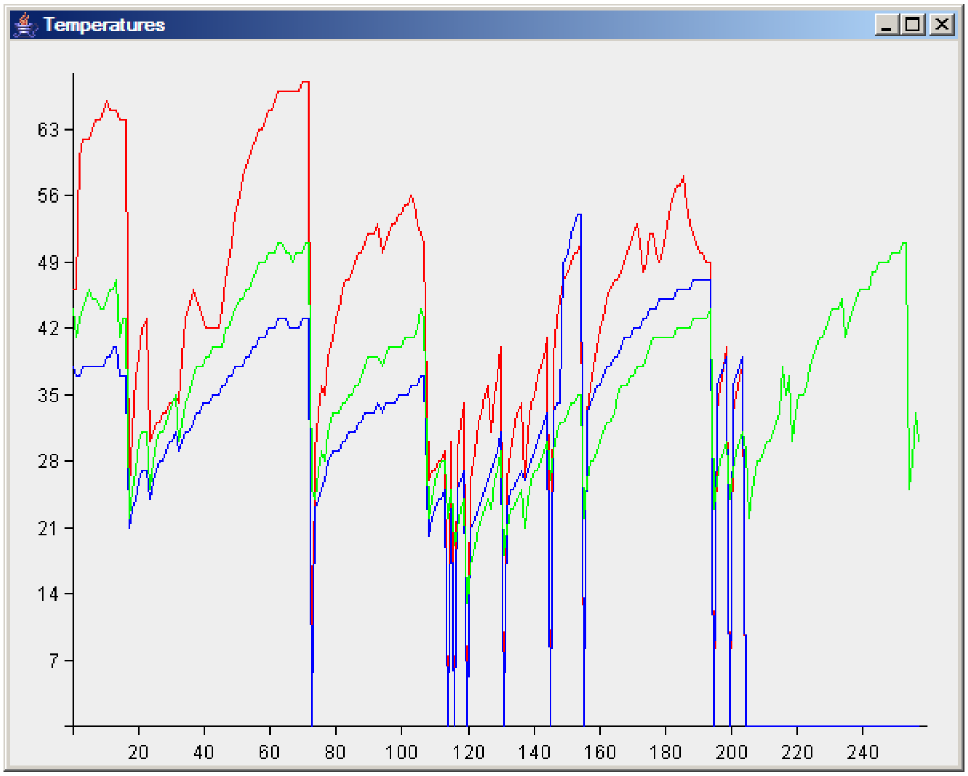


Fig. 101: Temperatures View Plot

The red line corresponds to the ambient temperature within the enclosure, while the green line represents the CPU temperature and the blue line indicates the temperature of the heatsink. The presence of a green line without any other lines indicates a loss of communication with the power supply, which was a problem with the initial prototypes.

While only a single database is used at one time for analysis, it is also possible to use multiple databases at once. The choice of one database at a time was made to facilitate the evaluation of individual clinical trials as well as conveniently separating the performance of one prototype from another. Section 9 will use the contents of all of the databases generated during clinical trials to shows the overall performance of the WUC.

8 System Integration

All of the preceding chapters focused on the individual system components that comprise the WUC. This chapter deals with the interactions between each of the components as well as other activities related to improving user interaction with the WUC.

8.1 Hardware Integration

The key piece of hardware that makes the WUC wearable is the vest. The vest is an off-the-shelf photographer's vest, called PhoTOGS, from a company called Domke. It must be at least a large in size to ensure that the vest pockets are large enough to accommodate everything. This is especially important for the batteries. The vest is shown in Fig. 102 and Fig. 103:

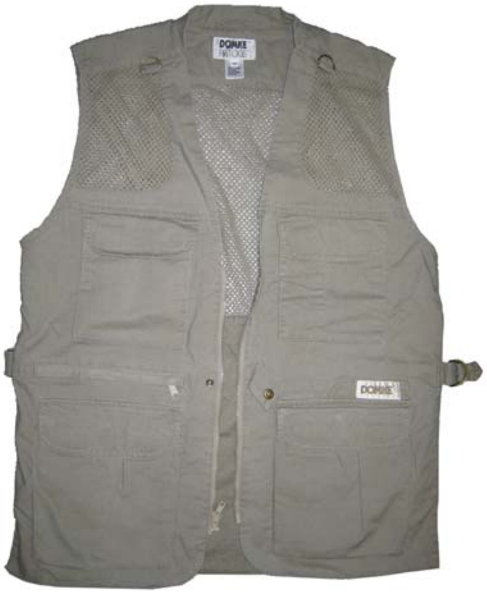


Fig. 102: Vest Front

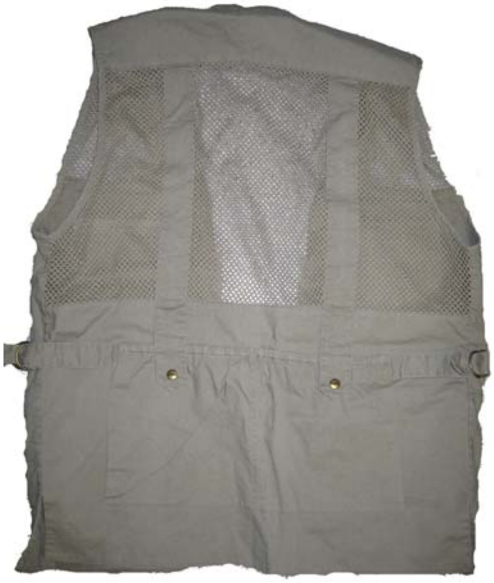


Fig. 103: Vest Back

In addition to housing all of the system components, the vest also contains all of the cables that interconnect the components. To this end, the vest was modified by a local tailor to include openings and channels in the vest for cable routing.

The vest is a two-layer design, with one piece of fabric forming the outside shell, and another piece of fabric forming the inner lining. Between these two pieces is a space that also contains all of the pockets in the vest. The vest was modified to place reinforced holes in the pockets that contain system components. All of these components are connected to the embedded computing platform via custom cable assemblies.

Each of the cable assemblies in the vest is customized for the component that it supports. There is one cable for each component, and one pocket for each component. The cables are all constructed from a 10 conductor, 24 AWG shielded cable. The end of the cable that terminates at the embedded computing platform has a single matching cord-connector for the panel-mount connector on the enclosure. The connector on the other end varies widely, depending on the component it is designed to connect to. Often, there are several connectors on a cable. For applications requiring the delivery of significant amount of current, such as the battery and AC adapter cables, multiple conductors are combined to increase the effective gauge of the conductors. A full description of all of the cables assemblies is contained in Appendix III – External Cable Assemblies.

The embedded computing enclosure is designed to fit into the back pocket of the vest, which was modified to facilitate airflow to cool the embedded computer. The bottom of the enclosure is contoured to fit the wearer's back. When housed in the back pocket of the vest, the cables are free to exit into the vest via two reinforced openings in the back pocket, into the internal space. Fig. 104 shows the location of each component in the vest:

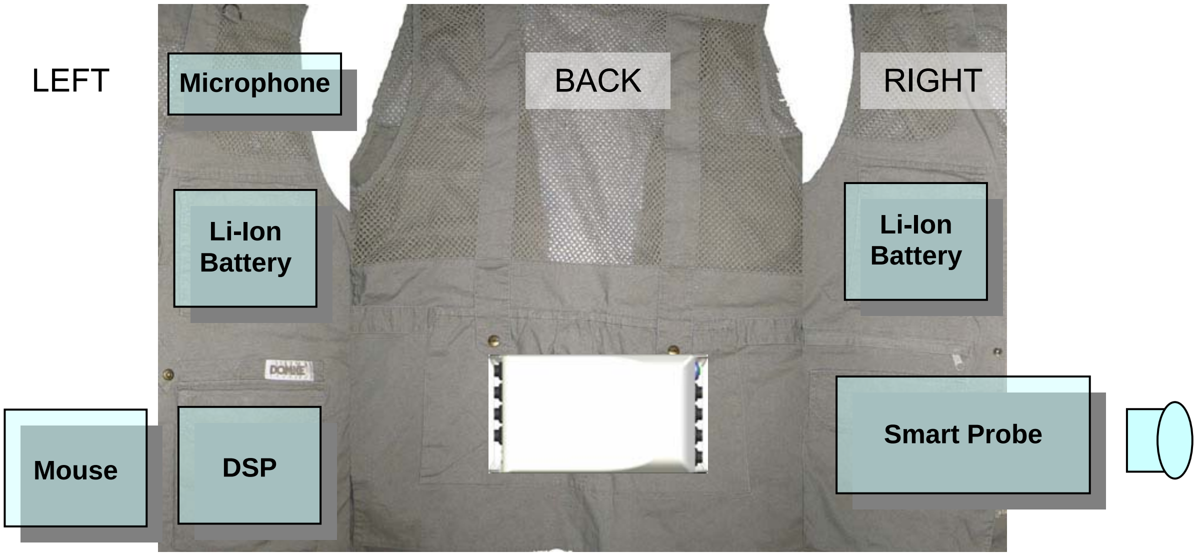


Fig. 104: Vest Component Layout

Two components, in particular, have been specially accommodated in the vest. Previous vest designs had the cable for the head-mounted display and the microphone external to the vest. This often resulted in the cables getting caught and interfered with the user's freedom of motion. To alleviate this problem, the cabling for these components was integrated into the vest.

The array microphone is located in the mesh area on the upper left portion of the vest. It is secured in a mesh pocket and angled towards the wearer's mouth. The cable for the microphone is routed internally, inside a channel created near the zipper.

The cable for the head-mounted display is routed inside a channel created in the back of the vest. The channel was created in the left-side suspender so that the cable exits near the collar.

An AC adapter is also provided for the WUC. The 24 V, 4.17 A rated AC adapter was modified by replacing the DC connector with an in-line cord connector of the same style used on the enclosure.

8.2 Software Integration

There are several software components that are used to produce the full functionality of the WUC. The components are listed in Table 26:

Table 26: Software Components

Executable	Description
Ultrasound.exe	Terason 2000 Ultrasound Application
wpiultrasound.exe	WPI Ultrasound Application
ultrasound_client.exe	WPI Ultrasound Remote Imaging Client
shutdown.exe	Shutdown Manager
rid.exe	Remote Imaging Server
inpout32.dll	I/O Port API
libmysql.dll	MySQL Database API
mfc71.dll	Microsoft Foundation Class (MFC) API
vocon3200api.dll	ScanSoft Vocon 3200 API
vocon3200g2penu.dll	ScanSoft Vocon 3200 English Grammar to Phoneme API
vocon3200rsrc.dll	ScanSoft Vocon 3200 Shared Resources API

The *wpiultrasound.exe*, *rid.exe* and *shutdown.exe* applications were all written in C++. The *wpiultrasound.exe* and *shutdown.exe* applications use the Win32 API and run on the Microsoft Windows XP operating system, while *rid.exe* uses the Microsoft Foundation Class (MFC) API and runs on the Microsoft Windows 2000 operating system. Windows XP is the operating system used on the WUC and it is backwards compatible with Windows 2000 applications. The Microsoft Visual Studio .NET 2003 development environment was used for all C++ software development. In total, 21,580 lines of C++ were written.

During normal operation, the *Ultrasound.exe*, *wpiultrasound.exe* and *rid.exe* processes are running. The *wpiultrasound.exe* processes is a Win32 application, while the *rid.exe* processes is a Microsoft Foundation Class (MFC). MFC is an alternate API for writing programs for the Windows operating system.

The dynamic link libraries (DLL) are required to support the executables and are loaded by the dependent executable when the executable is loaded. All of the DLLs, with the exception of *mfc71.dll*, support the execution of the *wpiultrasound.exe* process. *mfc71.dll* supports the execution of the *rid.exe* process by providing the

MFC API.

The *wpiultrasound.exe* process is comprised of two message loops, each running in its own thread. The main message loop processes the Dashboard GUI while another message loop processes speech recognition events. All other threads are pop-up threads that are created when there is work to be done. The use of pop-up threads maintains a responsive GUI.

The *ultrasound_client.exe* process contains a single message loop. It uses a separate thread to handle updating the display with newly received images.

The *shutdown.exe* process contains a single message loop. It uses a separate thread to monitor the state of the three processes that are normally running. Once all of these processes have exited, the embedded computer is shutdown. It was found that directly shutting down the embedded computer, while the three processes were running, could take over five minutes. By waiting until the processes have exited, the shutdown process completes in less than thirty seconds. It is unknown what causes this slowdown, which is manifested by a very slow logout process. While the *shutdown.exe* process is running, it displays a message reminding the user to shut off the head-mounted display.

The *rid.exe* process is an MFC application that contains a Terason supplied ActiveX object. The Terason ActiveX object is a frame server for the images being displayed by the *Ultrasound.exe* process. The image frames are transferred between the *Ultrasound.exe* process and the *rid.exe* process through a shared memory interface, which is accessed using the Terason ActiveX object. The *rid.exe* process is an MFC application, and not a Win32 application, because it was found that the Terason ActiveX object could not be used otherwise.

The Doxygen [53] documentation system was used to document all of the C++ source code written for the WUC. Doxygen works by parsing specially formatted comments in C++ source and header files to produce documentation in various formats. When viewed in textual format, the documentation is over 200 pages. The distributed documentation is in Microsoft Compressed HTML Help that can be viewed using tools provided as part of Windows.

To facilitate the installation of the software, an installer was written using the Inno Setup [54] installer program. Inno Setup is a script-driven installer that compiles all the required resources into a single executable file. The executable includes all of the resources required to install the application, along with an installation program. The installer installs all the software used by the WUC, configures it and additionally installs software and user documentation.

8.3 User Integration

The WUC is a new technology for most of the people who will use it. Wearable computing is not a ubiquitous concept, and some extra care was required to introduce people to the system and be able to take full advantage of it in a short period of time. To this end, a training manual was developed, along with an abbreviated version of the “Terason Ultrasound System User Guide” normally supplied with the Terason application software.

The sixty-nine page training manual is titled, “WPI Wearable Ultrasound System User’s Guide”. When used in conjunction with the Terason manual, it provides all the information a first-time user needs to begin using the WUC. The manual contains the following sections:

- Introduction
- Quick Start Guide
- General Usage Guide
- Tutorials
- Administrative Guide

- Specifications

In addition to the manuals, a CD containing three training videos was produced. The training videos were produced using a digital video camera and later transferred to a computer for editing. The final videos are in the Windows Media Player 9 format. The audio format is the same as a CD (two channels of 16-bit samples with a sampling rate of 44.1 kHz) and the video format is the same as the broadcast standard used in North America (NTSC, 720 x 480 pixels with a frame-rate of 29.97 fps). Each video is encoded for a data rate of 2,083 kb/s.

The training videos are described in Table 27:

Table 27: Training Videos

Video	Running Time	Size	Synopsis
Introductory Tutorial	8 m 00 s	63,584,578 Bytes	A complete introduction to the components of the WUC.
Patient Information Tutorial	1 m 41 s	7,606,324 Bytes	A short tutorial targeted at how to use the patient information system.
Voice Command Tutorial	9 m 07 s	37,600,988 Bytes	Selected examples from the tutorials contained in the WPI Wearable Ultrasound System User's Guide

The full scripts for the "Introductory Tutorial" and the "Patient Information Tutorial" videos are contained in Appendix VIII – Training Video Scripts.

9 Technical Performance

The following sections describe the performance of the completed system, beginning with the Smart Battery Charger and followed by the thermal performance, power supply and the speech recognition system. A complete system specification is also included.

9.1 Battery Charger

The battery charger is the most complex circuit on the power supply PCB. The design went through several iterations and two PCBs until satisfactory performance was achieved. A full description of the battery charger can be found in Section 4.3.

The first result shows the relative capacity vs. time for a single Smart Battery to be charged by the Smart Battery Charger. The Smart Battery was discharged into a constant load until the internal protection circuitry disabled the Smart Battery. The Smart Battery was then connected to the Smart Battery Charger and charged until the Smart Battery requested that the charging be terminated. The results were obtained by querying the electronics in the Smart Battery, and are presented in Fig. 105:

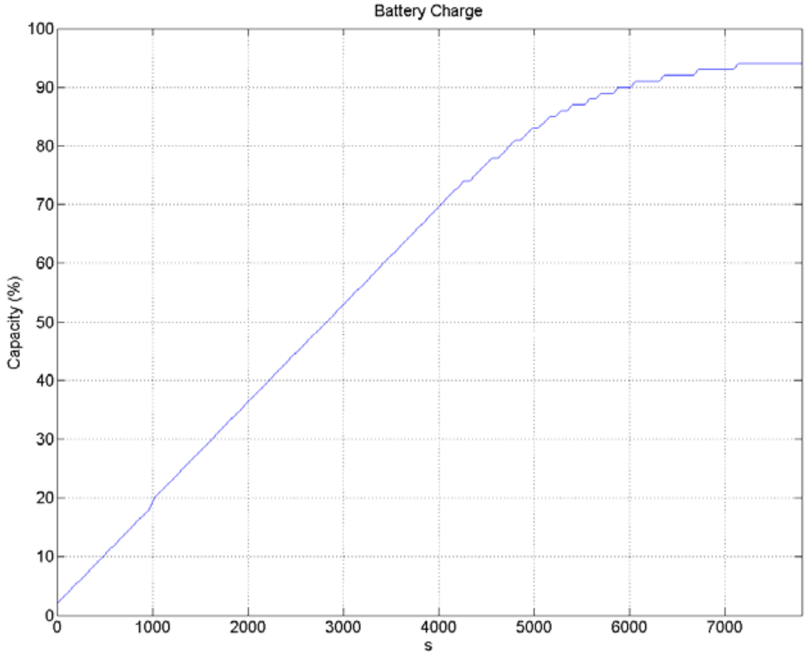


Fig. 105: Single Smart Battery Relative Charge Capacity vs. Time While Charging

The total time to charge the Smart Battery was 7,803 s [2 h 10 m 3 s]. The Smart Battery reported an average power consumption of 45.32 W while charging, and absorbed a total of 98.25 Wh [6.032 Ah] of energy.

Some of the energy absorbed by the battery is dissipated as heat during the charging process. The same is true during discharge, so not all of the energy used to charge the battery is available for use. In Fig. 105, the Smart Battery only reaches relative charge of 94 %. This is because the electronics, within the Smart Battery, are calibrated to read 100 % when charged to the full rating of the Smart Battery. In reality, the Smart Battery will always store somewhat less than the rating would suggest. This capacity will also degrade over time. A calibration cycle can be performed so that the Smart Battery will report a 100 % charge when fully charged to whatever the actual maximum capacity is. The Smart Battery used in these tests was not calibrated. A special charging cycle is required to perform the calibration, and while the Smart Battery Charger hardware does support this, the interface software does not provide this functionality.

For Li-Ion battery chemistries, charging occurs at a constant voltage. For this model of Smart Battery (*Inspired Energy* NL20204A22), the charging voltage is specified as 16.8 V ± 50 mV. However, there is also a 4 A charging current limit. This results in a charging profile that is initially current limited, resulting in a lower charging voltage than specified. As charging progresses, the charging current will drop, and the charging voltage will increase to 16.8 V. Fig. 106 shows the manufacturer's example of the charge characteristics for the Smart Battery:

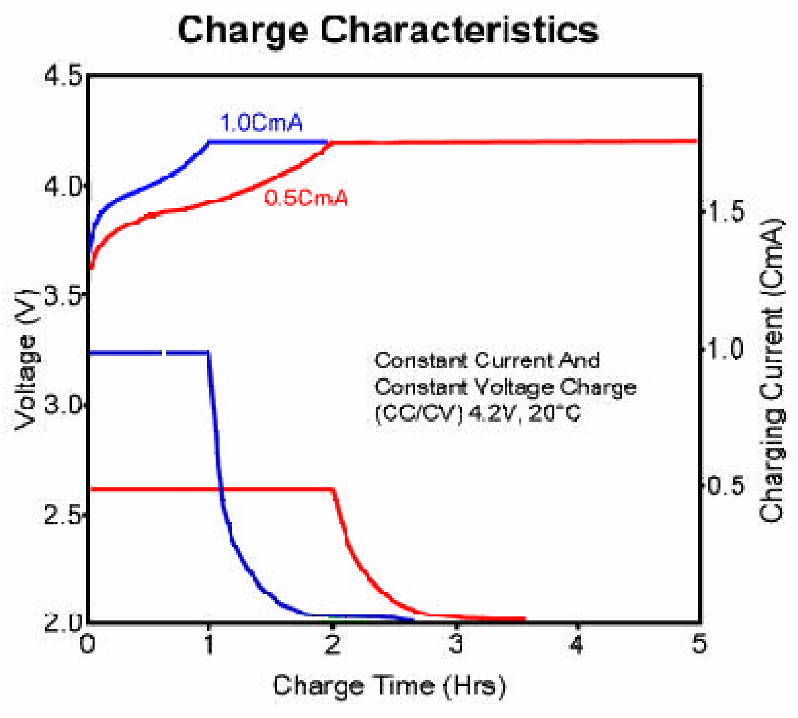


Fig. 106: Manufacturer Single Cell Charge Characteristics [37]

The plots are for a single cell within the Smart Battery pack, which are arranged in a 4 series / 3 parallel (4S 3P) configuration. The blue colored plot represents the full charging rate of the battery and shows the characteristic constant current and then constant voltage of a charging cycle. Fig. 107 shows the charging current and charging voltage vs. time for the same test as described in Fig. 105:

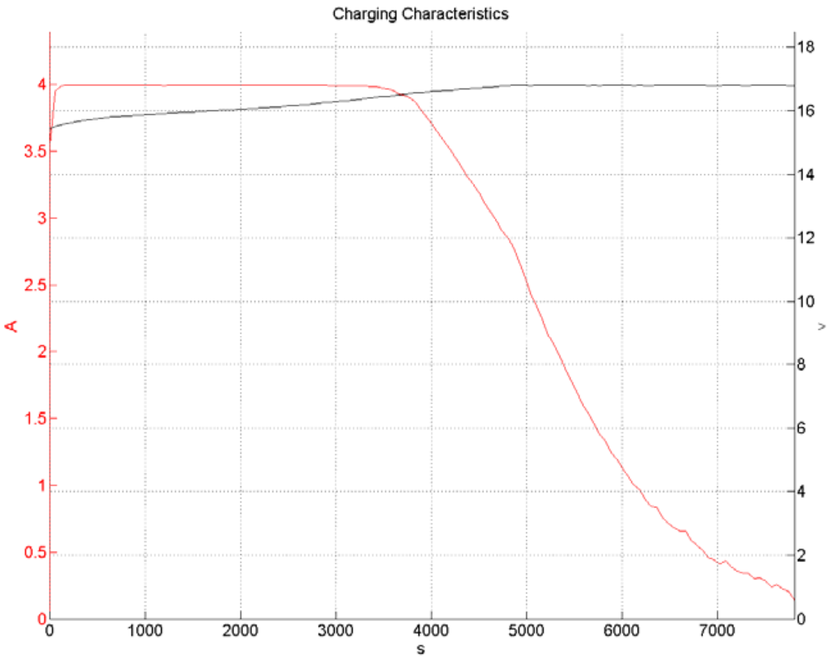


Fig. 107: Single Smart Battery Charge Characteristics

During the current limiting portion of the charging cycle, the current is consistently limited to 4 A, with the actual value being 3.995 A. After the current limiting portion of the charging cycle has completed, the charging voltage reaches 16.8 V ± 15 mV.

The same Smart Battery was then fully discharged into a constant load. The load was designed to draw a constant 37 W from the Smart Battery. This power draw represents the observed normal maximum power that the WUC can consistently draw during operation. The results are presented in Fig. 108 and Fig. 109:

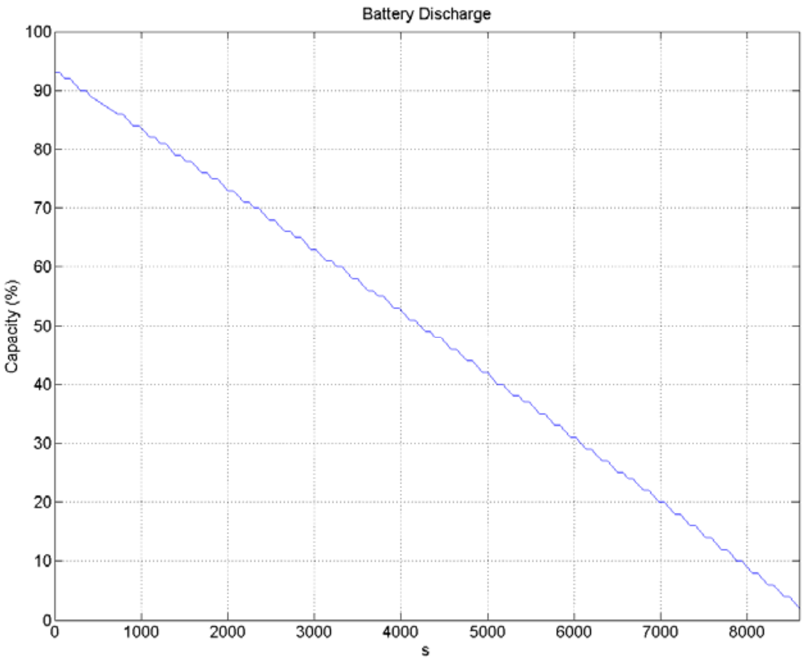


Fig. 108: Single Smart Battery Relative Charge Capacity vs. Time While Discharging

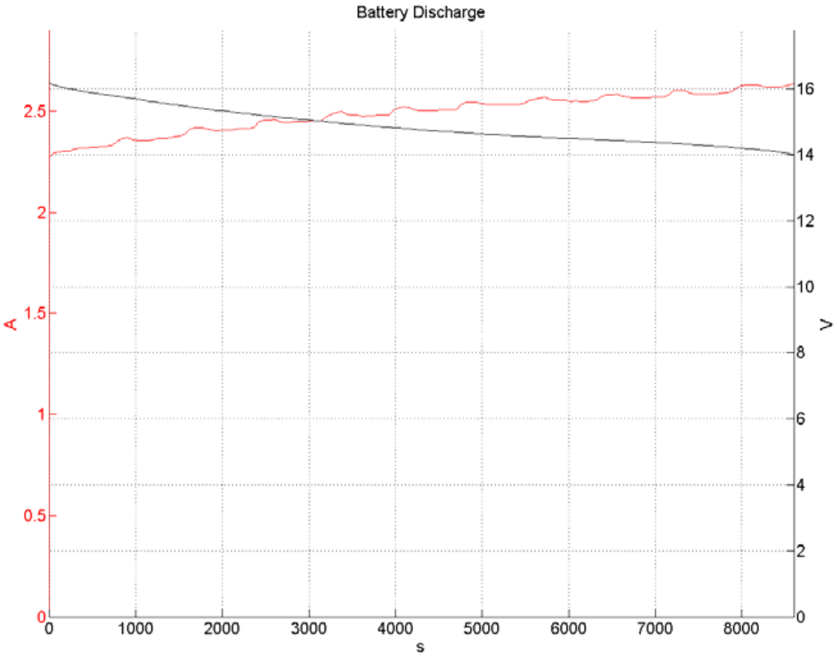


Fig. 109: Single Smart Battery Discharge Characteristics

The total time to discharge a single Smart Battery was 8,600 s [2 h 23 m 20 s]. The Smart Battery reported an average power draw of 37.01 W while discharging, and provided a total of 88.41 Wh [5.954 Ah] of energy.

These same tests were then repeated, but now two Smart Batteries were used. The first result shows the relative capacity vs. time for two Smart Batteries to be charged by the Smart Battery Charger. Both Smart Batteries were discharged into a constant load until the internal protection circuitry disabled the Smart Batteries. The Smart Batteries were then connected to the Smart Battery Charger and charged until both Smart Batteries requested that the charging be terminated

Each Smart Battery managed to discharge so fully, that the reported capacity from each Smart Battery was 0 %. This can occur when the Smart Battery electronics shutdown to conserver power and require a short charging period to “wake-up”.

The total time to charge the Smart Batteries was 13,169 s [3 h 39 m 29 s]. The Smart Batteries reported a total average power consumption of 56.66 W while charging, and absorbed a total of 207.28 Wh [13.036 Ah] of energy.

The current limiting is slightly different for charging two Smart Batteries. The AC adapter that provides power for charging the Smart Batteries can provide a maximum of 4.17 A of current at 24 V, for a maximum power draw of 100 W. The Smart Battery Charger was designed to enforce a 4 A limit on the current that can be drawn from the AC adapter. With more than one Smart Battery charging, the total power that can be consumed exceeds what can be provided by the AC adapter, and the charging current is subsequently limited by the Smart Battery Charger. After the current limiting portion of the charging cycle has completed, the charging voltage reaches 16.8 V ± 39 mV.

When two Smart Batteries are charging, they must share the available charging current. Since both of the Smart Batteries were at similar capacities, the available charging current is shared more or less equally between each Smart Battery.

When compared to charging a single Smart Battery, charging two Smart Batteries takes 69 % longer, and consumes 25 % more power while charging.

The same Smart Batteries were then fully discharged into a constant load. As before, the load was designed to draw a constant 37 W from the Smart Battery. The total time to discharge the Smart Battery was 18,362 s [5 h 6 m 2 s]. The Smart Batteries reported a total average power draw of 36.46 W while discharging, and provided a total of 185.97 Wh [12.346 Ah] of energy.

When compared to discharging a single Smart Battery, two Smart Batteries provided 110 % more power while requiring only 69 % more time to charge. The extra power delivered exceeds double what was delivered by a single Smart Battery because the second Smart Battery probably had a higher capacity than the original Smart Battery used in the original discharge test. As Li-Ion batteries are subjected to multiple charge and discharge cycles, they will naturally lose capacity. Therefore, the second Smart Battery used in the dual Smart Battery tests must have been a newer battery.

The charging voltage for the Smart Batteries is provided by a switching regulator circuit that is controlled by the Smart Battery Charger. A LeCroy LT342 digital oscilloscope was used. The sampling rate was 500 MS/s and no bandwidth limiting was used. The performance of this switching regulator, when providing 3 A of charging current as determined by the Smart Battery electronics, is shown in Fig. 110:

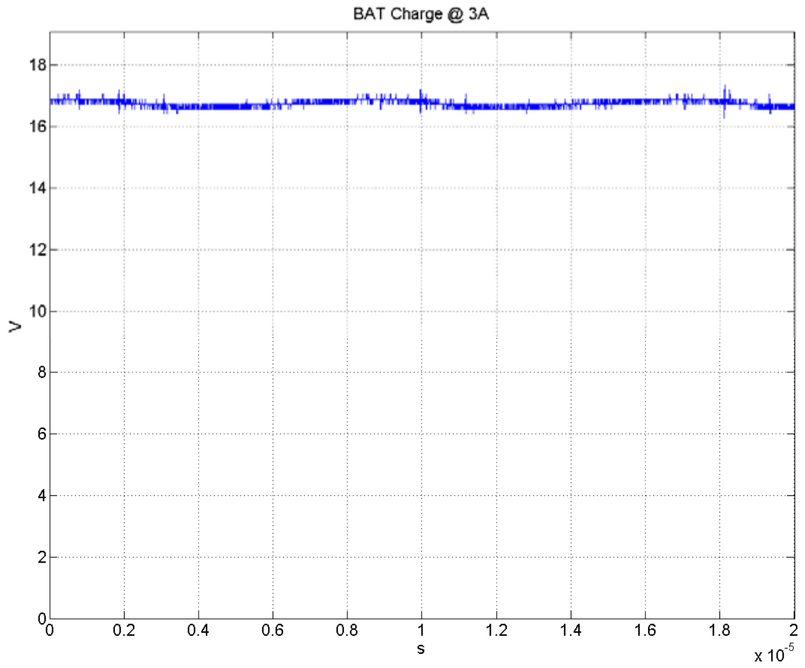


Fig. 110: Smart Battery Charger Switching Regulator Providing 3 A (DC Coupled)

The mean voltage output is 16.74 V. This is within 0.4 % of the proper value. Fig. 111 shows the same setup, except that the oscilloscope was set for AC coupling and the Voltage range is much smaller:

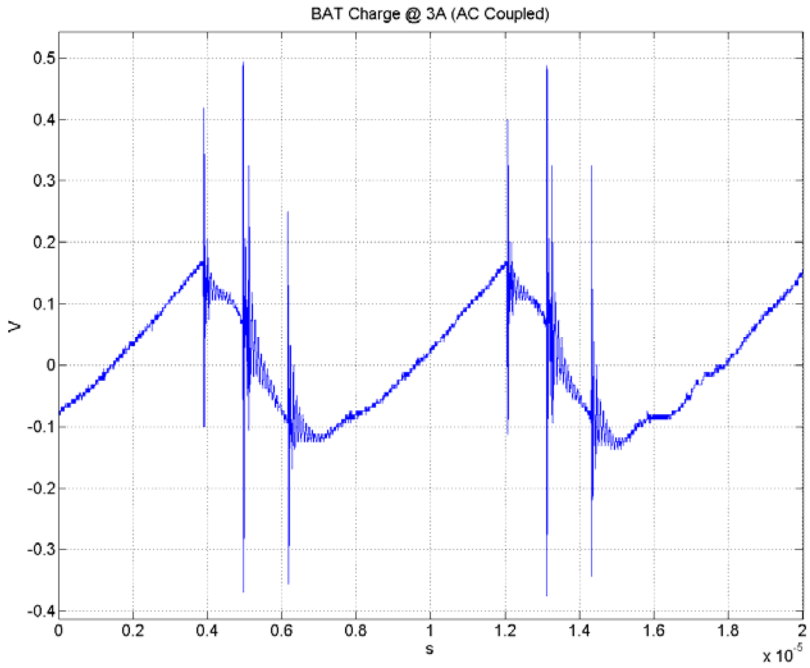


Fig. 111: Smart Battery Charger Switching Regulator Providing 3 A (AC Coupled)

The maximum overshoot is 493.8 mV and the maximum undershoot is 375.0 mV. This results in an output voltage ripple of 868.8 mV_{p-p}. While this performance appears to be rather poor, it does not appear to decrease the amount of energy that can be stored within the Smart Batteries. However, the extra power dissipated by the excessive transient voltages causes the linear regulator components to heat up considerably. During charging, the components become too hot to touch without causing injury.

As charging progresses, charging current will slowly decrease. The performance of this switching regulator, when providing 0.5 A of charging current, is shown in Fig. 112:

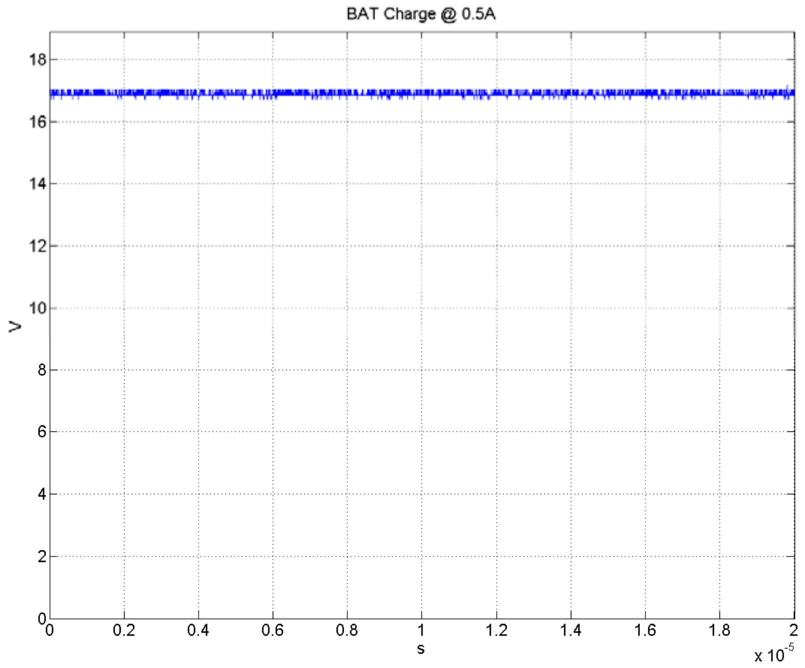


Fig. 112: Smart Battery Charger Switching Regulator Providing 0.5 A (DC Coupled)

The mean voltage output is 16.91 V. This is within 0.7 % of the proper value. Fig. 113 shows the same setup, except that the oscilloscope was set for AC coupling and the Voltage range is much smaller:

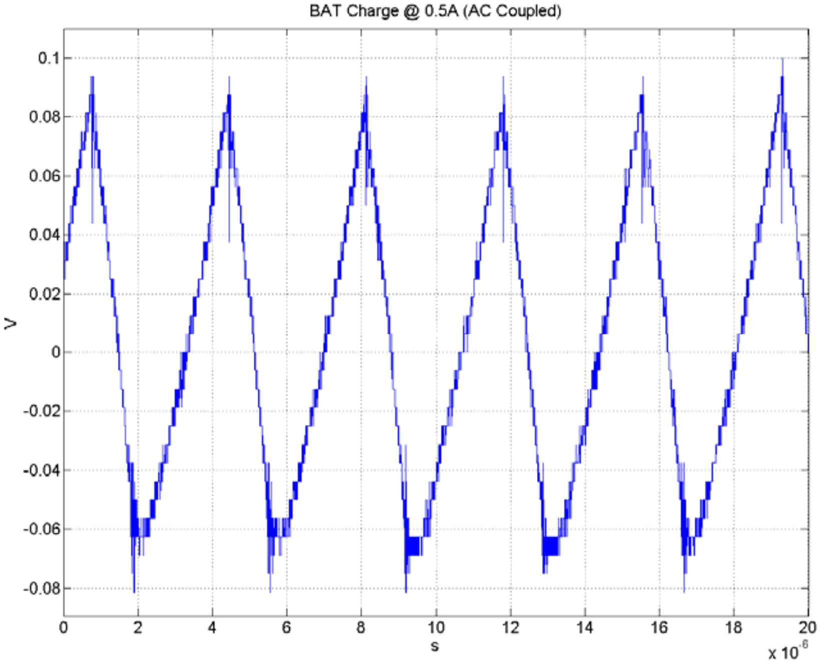


Fig. 113: Smart Battery Charger Switching Regulator Providing 0.5 A (AC Coupled)

The maximum overshoot is 100.0 mV and the maximum undershoot is 81.3 mV. This results in an output voltage ripple of 181.3 mV_{p-p}. As the charging current decreases, the performance of the switching regulator improves dramatically. These results are markedly better than the results obtained while charging at 3 A.

9.2 5 V Switching Regulator

The initial switching regulator design was plagued with switching transients that exceeded 700 mV. This was caused by a PCB design flaw that inadvertently coupled the switching node to the output. A PCB redesign to reduce this coupling, along with the addition of two capacitors improved the output voltage ripple to 50 mV. The capacitors are of different case sizes and different dielectrics to provide a good ground path for the AC transients. The final result was measured using a LeCroy LT342 digital oscilloscope. The sampling rate was 500 MS/s and no bandwidth limiting was used. When connected to a 35 W constant load, the performance of the 5 V switching regulator is shown in Fig. 114:

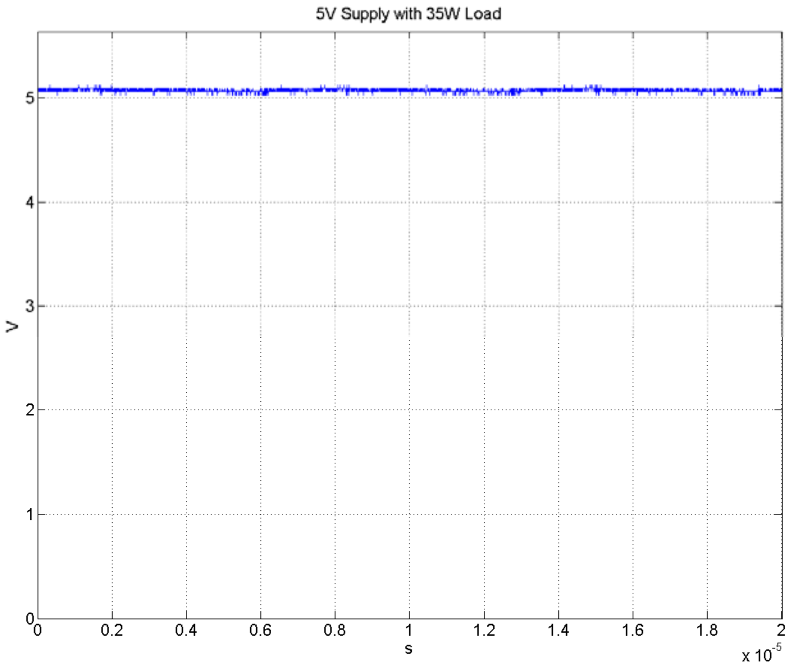


Fig. 114: 5 V Switching Regulator with 35 W Load (DC Coupled)

The mean voltage output is 5.07 V. This is within 1.4 % of the proper value. Fig. 115 shows the same setup, except that the oscilloscope was set for AC coupling and the voltage range is much smaller:

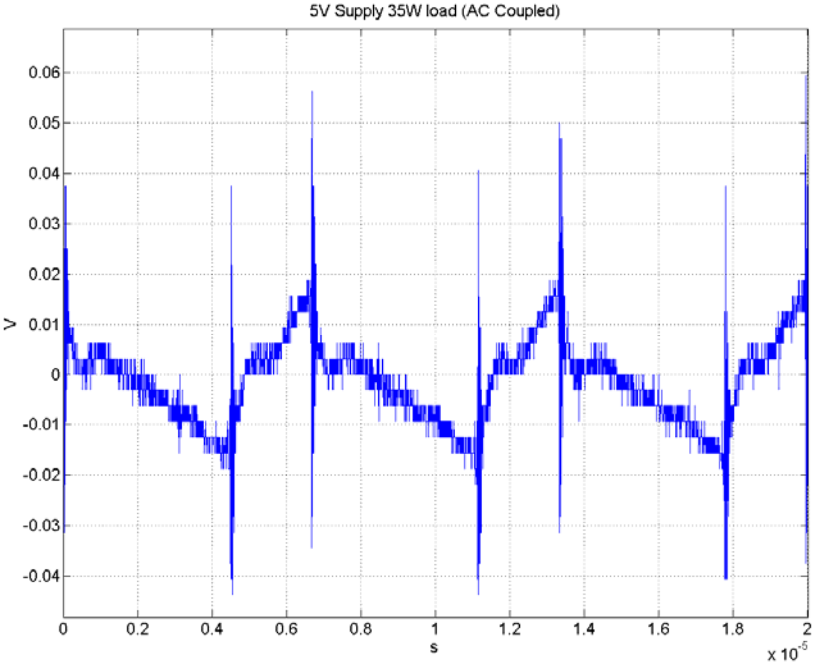


Fig. 115: 5 V Switching Regulator with 35 W Load (AC Coupled)

From Fig. 115, the switching transients can clearly be seen. The maximum overshoot is 62.5 mV and the maximum undershoot is 43.8 mV. This results in an output voltage ripple of 106.4 mV_{p-p}. This is well within tolerances for all system components.

Under very light loads, switching regulators often exhibit poor regulation. Fig. 116 shows the switching regulator with only the oscilloscope probe as a load:

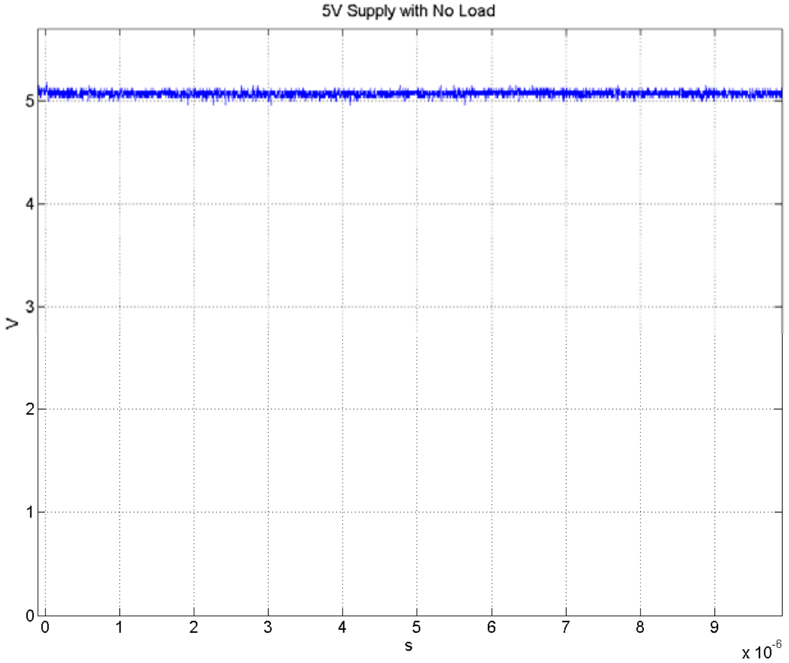


Fig. 116: 5 V Switching Regulator with No Load (DC Coupled)

With no load, the switching regulator still performs very well. The mean voltage output is 5.07 V. This is within 1.4 % of the proper value.

9.3 Embedded Computing Platform Thermals

The thermal performance of the embedded computing platform was tested using a small oven. A complete WUC system was placed in the oven and operated in Power Doppler imaging mode while a wireless Remote Desktop session was active. The Power Doppler imaging mode, combined with an active Remote Desktop session using the 802.11b/g link, draws the most overall system power (32 W), and fully exercises the CPU. The oven was set to 40 °C [104 °F] and the temperature was monitored using the temperature sensors provided by the power supply and the CPU. Once a steady state was reached, the oven door was opened and the system was allowed to continue running at the ambient room temperature of 22 °C [104 °F]. The results are shown in Fig. 117:

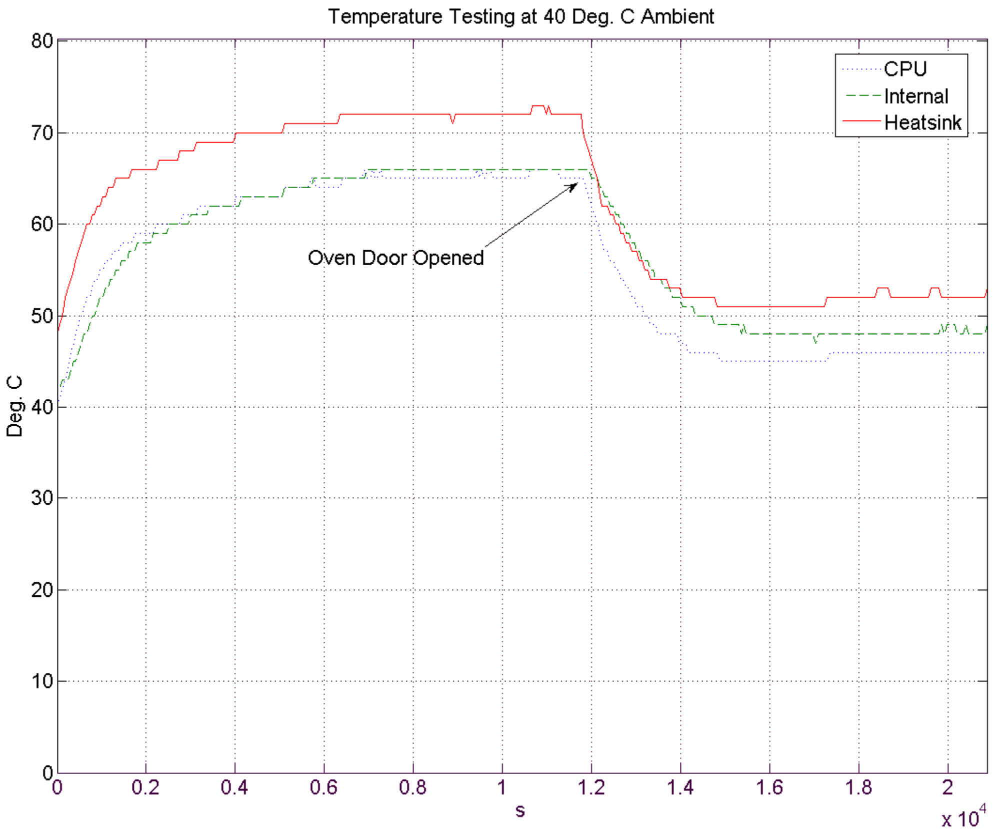


Fig. 117: Temperature Testing

The maximum ambient temperature that is allowed within the enclosure is 85 °C, based on manufacturer supplied temperature tolerances. The maximum ambient temperature was 66 °C. The highest temperature, 73 °C, was recorded by the temperature probe attached to the heatsink. The location oh this temperature probe places it at the hottest point on the heatsink. The system ran without errors for the entire duration of the test.

It was expected that the highest measured temperature would be from the sensor on the CPU die, as this is the location dissipating the most power. This, however, was not the case. Instead, the highest temperature was measured on the heatsink, followed by the CPU and finally, the fan controller on-die temperature sensor.

Each of the temperature sensors is a physically different piece of hardware. Both the fan controller and the CPU use on-die temperature sensors that were specifically designed for temperature sensing. The temperature sensor on the heatsink makes use of an inexpensive transistor that was not designed to be used as a temperature sensor. Therefore, it may no be as accurate as the other temperature sensors.

The temperature of 40 °C was selected for the test based on the maximum temperature tolerance of the Terason SmartProbe. Terason indicated that the SmartProbe had never been tested to determine its maximum temperature tolerance, but felt that 40 °C was the probable number. Based on the above results, however, it is expected that the WUC, with the exception of the ultrasound transducer, could safely operate up to 45 °C without alteration.

The lowest operating temperature for the WUC is governed by the Li-Ion batteries. The performance of Li-Ion batteries degrades significantly as the ambient temperature is reduced. The minimum allowable temperature for safe discharge of the Smart Batteries is -10 °C.

9.4 Speech Recognition

A critical feature of the logging system, described in Section 7, was the capture of information pertaining to speech recognition performance. During the clinical trials performed at MAMC, which included training sessions and individual first-time users, 840 utterances were captured. The following figures show statistical results for utterances gathered during these sessions. Not every possible utterance was used during this testing, so only utterances that were used are shown. Each chart is sorted in a descending order. Fig. 118 shows the relative frequency of each utterance while Fig. 119 shows the average confidence scores:

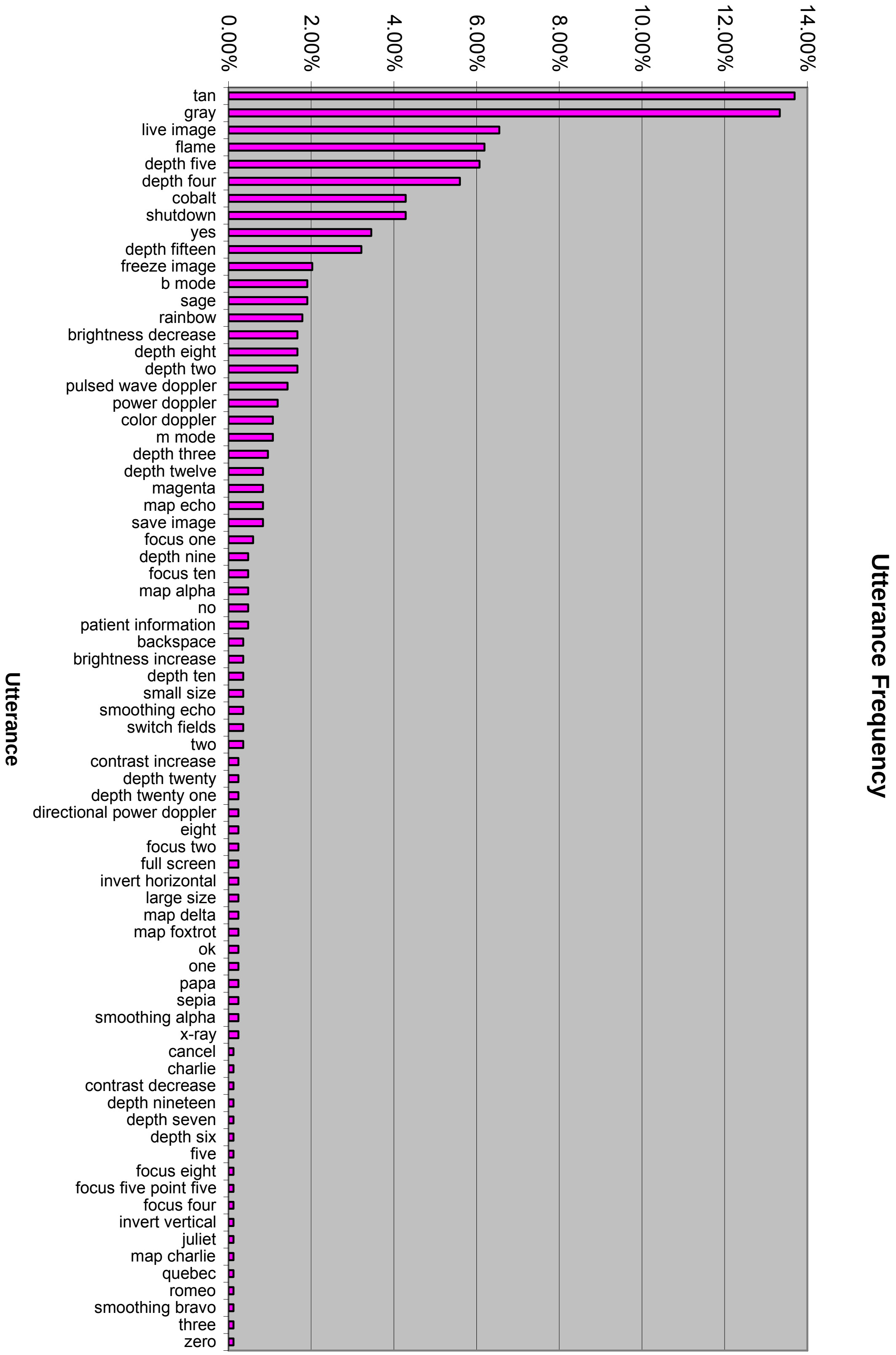


Fig. 118: Utterance Frequency

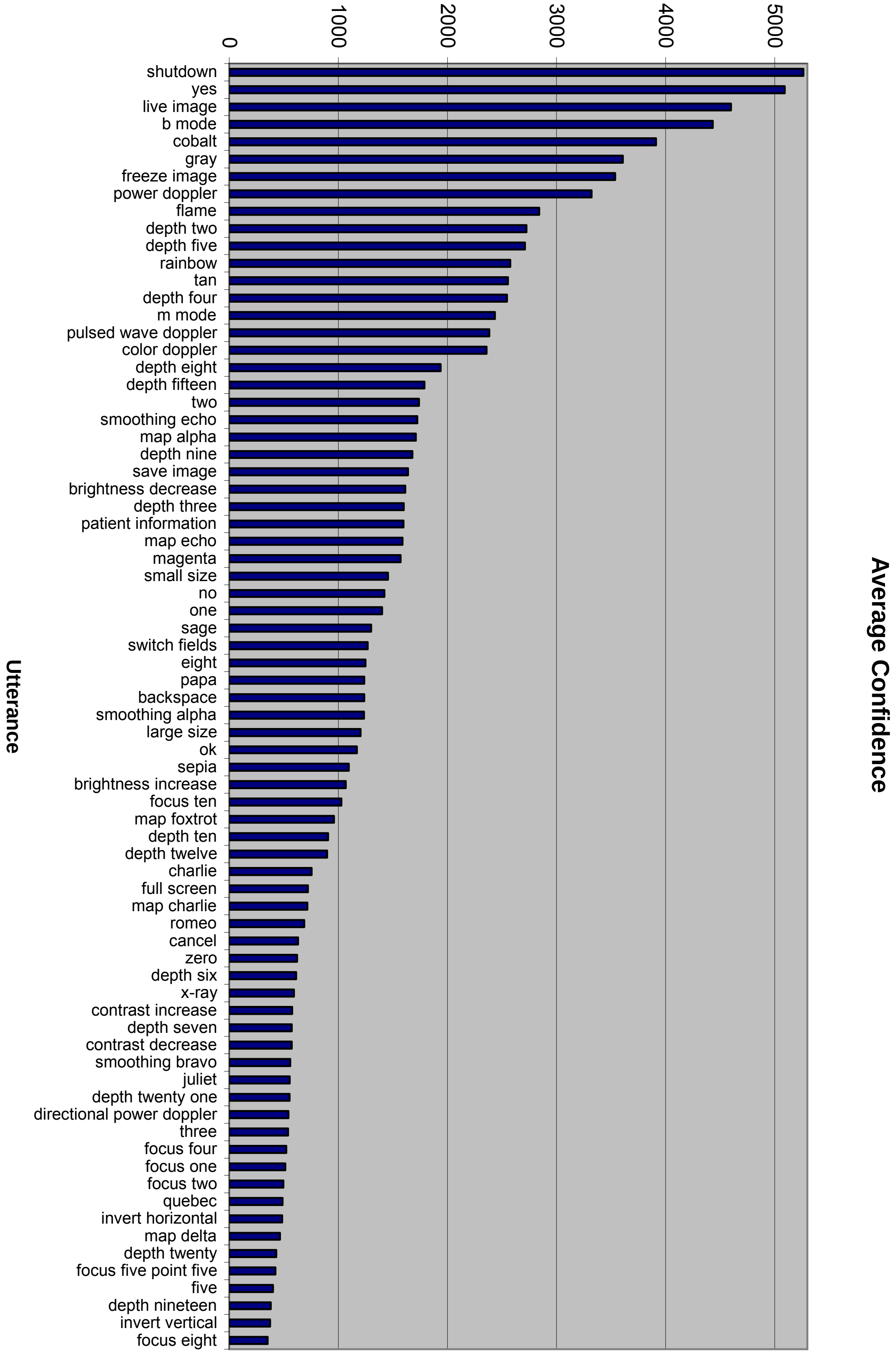


Fig. 119: Average Utterance Confidence

Most of the utterances occurred during training sessions conducted at MAMC and elsewhere. Of the 135 possible utterances, only 74, or 54.8 %, were actually used.

There is a sharp drop in confidence scores following the “color doppler” command. This is most likely due to the training session scenario. Most training session began with a demonstration by someone familiar with the speech recognition system issuing the same series of commands. These commands appear in Fig. 119 grouped together and have the highest confidence scores. Following this demonstration, training attendees were then given manuals and instructed to perform the tutorials. However, this advice was never followed. Training attendees would instead begin issuing voice commands, without knowing what the proper commands were.

It is important to note that a confidence score is relative. It is directly related to the phonetic diversity of an utterance. For a given grammar, confidence scores may improve or degrade with different microphones. However, changing the grammar will also affect the confidence scores. The various parameters that control the operation of the speech recognition system must be tuned for each implementation.

The speech recognition engine will always return a value, and the confidence score is used to accept or reject the result. Through laboratory testing, a minimum confidence value of 3,700 was set for the acceptance threshold. Recognition results, that were returned with a confidence score of 3,700 or lower, were rejected. The value of 3,700 was selected to provide a balance between falsely accepting invalid recognition results verse rejecting valid recognition results. This threshold is highly subjective and will vary greatly, depending on factors such as ambient noise, or the accent of the speaker. It was constantly adjusted during testing, until a good balance was achieved. Fig. 119 shows the average confidence score for the majority of the possible utterances falling well below this threshold. Only six utterances averaged better. This poor performance is mainly due to the large number of invalid commands that were issued during clinical trials. In laboratory and clinical use, by persons properly trained in using the speech recognition system, recognition rates were excellent and often exceeded 95 %.

Also, the high frequency of “tan” and “gray”, shown in Fig. 118, is due to their relative lack of phonetic diversity. When invalid commands were issued, the recognition engine tended to return these two utterances for the recognition result, with accompanying low confidence scores.

In addition to issuing invalid commands, it was often found that utterances that had poor confidence scores were the result of users pressing the PTT button and not saying anything meant for the WUC. Since the logging system recorded utterances with poor confidence scores, later analysis showed either invalid commands were being issued, or long conversations that were clearly not intended as commands for the WUC.

The conclusion, from these results, is that speech recognition works well with trained users, but does not work well with untrained users. The poor results returned from the clinical trials was a direct result of people not reading instructions, or watching the training videos, and just saying whatever came to mind. It could possibly be argued that this means that the system does not work. The difficulties are mainly operational in nature, and not technical. The user interface does still provide access to all of the same commands by using the mouse, should that be the user’s preference, or if they are simply uninterested in learning proper speech recognition commands. A further discussion of how this may be approached can be found in Section 11.

9.5 Specifications

The following specifications were determined by detailed inspection of the manufacturer’s specifications for individual items in the embedded computing platform.

Table 28: WUC Specifications

Specification	Value
Embedded Computing Platform	
Weight	1.795 kg [3.95 Lbs.]
Dimensions	25.7 x 14.0 x 7.6 cm [10.1 x 5.5 x 3.0 in.]
WUC Weight	5.45 kg [12.00 Lbs.]
Power Consumption	
Standby	12 W
Idle	23 W
Scanning	32 W
Operating Time	
Idle	> 8 Hours
Scanning	5.5 Hours
Operating Temperature	-10 to +40 °C
Storage Temperature	-20 to +60 °C
Battery	
Chemistry	Lithium Ion
Voltage	14.4 V Nominal
Capacity	95 Wh / 6600 mAh
Weight	647 g [1.43 Lbs.]
Battery Charger	
Maximum Charging Time	< 4 Hours
Charger Input Voltage	24 V
Charger Input Current	4 A
DC Adapter Input Voltage	110 – 240 V (US and International)
Vibration	
Operating	3 G
Non-Operating	300 G
Wireless Communications	802.11b/g
Operating System	Windows XP Professional Service Pack 2
Head-mounted Display (i-glasses)	
Weight	
Resolution	800x600 [1.44 MPixels]
Colors	16,777,216

10 Clinical Usage and Value

The WUC is a unique university research project in that a prototype was developed and employed by medical professionals in a variety of situations. Over a period of nine months, at least one, and usually more, of the four prototype devices was being used. The facilities ranged from Emergency Departments, Vascular Departments, simulated Combat Surgical Hospitals (CSH), tradeshows, meeting rooms and medical offices. Through all of these collective experiences, a great deal was learned about portable ultrasound. This section focuses on feedback and observations gathered over this period.

Portable ultrasound represents the fastest growing segment of the ultrasound market. Every major ultrasound vendor is either in the process of, or already has, released a portable ultrasound product. These devices tend to mimic laptops in their general form factor, such as the Sonosite MicroMaxx pictured in Fig. 120:

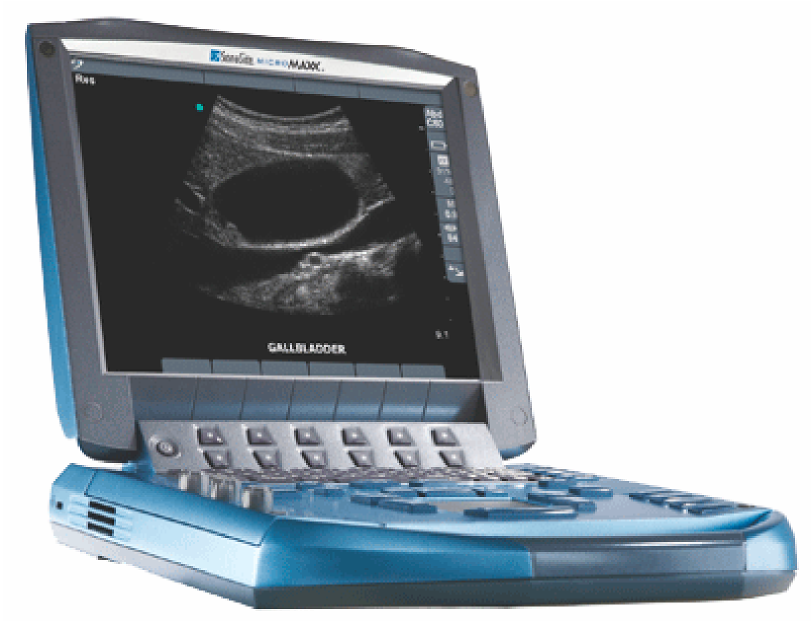


Fig. 120: Sonosite MicroMaxx [55]

The MicroMaxx is representative of many other vendors' offerings. Where a keyboard would normally be found on a laptop, is a control panel more akin to what might be found on a full-size cart-based ultrasound system. It contains a familiar set of knobs and sliders to control the ultrasound machine. These portable machines also usually have batteries to allow a short period of autonomous operation. They can store images and video clips, support a number of different transducers and produce good quality images. In short, they offer excellent value for use in a clinical setting.

10.1 Applications

There are several applications for portable ultrasound outside of the clinical setting that are uniquely suited to using the WUC. Each of these applications is underserved by the current generation of portable ultrasound equipment. The five main applications are in telemedicine, disaster relief, medical transport, rural healthcare, and military field use.

The WUC addresses many of the shortcomings of the current generation of portable ultrasound equipment when it comes to these applications. Its main advantages are the ruggedness of the system, long battery life, wearable display, open-systems architecture and communications capabilities.

10.1.1 Telemedicine

Telemedicine is a relatively recent concept that literally means “to practice medicine at a distance”. This can take several forms, from a basic video-conferencing system, to a network-enabled medical device. The American Telemedicine Association (ATA) estimates that there were approximately 200 telemedicine networks operating in the United States in 2005, with half of these providing active day-to-day patient care. They are most often used in rural areas to improve the available quality of care.

The WUC has an on-board 802.11b/g interface, which is a ubiquitous short range wireless communication protocol. For ranges up to 100 m, this interface can be used as is to provide images, both still and moving, to a remote viewer. For other applications, such as specialized long-range radio links or satellite communications, the 802.11b/g interface can be used to connect to a gateway device that could provide communications capabilities using these other services.

10.1.2 Disaster Relief

Disaster relief is perhaps the most promising of the potential applications for the WUC. Relief workers must typically work in areas where the public utility infrastructure has been partly or completely disabled. There are probably numerous people in need of medical care and efficient triage is difficult.

The wearable form-factor of the WUC is uniquely suited to this application. Ultrasound examinations can very quickly detect abdominal bleeding and collapsed lung (pneumothorax), which are two conditions that will immediately affect the treatment plan for a disaster victim. Additionally, ultrasound can be used to help in the placement of catheters and central lines, making these procedures faster and allowing medical personnel to treat more disaster victims in a shorter time period.

Also, the long battery life of the WUC would allow it to be used in the field for many hours. Medical personnel using the WUC would not need to frequently interrupt their work to find a power source to recharge the batteries. Also, multiple batteries can be carried, and hot-swapped when needed to continue scanning indefinitely.

Finally, the telemedicine capabilities would be extremely valuable in a disaster zone. Medical personnel with less training in ultrasound procedures, such as medics, could be issued a WUC and have instant access to expert sonographers who could potentially oversee multiple medics. This could help to further increase the number of medical personnel performing triage during the critical initial phase of a disaster relief effort. Also, post triage care could be improved by better planning if the ultrasound images were available before the disaster victim arrived for treatment.

10.1.3 Medical Transport

Medical transport is another interesting application area for portable ultrasound equipment. Transportation modes can include ambulances, helicopters, airplanes and ships.

In discussions with doctors who practice emergency medicine, the utility of ultrasound in urban environment, most notably in southern New England, during medical transport is in doubt. Generally, it is best to move the patient to a hospital facility as soon as possible since average transport times are on the order of minutes. However, Life Flight personnel, who transport critical patients via helicopter, often must travel to rural areas. The medical flight crew rarely has prior knowledge of what facilities they will encounter, and having a familiar and reliable ultrasound machine as part of their equipment would be an advantage. Patients with pneumothorax need special attention before traveling by air. This condition is potentially fatal if not addressed, and ultrasound can quickly diagnose its presence.

It is in rural areas that the WUC becomes a potentially valuable tool for use during medical transport. Ambulance trips can often take over an hour. This allows for plenty of time to perform more advanced procedures on patients while on route. When combined with telemedicine, ultrasound could be used to better assess the patient and prepare for their arrival.

The long battery life, ruggedness and communications capabilities make the WUC a good fit for use in medical transport. The WUC could easily operate for several trips without needing to be recharged. Additionally, the flexibility of the communications system should allow it to be adapted to the various telemedicine systems that may be encountered.

10.1.4 Rural Healthcare

Rural healthcare is a term encompassing the unique circumstances that the healthcare industry faces in rural areas. According to the U.S. Census Bureau, in the year 2000 59 million people, or 21 % of the population, lived in rural America. The lower population density often means that medical facilities are smaller and less equipped. The medical staff generally fulfills multiple roles, and transport to these facilities may take an hour or more. There are often no specialists available, and more complicated or critical medical issues must be addressed at nearby urban centers.

Again, it is the portability and long battery life that makes the WUC well suited for rural healthcare applications. Medical personnel, who must travel to see patients, or work in facilities lacking adequate backup power, could have access to the diagnostic capabilities of ultrasound where they previously didn't. A single practitioner could also use the telemedicine capabilities to receive expert opinions from colleagues in urban centers.

10.1.5 Military

So far, in extensive discussions with both the Army and Air Force, the applications with the WUC in the military seem to fall into two distinct categories. The first, and the source for the funding that developed the WUC, is in Army CSHs. The second application is for Special Forces use.

The Army maintains five levels of classification for its CSHs. The levels are numbered one through five, and increasing numbers bring with them increasing capabilities and levels of care. A level one facility is essentially an Army medic in the field, while a level five facility is a major trauma center. Somewhere in the middle are level two and level three facilities that are generally housed in tents and provide centralized care for entire companies or battalions. It is in these facilities, where conventional ultrasound machines, whether portable or otherwise, that the

WUC was originally designed for.

Military equipment must be as rugged as possible to withstand the possible rough handling that it must endure. Desert conditions often bring temperatures exceeding 45 °C [114 °F]. Equipment must be transported in trucks where it will experience harsh vibrations. Power supplies are intermittent. Also, replacements or spare parts are difficult and time-consuming to obtain.

The WUC was designed to operate reliably under these severe conditions, as shown in Table 28. The wearable form-factor allows the Army surgeon to move about untethered and work without restriction. The long battery life allows the WUC to operate when power is not available. The Army is also quickly moving towards using more sophisticated patient management systems that are more and more electronic rather that paper based. The communications flexibility, and COTS hardware employed in the WUC, will make adapting it to the changing patient management system both fast and cost effective.

The same features of the WUC that make it suitable for use in a CSH also make it suited for Special Forces operations. For these applications, the small size is also a key feature. Weight and size restrictions severely limit the equipment that Special Forces members can utilize. The wide variety of diagnostics procedures that can be performed, or assisted, by ultrasound, makes it a potentially valuable addition.

10.2 Out-of-Box Experience

The WUC is a new concept in medical imaging in that it is significantly different from what a traditional ultrasound machine, whether portable or not, looks and operates like. The three most often observed aspects that confronted first-time users of the system are the wearable form-factor, head-mounted display and the voice commands.

The wearable form-factor of the WUC is a new concept for many people when they first encounter the device and evokes a wide range of reactions. These reactions have ranged from curiosity, fashion critiques and ambivalence, to confusion and apprehension. For some reason, many people are initially overly concerned with the weight of the device and simply refuse to believe that it could possibly be comfortable to wear for even a short period of time. After finally wearing it, however, these concerns were quickly allayed. Other people immediately set about trying to redesign the vest, before even trying it on. Some valid feedback has been received on the use of cotton as the vest material. This is a poor choice from the standpoint of durability, since the cotton can rip easily and may be too warm. A nylon material of some sort seems to be the preferred material in the military, and was a common comment received from military personnel.

The head-mounted display was a constant source of apprehension for new users when demonstrating the WUC. Many people are simply reluctant to wearing it. In fact, almost everyone, upon first encountering the system, would only hold up the head-mounted display to their eyes to view it. Since it is a head-mounted display, and not a hand-held display, the viewing experience is sub-optimal when used in this manner. For the people who could be convinced to use the head-mounted display in the manner it was intended, feedback was universally positive.

The voice command system was, universally, the most challenging feature of the system for first-time users. Unsurprisingly, not a single person took the time to understand the operation of the speech recognition system before attempting to operate it. It is also by far the single feature that most differentiates the WUC from other ultrasound systems. While there are some high-end ultrasound machines that also have the ability to be controlled with voice commands, few sonographers seem inclined to use it. Most people seemed to instinctively want to use the mouse to control the system, rather than use the voice commands. It is unknown why this is so, and no one was asked why they behaved this way. It may be that they have had negative experiences in the past with speech recognition, or that the mouse is simply so familiar that it is more comfortable.

Finally, many people commented that they would like to have a light that indicates that the system is on. It was erroneously assumed that being able to look into the head-mounted would be an adequate indication of the system's status. However, the reluctance to wearing the head-mounted display served to undermine this assumption.

The WUC complements the current generation of portable ultrasound products by extending their reach into application areas that they were previously unsuited for. The rugged nature of the device, long battery life, and telemedicine capabilities make the WUC well suited for operation outside of the clinical environment.

11 Conclusion and Further Work

The goal of this thesis was to produce a wearable ultrasound system for use in clinical trials at MAMC. Where possible, COTS equipment was used, and where required, custom design work was performed. Included in the custom design work, was the development of a power supply and an enclosure to house an embedded computer, wireless interface and the power supply. There were also several software applications that were written. The main piece of software integrated speech recognition, data logging, power supply monitoring and control and also included an interface to the Terason Ultrasound Application. A small server program was written to acquire ultrasound images and make them remotely available, in real-time, to a client application. Also, another application was written to analyze data stored by the data logger.

This wearable ultrasound system was developed, manufactured and tested in clinical trials. The clinical trials occurred over a period of 10 months at MAMC in Tacoma, WA. It is the third generation in a series of prototypes that evolved from a traditional laptop in a backpack, to a completely ruggedized and wearable system. It is medical in appearance and was used over a one week period in the deserts of the southwestern United States. A total of four prototypes were successfully built. Two conference papers were presented. One was presented at the American Institute of Ultrasound in Medicine (AIUM) 2006 annual conference [57], and the other was presented at the American Telemedicine Association (ATA) 2006 annual conference [58].

In the end, all but one of the requirements, as put forth in Section 2.42.3, was met. One of the requirements was that the third generation embedded computing platform be smaller than the previous generation. It became evident during the design process that this was going to be difficult to achieve. The requirements were then relaxed and only the overall height of the enclosure was reduced. Note that the enclosure's height determines how far the enclosure extended outwards from the wearer's back. The 2nd generation enclosure extended 6.5 cm [2.6 in.] from the wearer's back. It was a metal box, so the surface in contact with the wearer's back was flat. The 3rd generation enclosure was designed to be contoured to fit the wearer's back and has a gentle curve to the bottom of the enclosure. Therefore, the specified height of 7.6 cm [3.0 in.] is greater than the actual height of the enclosure, which is between 6.0 cm [2.4 in.] and 7.1 cm [2.8 in.]. Also, because it has a curved surface, it sits flush with the wearer's back and protrudes a shorter distance than the previous generation's enclosure did. The size increase was generally caused by design decisions meant to ruggedize the device. The connectors on the enclosure, and the strain relief designed into the enclosure's shape, add over 7 cm [2.8 in.] to the overall length of the enclosure.

The embedded computer chosen for the design has some deficiencies that can only be addressed by moving to a different product. The IDE interface has some compatibility issues with certain HDDs. It has even rendered several HDDs inoperable. The audio circuitry has noticeable noise, and the documentation does not correctly describe the pinout. The most severe problem has been with the VGA interface. The VGA interface is used to provide the image that is displayed on the head-mounted display. The software driver sometimes fails and leaves the system in an unusable state until it is reinstalled. This situation remains unresolved and is serious enough on its own to warrant consideration of another embedded computer. To this end, preliminary investigation has led to a promising replacement in the form of mezzanine CPU boards in industry standard form-factors. This is no guarantee that there will not be future driver issues, but only this embedded computer has shown this behavior.

There are several standards for mezzanine CPI boards that can provide the necessary processing power. A mezzanine CPU board uses a standardized connector to sit on a carrier board. These connectors are standardized, and provide a path for a carrier board design to support a selection of different mezzanine CPU boards. This has several advantages, most notably the removal of the current reliance on a single vendor's products. Also, newer CPU technologies are already available on these mezzanine CPU boards than on the currently used PC/104-*Plus* form-factor. Some of these newer CPU technologies provide equivalent processing power, while consuming less energy. Others provide significantly more processing power and may allow new applications to become possible.

A carrier/mezzanine CPU board may also carry other benefits. This combination could potentially result in a smaller overall design. Only the necessary components could be included, reducing the potential for hardware failure. Also, the inclusion of specialized coprocessors, such as an FPGA or DSP may be easier. The non-volatile storage, currently in the form of a HDD, could also be mounted on the carrier board. Additionally, connectors may also be mounted on the carrier board, which would reduce manufacturing and assembly costs by taking advantage of the automation techniques used in PCB manufacturing.

While no problems have been encountered in the form of HDD failures in the field, it remains the most sensitive component in the embedded computing platform. Besides the fans, it is the only other moving part and is especially susceptible to vibration. A solid-state storage device, such as flash memory, has several advantages. It would generally consume significantly less power, provide faster performance when reading or writing data, is smaller and is highly vibration resistant. Storage capacity has been steadily increasing and pricing decreases will make this a viable alternative in the very near future.

In addition to hardware changes, the software that currently runs the WUC has reached the limit of its maintainability. This is the point where adding new features becomes overly difficult because the original architecture of the software never envisioned some of the features that have become clear choices for implementation in the future. Adding features, more often than not, breaks current features or requires that current features be rewritten.

Some desirable new features include that ability to save a voice annotation along with stored images, saving long duration video clips (they are currently limited to the last 60 frames by the Terason application) and picture archiving and communications systems (PACS) integration.

Current ultrasound systems have only very short video clip capabilities (2 - 6 s), and are often augmented with external DVD recorders to store video clips. This is not sufficient for all possible situations, and the WUC could be modified to store video clips that were limited in duration only by the available storage space on the HDD.

PACS integration would also be a valuable feature. In discussions with emergency department personnel, having a portable ultrasound system that automatically disseminates stored images would save valuable time during a trauma and free the practitioner to focus on the patient.

An additional improvement to the software architecture would be the integration of the RID process into the main application. Inter-process communication has proven to be tedious and error prone, also, multiple threads are more efficiently handled by the operating system than multiple processes. Late in the project, the source code to the Terason software that prevented running the RID in the same process became available. This enabled a test to be performed whereby the remote imaging software was moved into the main program. The results were encouraging, mainly from a performance point of view. The application loaded noticeably quicker, and the issue with a slow system shutdown also disappeared.

The RID also has room for improvement. The entire RTP protocol stack was implemented, but none of the information regarding link congestion and latency is used to improve the overall frame rate of the transmitted real-time images. This is an important feature of RTP, and future revisions to the RID should take advantage of this.

The RID client application has some shortcomings as well. Currently, the IP address of the WUC that the program should connect to needs to be known a priori. This requirement creates extra network administration work, and adds a level of complexity that may confuse RID users. A mechanism should be developed that allows for the discovery of systems that are available for remote viewing, and provides more information about the system being viewed, such as location, user, software revision, etc. A successful test was conducted using UDP multicast to broadcast a message and listen for active systems to reply. This method has limitations, however, and a more robust registry system may better address this need. Also, the RID client is currently only available for the Windows operating system, running on x86 compatible CPUs. There are other operating systems, including Mac OS X and Solaris, and CPU architectures, such as PowerPC, that may want to use the remote viewing capabilities of the WUC. Providing an RID client application, that uses the Java virtual machine for its execution environment, would make this feature available to a wider audience. Finally, there is no control protocol for interaction between the RID client application and the WUC. An implementation, using extensible markup language (XML) technologies such as simple object access protocol (SOAP) could potentially provide a framework for a future implementation. It is important to note that web technologies, while currently popular and becoming very capable, place much of the processing burden on the server, which in this case would be the embedded computer in the WUC. Remote viewing and control features should place as much of the processing burden on the client, so as to not reduce the battery life of the WUC or potentially degrade the imaging performance.

In addition to software improvements for the remote data facilities, there are potential improvements to the wireless data interface. The wireless data interface is 802.11b/g. It is designed for communications over distances of less than 100 m. This not adequate for situations where it may be impractical to locate an access point within this range. However, due to the open nature of the embedded computing platform, the 802.11b/g interface is a standard USB peripheral. It can be replaced or augmented with other wireless communications devices. These may include cellular network data access, such as EVDO for CDMA networks, or EDGE for GSM networks. For applications requiring greater range, or for operation in truly remote areas that are not served by terrestrial wireless networks, satellite communication is a possibility. Companies, such as Globalstar, provide satellite based network access using portable phones which could interface with the WUC.

Based on the lack of initial user success with the speech recognition system, it is clear that the learning curve must be further reduced. Methods for integrating a speech command reference and addressing the eagerness of first-time users should be pursued.

A more conventional on/off indication should also be included. There have also been comments made to include indications for HDD activity or network activity as might be found on laptop computers. There is a clear need to include an on/off indication that can be viewed while wearing the vest, or whatever other configuration may be produced. The inclusion of other indicators, however, may be unnecessary distractions. The embedded computing platform does not look like a computer, even though it is, and adding indications that do not clearly contribute to its operation as an ultrasound device should be avoided.

One of the more challenging aspects of this project was working extensively with military personnel. The culture is very different from either corporate or academic environments. The medical personnel are every bit as talented and qualified as their civilian counterparts, but the work environment can be very different. There were three main facts of military life that, while initially viewed as obstacles, eventually contributed to producing a better system.

The biggest challenge was personnel turnover. With the current political situation, many people involved in clinical trials were often deployed soon after receiving training on the system. This was addressed by making the manuals for the WUC available on the Army intranet, and obtaining an Army email address to facilitate communications.

The second challenge was providing physical access to the WUC during clinical trials. MAMC is a major trauma center that receives approximately 821,000 [56] outpatient visits per year. It was important that physical security be provided to prevent misplacement or theft of evaluation systems. It took several visits to fully understand how the Army tracks equipment and assigns personnel responsible for providing maintenance and access to the equipment. This problem was eventually solved by identifying the key personnel and personally instructing them on what was required to keep the equipment in good working order.

The final problem is difficult to address and has manifested itself by low usage of the WUC during clinical trials performed at Army facilities. The modern soldier is extremely busy and their performance is constantly evaluated according to certain metrics. Their career opportunities and promotion potential are directly related to how well the individual scores in these evaluations. This makes finding time to perform research work, which could potentially reduce their performance scores, difficult and unattractive. This becomes a so called chicken and egg problem. To allow personnel the time to use new and unproven technologies, by granting a relief from their regular duties, requires a mandate from the higher echelons. And with the already heavy workload, commanders are reluctant to use unproven and unfamiliar technologies when familiar and accepted alternatives already exist. The WUC brings new capabilities to medical personnel where none currently exists, but it must be proven before it can be deployed. This circular argument is difficult to reconcile, but it is hoped that continued attention and success will eventually overcome these obstacles.

The wearable form-factor, though a novel and innovative approach allowing new applications for ultrasound imaging, is not necessarily the best choice for all circumstances. Ultrasound examinations are often performed for short periods of time, usually lasting less than ten minutes. Other than sonographers, whose primary job responsibility is performing ultrasound examinations, most portable ultrasound users will then switch to another task. They may not require the use of ultrasound for some time and will probably want to take off the vest. Constantly donning and removing the vest is inconvenient. Military personnel also often wear load-bearing vests. These are rip-stop nylon vests with various compartments for supplies, such as food, ammunition, firearms and ballistics protection. Wearing the WUC over this vest is not feasible. Finally, there is the size issue to take into account. People come in many different shapes and sizes, and having a piece of equipment that may only be efficiently used by a subset of the potential audience limits its adoption.

To address this issue, one of the prototype embedded computing platforms was placed into a small medical bag, along with the rest of the WUC hardware, and is shown in Fig. 121:

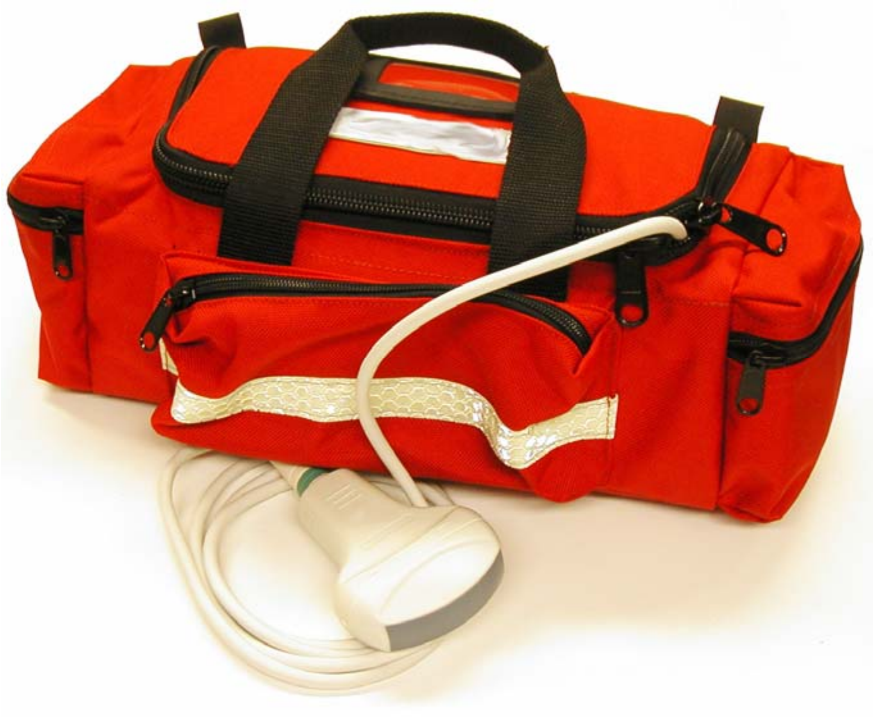


Fig. 121: Bag Based Ultrasound System

This exercise had two benefits. First, it showed that adaptability of the underlying WUC components to different environments, and even form-factors. And second, allowed for the system to be utilized in applications where a wearable system was not the optimal solution. This exercise was initiated after receiving feedback about some of the shortcomings of the wearable form-factor, and should be investigated further. Some thoughts have included a version contained in an across-the-chest backpack or even a fanny pack configuration.

One final possibility for future work involves the modification of the current embedded computing platform to support a variety of external physiological sensors. By utilizing the USB connections found on most embedded computers, along with custom hardware to interface to it, the embedded computing platform could support an ever wider variety of applications.

The WUC has the potential to make a positive contribution to the field of ultrasound imaging. It opens new applications for portable ultrasound, and improves upon the status quo in others. Further investment in this research is greatly encouraged.

References

[1] Thomas Szabo, "Diagnostic Ultrasound Imaging", Elsevier Academic Press, Burlington, MA 2004.

[2] http://www.aium.org/aboutAIUM/timeline/intro.asp.

[3] http://www.ob-ultrasound.net/project/japan_brainscan2.jpg.

[4] Terason, "Terason Ultrasound System User Guide", June, 2005.

[5] GE, http://www.logiqlibrary.com/library/LOGIQ3/LOGIQ3_001661.jpg.

[6] GE, http://www.logiqlibrary.com/library/LOGIQ9/LOGIQ9_001928.jpg, 2004.

[7] GE, http://www.logiqlibrary.com/library/LOGIQ9/LOGIQ9_002140.jpg, 2005.

[8] Douglas S. Richards, http://www.obgyn.ufl.edu/ultrasound/1ObtainImage/1Equipment/2frequency.html, June, 2003.

[9] GE, http://www.gehealthcare.com/usen/ultrasound/genimg/images/img7339_72_500.jpg.

[10] SonoSite, http://www.sonosite.com/images/stories/180pluscarrying.jpg.

[11] Renee Dilulio, "Portable Ultrasound: Small Modality, Big Impact", Imaging Economics, July, 2006.

[12] SonoSite, http://www.sonosite.com/content/view/21/77/, 2006.

[13] GE Healthcare, "LOGIQ Book XP", 04-9365, Buckinghamshire, UK, 2004.

[14] Siemens Medical Solutions USA, "ACUSON Cypress Cardiovascular System *PLUS* Portable and complete cardiovascular applications", A91US-7-1C-A400, Mountain View, CA, 2006.

[15] Terason, http://www.terason.com/products/techo.asp, 2005.

[16] i-O Display Systems, http://www.i-glassesstore.com/patiententertainment.html, 2006.

[17] eMagin, http://www.3dvisor.com/products.php, 2006.

[18] Dalys Sebastian, "Development of a Field-Deployable Voice-Controlled Ultrasound Scanner System", WPI, 2004.

[19] Carsten Poulsen, "Design of 2nd Generation Wearable Ultrasound System", WPI, Worcester, MA, Jul. 2004.

[20] PC/104 Embedded Consortium, "PC/104 Specification, Version 2.5", Nov. 2003.

[21] PC/104 Embedded Consortium, "PC/104-*Plus* Specification, Version 2.0", Nov. 2003.

[22] PC/104 Embedded Consortium, "PC-104 Specification, Version 1.0", Nov. 2003.

[23] Lippert-AT, “Cool RoadRunner 4 Datasheet”, February, 2006.

[24] DIGITAL-LOGIC AG, “Technical User’s Manual for: MICROSPACE© PC/104 plus smartModule 855 MSM855”, ver. 1.1I, 2004.

[25] IEEE Std 1394-1995, “IEEE Standard for a high performance serial bus”, August, 1996.

[26] DuPont, http://heritage.dupont.com/floater/fl_delrin/floater.shtml, 2003.

[27] DuPont, “Delrin© 100P NC010”, 2006.

[28] BB-04, http://www.ocean-server.com/modules.html#bbs, 2004.

[29] DC-023, http://www.ocean-server.com/converters.html, 2004.

[30] DATEL, “Single Output ULE 20A Models”

[31] SBS Implementers Forum, “System Management Bus (SMBus) Specification, Version 2.0”, Aug. 2000.

[32] SBS Implementers Forum, “Smart Battery System Manager Specification, Revision 1.0”, Dec. 1998.

[33] Smart Battery System Implementers Forum (SBS-IF), “Smart Battery Charger Specification”, Revision 1.1”, Dec. 1998.

[34] SBS Implementers Forum, “Smart Battery Selector Specification, Revision 1.1”, Dec. 1998.

[35] SBS Implementers Forum, “Smart Battery Data Specification, Revision 1.1”, Dec. 1998.

[36] Isidor Buchmann, “Batteries in a Portable World”, Cadex Electronics Inc., May 2001.

[37] Inspired Energy, “Battery Specification, Document Number DS129”, July, 2003.

[38] Appnote 751, http://www.maxim-ic.com/appnotes.cfm/appnote_number/751, 2005.

[39] Linear Technology, “LTC1775 - High Power No RSENSE Current Mode Synchronous Step-Down Switching Regulator”, 2004.

[40] Philips Semiconductors, “The I^{2}C Bus Specification, Version 2.1”, Jan. 2000.

[41] Thomas A. Sudkamp, “Languages and Machines, 3rd ed.”, Pearson Education, Inc., Boston, 2006.

[42] ScanSoft, Inc., “ScanSoft VoCon 3200 Software Development Kit Version 2.0 Developer’s Guide”, Feb. 2004.

[43] Wikipedia, http://en.wikipedia.org/wiki/OSI_model, 2006.

[44] IEEE, “IEEE Std 802.11-1999”, IEEE-SA Standards Board, 1999.

[45] IEEE, “IEEE Std 802.11b-1999”, IEEE-SA Standards Board, 1999.

[46] IEEE, “IEEE Std 802.11g-2003”, IEEE-SA Standards Board, 2003.

[47] IETF RFC3550, “RTP: A Transport Protocol for Real-Time Applications”, 2003.

[48] Jean-loup Gailly, Mark Adler, http://www.zlib.net/, 2005.

[49] IETF RFC1950, “ZLIB Compressed Data Format Specification version 3.3”, 1996.

[50] IETF RFC1951, “DEFLATE Compressed Data Format Specification version 1.3”, 1996.

[51] Virginia Polytechnic Institute and State University Center for Wireless Telecommunications, “http://www.cwt.vt.edu/faq/gsm.htm”, 2002.

[52] IETF RFC3551, “http://www.ietf.org/rfc/rfc3551.txt?number=3551”, July, 2003.

[53] Dimitri van Heesch, “doxygen, Manual for version 1.4.2”, 2004.

[54] Jordan Russell, “http://www.jrsoftware.org/isinfo.php”, 2006.

[55] http://www.sonosite.com/images/stories/05.SNO.174_MicroMaxx3.gif

[56] http://www.mamc.amedd.army.mil/mamc/mamcinfo.htm

[57] P.C. Pedersen, P. Cordeiro, R.J. Duckworth and T.L. Szabo, “Development and testing of wireless wearable ultrasound scanner,” *2006 AIUM Annual Convention*, Washington DC, March 23-26, 2006.

[58] R.J. Duckworth and P.C. Pedersen, “Clinical evaluation of wearable ultrasound imaging system,” *2006 American Telemedicine Association*, San Diego, CA, May, 2006.

Appendix I – Bill of Materials

Table 29: Power Supply Bill of Materials

Description	Reference Designator	Quantity	Vendor	Vendor Part #
FAN CONTROLLER 16-QSOP	U3	1	Analog Devices	ADM1030ARQ
CAP OS-CON SC series 22 uF, 30 V	C33, C34, C35, C36	4	Capacitors Plus	30SC22M
CAP OS-CON SP series 680 uF, 6.3 V	C37	1	Capacitors Plus	6SP680M
CAP 0603 .1 uF 50 V	C4, C5, C9, C11, C16, C17, C21, C24, C25, C27, C38, C39, C42, C45	14	DIGI-KEY	PCC2398CT-ND
CAP 0603 .01 uF 16 V	C18	1	MOUSER	581-0603YC103K
CAP 0603 .015 uF 25 V	C19	1	DIGI-KEY	PCC1765CT-ND
CAP 0603 2200 pF 50 V	C6	1	DIGI-KEY	311-1081-1-ND
CAP 0603 .15 uF 25 V	C20	1	DIGI-KEY	399-1290-1
CAP 0603 1000 pF 25 V	C7	1	DIGI-KEY	490-1570-1-ND
CAP 0603 2.2 nF 50 V	C22	1	MOUSER	581-06035C222K
CAP 0603 220 pF 50 V	C8	1	DIGI-KEY	311-1073-1-ND
CAP 0603 .047 uF 16 V	C13	1	DIGI-KEY	490-1529-1-ND
CAP 0805 .33 uF 25 V	C12, C14, C15	3	DIGI-KEY	490-1677-1-ND
CAP 0805 .22 uF 25 V	C26	1	DIGI-KEY	478-1399-1-ND
CAP 0805 .1 uF 10 V X7R	C44	1	MOUSER	581-0805ZC104K
CAP 1210 4.7 uF 16 V	C28	1	DIGI-KEY	490-1872-1-ND
CAP 1210 .47 uF 50 V	C2	1	DIGI-KEY	399-3089-1-ND
CAP 1210 1 uF 50 V	C1	1	DIGI-KEY	399-3076-1-ND
CAP 1210 .68 uF 50 V	C3	1	DIGI-KEY	490-1860-1-ND
CAP 1210 10 uF 10 V Y5V	C43	1	MOUSER	581-1210ZG106Z
DIODE SOD-323 Schottky 30 V 100 mA	D6, D8	2	Anchor Engineering	CMDSH-3
Ceramic Resonator 3.68 MHz	X1	1	MOUSER	581-PBRC-3.68B
INDUCTOR DR-127 15 uH 5 A	L1	1	DIGI-KEY	513-1040-1-ND
MOSFET SOIC-8 Dual N-Channel 6 A 30 V	Q1	1	MOUSER	512-FDS6912A
LINEAR REGULATOR D2PAK-3/TO-263 Adjustable 1.2 - 37 V 1.5 A	U6, U7	2	DIGI-KEY	497-1571-1-ND
BATTERY CHARGER TSSOP-48 FW Dual Li-Ion	U1	1	Linear Technology	LTC1760CFW
SWITCHING REGULATOR SSOP-16N GN 5 V 10 A	U5	1	Linear Technology	LTC1775CGN
RS-232 Transceiver SSOP-16 1 TX 1 RX	U9	1	Maxim	MAX3221CAE+
RECTIFIER 403-3 Schottky 40 V 3 A	D7	1	DIGI-KEY	MBRS340T3OSCT-ND
RECTIFIER SOD-123 Schottky 30 V 1 A	D5	0	DIGI-KEY	MBR130T1OSCT-ND
MOSFET SOT-223 P-Channel -7.5 A -30 V	Q9	1	DIGI-KEY	NDT456PCT-ND
RES 0603 33.2K .0625 W 1%	R18	1	DIGI-KEY	P33.2KHCT-ND
RES 0603 1K .1 W 5%	R30, R42	2	DIGI-KEY	P1.0KGCT-ND
RES 0603 100 .1 W 5%	R11, R14	2	DIGI-KEY	P100GCT-ND
RES 0603 51K .1 W 5%	R12, R19	2	DIGI-KEY	P51KGCT-ND
RES 0603 3.3K .1 W 5%	R13	1	DIGI-KEY	P3.3KGCT-ND
RES 0603 270K .1 W 5%	R10	1	DIGI-KEY	P270KGCT-ND
RES 0603 5.1K .1 W 5%	R6	1	DIGI-KEY	P5.1KGCT-ND
RES 0603 13K .1 W 5%	R15	1	DIGI-KEY	P13KGCT-ND
RES 0603 1.2K .1 W 5%	R16	1	DIGI-KEY	P1.2KGCT-ND
RES 0603 20K .1 W 5%	R44, R45	2	DIGI-KEY	P20KGCT-ND
RES 0603 1.1K .1 W 5%	R28, R29	2	DIGI-KEY	P1.1KGCT-ND
RES 0603 56K .1 W 5%	R3, R4	2	DIGI-KEY	P56KGCT-ND

Description	Reference Designator	Quantity	Vendor	Vendor Part #
RES 0603 10K .1 W 5%	R5, R9, R17, R31, R46	5	DIGI-KEY	P10KGCT-ND
RES 0603 0 .1 W 5%	R43	1	DIGI-KEY	P0.0GCT-ND
RES 0603 332 .1 W 1%	R41	1	DIGI-KEY	P332HCT-ND
RES 0603 1.2 .1 W 5%	R7	1	DIGI-KEY	P1.2GCT-ND
RES 0603 237 .1 W 1%	R37	1	DIGI-KEY	P237HCT-ND
RES 0603 1.47K .1 W 1%	R38	1	DIGI-KEY	P1.47KHCT-ND
RES 0603 8.87K .0625 W 1%	R39	1	DIGI-KEY	P8.87KHCT-ND
RES 0603 1.05K .0625 W 1%	R40	1	DIGI-KEY	P1.05KHCT-ND
MOSFET TO-252 N-Channel 10 A 30 V	Q7, Q8	2	MOUSER	781-SUD50N03-10AP
MOSFET SO-8 Dual P-Channel -4.3 A -30 V	Q4, Q5, Q6	3	MOUSER	781-SI4925BDY
MOSFET TSSOP-8 Dual N-Channel 3.2 A 30 V	Q2, Q3	2	MOUSER	781-SI6928DQ
CAP TANTALUM AVX_A 1 uF 20 V	C40, C41	2	MOUSER	581-TAJA105K020
CAP TANTALUM KEMET_B 4.7 uF 10 V	C32	1	DIGI-KEY	399-1566-1-ND
CAP TANTALUM KEMET_X 22 uF 35 V	C29 (2), C30 (2), C31	5	DIGI-KEY	399-1801-1-ND
INDUCTOR TOROID 6.3 uH 10 A	L2	1	MOUSER	542-2101-V
RES 2010 .025 .5 W 1%	R34, R35	2	MOUSER	71-WSL2010-0.025
RES 1206 1 .25 W 1%	R33	1	MOUSER	660-SR732BLTE1R00F
RECTIFIER DO-204AL 50 V 1 A	D3, D4	2	MOUSER	512-1N4001
DIODE DO-35 75 V 150 mA	D1, D2	2	DIGI-KEY	1N4148MSCT-ND
Power Supply Board	PCB	1	WPI - ECE Department	WPI-UPS Rev. B
PIC 16F767 Microcontroller QFN-28	U8	1	Microchip	PIC16LF767-I/ML
Header 1x2 4A	J33, J34	2	DIGI-KEY	WM6602-ND
Header 1x2 4A RA	J35, J36	2	DIGI-KEY	WM6002-ND
Header 2x2 4A	J37, J38	2	DIGI-KEY	WM6804-ND
Header 2x2 4A RA	J31, J32	2	DIGI-KEY	WM7104-ND
Header 1x2 7A RA	J41, J42	2	DIGI-KEY	WM4500-ND
Header 1x3 4A	J29, J39, J40	3	DIGI-KEY	WM6403-ND
Header 1x5 4A RA	J30	1	DIGI-KEY	WM6005-ND

Table 30: Embedded Computer Bill of Materials

Description	Reference Designator	Quantity	Vendor	Vendor Part #
Pentium M Processor Baseboard		1	Advanced Digital Logic	803010
Pentium M Processor Board		1	Advanced Digital Logic	805164
PC/104+ Long Connector		1	Advanced Digital Logic	807006
DDR RAM 1 GB		1	Advanced Digital Logic	992025
Cable Kit		1	Advanced Digital Logic	803030
PC/104+ Assembly Kit		2	Advanced Digital Logic	710460
Header 1x4 4A RA	J1, J24, J26	3	DIGI-KEY	WM6004-ND
Header 1x3 4A RA	J16	1	DIGI-KEY	WM6003-ND
HDD		1	Arrow	HEJ423020F9AT00
802.11b		1	D-Link	DWL-G132
IEEE 1394a		1	Ampro	MM3-1394-K-10
Photo Relay		1	DIGI-KEY	PVDZ172NS-ND
N-Channel MOSFET		1	MOUSER	512-FDV303N
RES 0805 1K .125 W 5%		1	DIGI-KEY	P1.0KACT-ND
RES 0805 390 .125 W 5%		1	DIGI-KEY	P390ACT-ND

Table 31: Internal Cable Bill of Materials

Description	Reference Designator	Quantity	Vendor	Vendor Part #
Crimp Terminal 4A		52	DIGI-KEY	WM2510-ND
Terminal Housing 1x2 4A		5	DIGI-KEY	WM2800-ND
Terminal Housing 1x3 4A		2	DIGI-KEY	WM2801-ND
Terminal Housing 1x4 4A		3	DIGI-KEY	WM2802-ND
Terminal Housing 1x5 4A		1	DIGI-KEY	WM2803-ND
Terminal Housing 2x2 4A		3	DIGI-KEY	WM2519-ND
Crimp Terminal 7A		4	DIGI-KEY	WM2300-ND
Terminal Housing 1x2 7A		2	DIGI-KEY	WM2100-ND
IDE Cable for 2.5" HDD		1	MOUSER	517-2M-ACAC-044-12
NPN general purpose small signal transistor	TEMP PROBE	1	MOUSER	610-2N3904
Panel-Mount Connector, 2 position, Female	CHARGER	1	MOUSER	502-EN3P2F
Panel-Mount Connector, 5 position, Female	BAT	2	MOUSER	502-EN3P5F
Panel-Mount Connector, 7 position, Male	MOUSE	1	MOUSER	502-EN3P7M
Panel-Mount Connector, 4 position, Female	USB	1	MOUSER	502-EN3P4F
Panel-Mount Connector, 6 position, Female	AUDIO	1	MOUSER	502-EN3P6F
Panel-Mount Connector, 8 position, Male	VGA	1	MOUSER	502-EN3P8M
Ribbon cable w/ 10 pin socket	VGA	1	DIGI-KEY	M1AXA-1036J-ND
Panel-Mount Sealed Momentary Pushbutton	POWERSWITCH	1	MOUSER	642-IPR3SAD2
IEEE 1394a 1 m		1	MOUSER	172-1393

Table 32: External Cable Bill of Materials

Description	Reference Designator	Quantity	Vendor	Vendor Part #
Cord Connector, 6 position, Male	AUDIO	1	MOUSER	502-EN3C6M
USB type b connector	AUDIO	1	MOUSER	154-2010
3.5 mm female stereo connector	AUDIO	2	MOUSER	161-3300
Cord Connector, 8 position, Female	VGA	1	MOUSER	502-EN3C8F
VGA Socket	VGA	1	MOUSER	523-015S-AA000
VGA Socket Backshell	VGA	1	MOUSER	538-DMHE001
VGA CONN POWERPLUG .1" BLACK	VGA		DIGI-KEY	SC1051-ND
Cord Connector, 5 position, Male	BAT	2	MOUSER	502-EN3C5M
Battery Connector	BAT	2	MOUSER	538-39-01-3063
Battery Connector Pins	BAT	10	MOUSER	538-39-00-0041
Cord Connector, 2 position, Male	CHARGER	1	MOUSER	502-EN3C2M
Cord Connector, 3 position, Male, 16 AWG	CHARGER	1	MOUSER	502-EN3C3M16
Inline Cord Connector, 3 position, Female, 16 AWG	CHARGER	1	MOUSER	502-EN3C3F16
Cord Connector, 4 position, Male	USB	1	MOUSER	502-EN3C4M
USB type a receptacle	USB	1	MOUSER	806-KUSBV-AS-1-N-BLK
Cord Connector, 7 position, Female	MOUSE	1	MOUSER	502-EN3C7F
SWITCH TACT SPST-NO 120GF J-LEAD		1	DIGI-KEY	401-1458-1-ND
5/16 inch WOVEN WRAP-AROUND	TRANSDUCER	1	cableorganizer.com	RDT0312
10 Conductor Cable, 100’, #24, shielded		1	MOUSER	566-9540-100

Table 33: Assembly Bill of Materials

Description	Quantity	Vendor	Vendor Part #
Enclosure	1	Datum3D	
Fan 40x6 mm 5V 5.5 CFM .4 W 6000 RPM 26 dBA	2	Allied Electronics	997-0064
Vest (L)	1	B&H Photo	DOVPL
SMART LI-ION BATTERY PACK, 95Whr, 14.4V, 6.6Ah	2	Ocean Server	BA95HC-FL
Microphone	1	Planning Systems, Inc.	
i-glasses PC/SVGA	1	i-glasses	A502085

Description	Quantity	Vendor	Vendor Part #
Transducer, Terason 2000	1	Terason	
Mouse	1	Geeks.com	BLK-FDM-G51-USB
AC Adapter 24VDC DESKTOP 100W	1	MOUSER	418-TR100A240-02
Software Licenses	1		

Appendix II – Internal Cable Assemblies

Please note that the indicated cable lengths are measured using the exposed cable sheath between connectors as shown in Fig. 122:

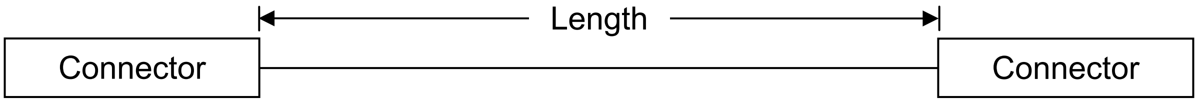


Fig. 122: Cable Length Measurement

The cable lengths are indicated with a number over another number in parenthesis. The top number is in cm while the bottom number is inches. Fig. 123 shows an example cable length of 25 cm (9.8 in.):

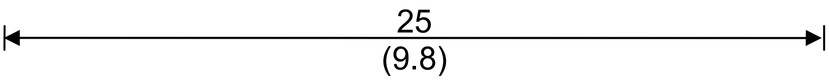


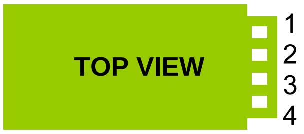
Fig. 123: Cable Length Measurement Example

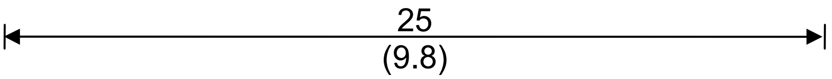
The controlling dimension is in cm.

Whenever a connector pin-out is shown for a device, the view will always be looking into the connector at the mating face.

Unless otherwise instructed, all connections are made using individual AWG 26 cable.

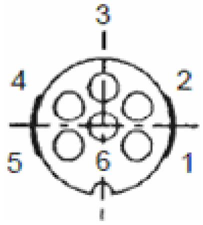
Table 34: Internal 802.11g Cable Assembly

Device	Pin	Signal	Pin	Device
	1	+5V	J1.1	1x4 pin Shrouded Connector CPU
	2	-DATA	J1.2	
	3	+DATA	J1.3	
	4	GND	J1.4	



Special Instructions: Replace J1 on the CPU board with a right angle 1x4 pin header. Remove the USB connector from the 802.11g board. Solder wires directly to the pads, remembering that they must pass through a small opening in the heatsink that will not accommodate the 1x4 pin shrouded connector.

Table 35: Internal Audio Cable Assembly

Device	Pin	Signal	Pin	Device
 FEMALE SOCKET	1	+5 V	J36.2	1x2 pin Shrouded Connector Power Supply
	2	GND	J36.1	
	3	Line-in Signal	J30.7	Directly soldered to CPU
	4	Line-in GND	J30.8	
	5	Line-out Signal	J30.19	
	6	Line-out GND	J30.20	

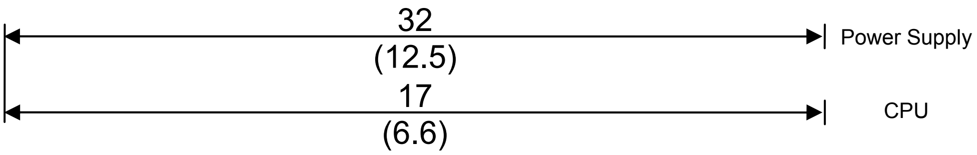
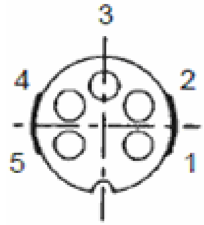
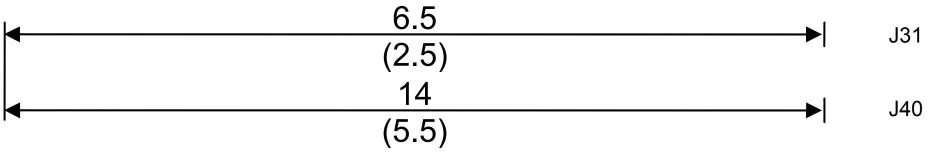


Table 36: Internal Battery 1 Cable Assembly

Device	Pin	Signal	Pin	Device
 FEMALE SOCKET	1	BAT+	J31.3 J31.4	2x2 pin Shrouded Connector Power Supply
	2	BAT-	J31.1 J31.2	
	3	SDA	J40.3	1x3 pin Shrouded Connector Power Supply
	4	SCL	J40.2	
	5	TH	J40.1	



Special Instructions: Use AWG 18 cable for BAT+ and BAT-signals. Ensure that all pins are connected on the J31 connector on the power supply.

Table 37: Internal Battery 2 Cable Assembly

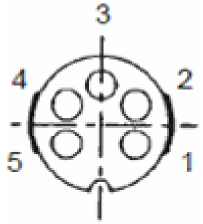
Device	Pin	Signal	Pin	Device
 FEMALE SOCKET	1	BAT+	J32.3 J32.4	2x2 pin Shrouded Connector Power Supply
	2	BAT-	J32.1 J32.2	
	3	SDA	J39.3	1x3 pin Shrouded Connector Power Supply
	4	SCL	J39.2	
	5	TH	J39.1	
		6.5 (2.5)		J32
		14 (5.5)		J39
Special Instructions: Use AWG 18 cable for BAT+ and BAT-signals. Ensure that all pins are connected on the J32 connector on the power supply.				

Table 38: Internal Charger Cable Assembly

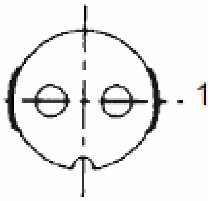
Device	Pin	Signal	Pin	Device
 FEMALE SOCKET	1	+24 V	J41.1	Power Supply
	2	GND	J41.2	
		14.2 (5.6)		
Special Instructions: Use AWG 18 cable for all signals. Also indicate a pin 1 on the connector used to attach to the power supply.				

Table 39: Internal CMOS Battery Cable Assembly

Device	Pin	Signal	Pin	Device
3.6 V Lithium Battery	+	BAT+	J29.6	Directly soldered to CPU
	-	BAT-	J29.7	
		7 (2.7)		
Special Instructions: Weld nickel tabs onto the battery to have a surface that solder will adhere to. Attach the battery in place to the heatsink using a small piece of Velcro. The battery should be placed between the power supply and the heatsink, near L1 on the power supply.				

Table 40: Internal Fan Power Cable Assembly

Device	Pin	Signal	Pin	Device
	1	Fan 1+	J38.1	2x2 pin Shrouded Connector Power Supply
	2	Fan 1	J38.3	
	3	Fan 2+	J38.2	
	4	Fan 2	J38.4	
11 (4.3)				

Table 41: Internal HDD Cable Assembly

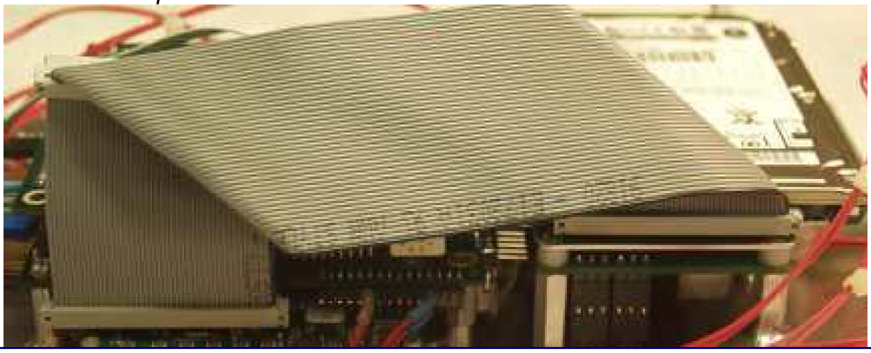
Device	Pin		Signal	Pin	Device
HDD	N/A		IDE	J21	CPU
20 (7.8)					
Special Instructions: Fold the IDE cable as shown. 					

Table 42: Internal IEEE 1394a Auxiliary Power Cable Assembly

Device	Pin	Signal	Pin	Device
1x2 pin Shrouded Connector Power Supply	J35.2	IEEE 1394a Power	J5.4	2x2 pin Shrouded Connector 1394a Board
	J35.1	GND	J5.5	
30 (11.7)				
Special Instructions: The two pins that are used in the 2x2 shrouded connector are diagonally across from each other.				

Table 43: Internal IEEE 1394a Cable Assembly

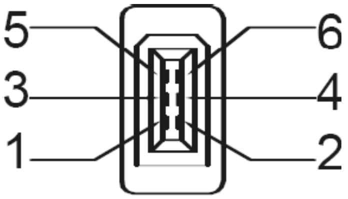
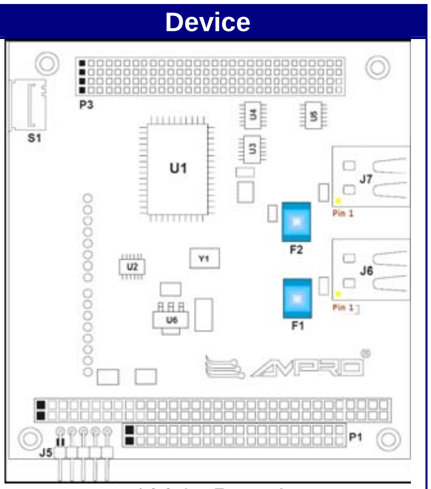
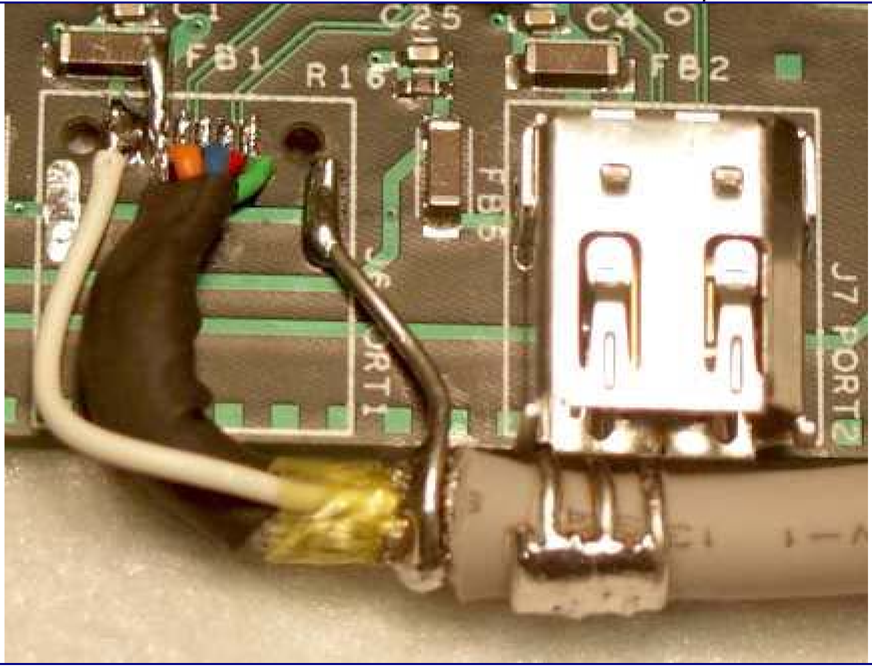
Device	Pin	Signal	Pin	Device
 1394a Cable	1	IEEE 1394a Power	J6.1	 P3 S1 U1 J7 Pin 1 F2 U2 Y1 J6 Pin 1 F1 U6 AMPRO J5 P1 1394a Board
	2	GND	J6.2	
	3	TPB	J6.5	
	4	TPB+	J6.6	
	5	TPA	J6.3	
	6	TPA+	J6.4	
	Shield	Shield	J6.Shield	
14 (5.5)				
Special Instructions: TEST the 1394a board before performing any of these instructions! Cut the cable in half. Remove J6 from the 1394a board. Solder the bare-wire end of the cable to the pads on the board where J6 was.				
 C25 C4 FB1 R16 FB2 FB5 J6 PORT1 J7 PORT2				

Table 44: Internal Mouse Cable Assembly

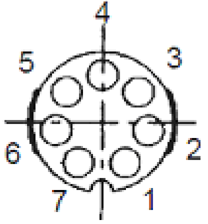
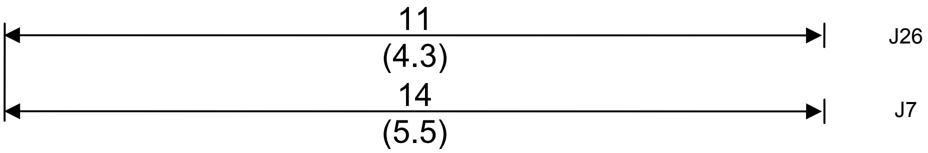
Device	Pin	Signal	Pin	Device
 MALE SOCKET	1	+5V	J24.1	1x4 pin Shrouded Connector CPU
	2	-DATA	J24.2	
	3	+DATA	J24.3	
	4	GND	J24.4	
	5	PTT	J7.21	2x2 pin Shrouded Connector CPU
	6	RADIO	J7.19	
	7	Common (GND)	J7.22	
				
Special Instructions: Replace J24 on the CPU board with a right angle 1x4 pin header. Please indicate a ‘pin 1’ on J7 on the CPU board that corresponds to pin 1 on the 2x2 pin shrouded connector.				

Table 45: Internal MSM855 CPU Power Cable Assembly

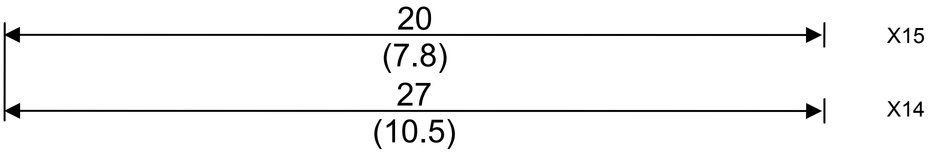
Device	Pin	Signal	Pin	Device
 Power Supply	J42.2	+5 V	X15	Soldered directly to CPU blade connectors
	J42.1	GND	X14	
				
Special Instructions: Use AWG 18 cable for all connections. Also indicate a pin 1 on the connector used to attach to the power supply.				

Table 46: Internal Power Switch Cable Assembly

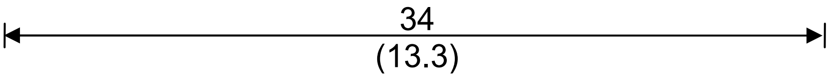
Device	Pin	Signal	Pin	Device
 Momentary Switch	1	Main Switch	J16.1	1x2 pin Shrouded Connector CPU
	2	GND	J16.2	
				

Table 47: Internal Temperature Probe Cable Assembly

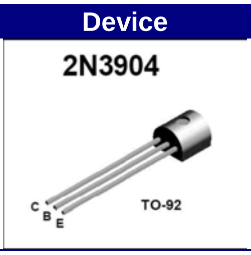
Device	Pin	Signal	Pin	Device
	C	D+	J34.2	1x2 pin Shrouded Connector Power Supply
	B			
	E	D-	J34.1	
16.5 (6.5)				
Special Instructions: The collector and the base can be connected together at the transistor. Ensure that the cable is twisted between the transistor and the header with at least 2 twists per cm.				

Table 48: Internal USB Cable Assembly

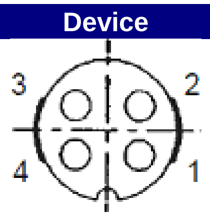
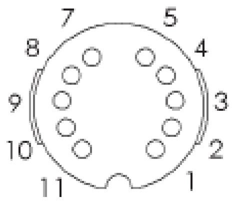
Device	Pin	Signal	Pin	Device
 FEMALE SOCKET	1	+5V	J26.1	1x4 pin Shrouded Connector CPU
	2	-DATA	J26.2	
	3	+DATA	J26.3	
	4	GND	J26.4	
10 (3.9)				
Special Instructions: Replace J26 on the CPU board with a right angle 1x4 pin header.				

Table 49: Internal VGA Cable Assembly

Device	Pin	Signal	Pin	Device
 FEMALE SOCKET	1	Red	J15.2	Supplied VGA Cable from CPU Cable Kit
	2	Green	J15.4	
	3	Blue	J15.6	
	4	HSYNC	J15.8	
	5	VSYNC	J15.9	
	7	VGA Signal GND	J15.1	
	10	DDC-Data	J15.7	
	11	DDC-Clock	J15.10	
	8	VGA+	J37.2	2x2 pin Shrouded Connector Power Supply
	9	VGA-	J37.4	
17.5 (6.9)				J15
21.1 (8.3)				J37

Appendix III – External Cable Assemblies

Please note that the indicated cable lengths are measured using the exposed cable sheath between connectors as shown in Fig. 122:

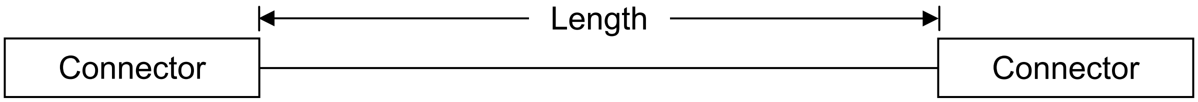


Fig. 124: Cable Length Measurement

The cable lengths are indicated with a number over another number in parenthesis. The top number is in cm while the bottom number is inches. Fig. 123 shows an example cable length of 25 cm (9.8 in.):

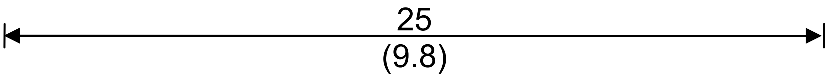


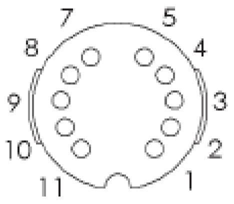
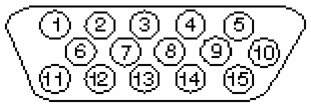
Fig. 125: Cable Length Measurement Example

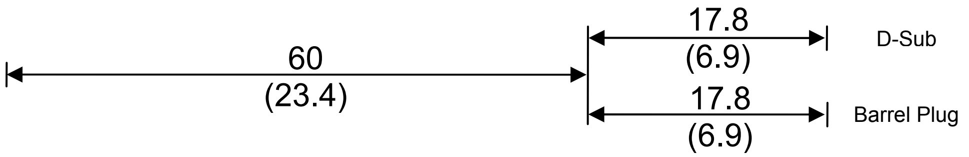
The controlling dimension is in cm.

Whenever a connector pin-out is shown for a device, the view will always be looking into the connector at the mating face.

Unless otherwise instructed, all connections are made using individual AWG 26 cable.

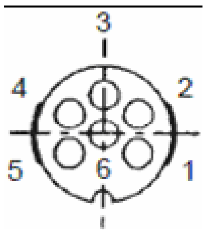
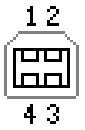
Table 50: External VGA Cable Assembly

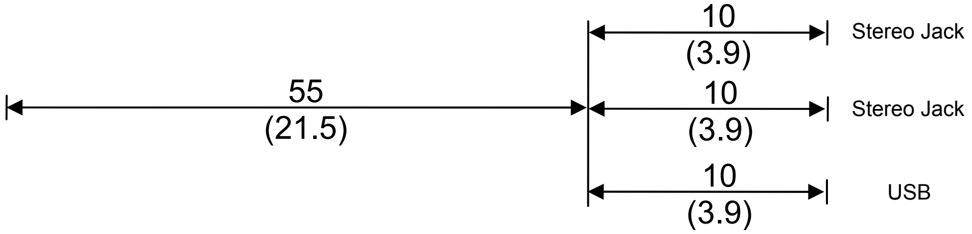
Device	Pin	Signal	Pin	Device
 MALE CONNECTOR	1	Red	1	 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 15 Pin High Density D-Sub
	2	Green	2	
	3	Blue	3	
	4	HSYNC	13	
	5	VSYNC	14	
	7	VGA Signal GND	7	
	10	DDC-Data	12	
	11	DDC-Clock	15	
	8	VGA+	Center	2.1 mm (id), 5.5 mm (od) Barrel Plug
	9	VGA-	Outside	



Special Instructions: Pins 5 & 8 are bridged on the D-Sub connector.

Table 51: External Audio Cable Assembly

Device	**Pin**	**Signal**	**Pin**	**Device**
 MALE CONNECTOR	1	+5 V	1	 USB Type B Connector
	2	GND	4	
	3	Line-in Signal	Tip/Ring	3.5 mm Stereo Jack
	4	Line-in GND	Collar	
	5	Line-out Signal	Tip/Ring	3.5 mm Stereo Jack
	6	Line-out GND	Collar	



Special Instructions: Pictured USB type B connector is the socket. The connector will connect into this socket. Tie together the tip and ring on the 3.5 mm stereo audio socket. This effectively makes it a mono jack.

Table 52: External Mouse Cable Assembly

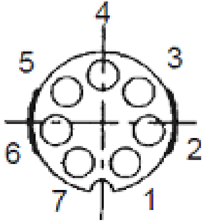
Device	Pin	Signal	Pin	Device
 FEMALE CONNECTOR	5	PTT	1	Panel-Mount Sealed Momentary Switch
	7	Common (GND)	2	
200 (78)				
Special Instructions: Use 2 conductor flex cable, attached with hot-melt glue, to attach the button (also attached with hot-melt glue) on the ultrasound transducer. Attach the cable from the connector to the flex cable at the base of the transducer.				

Table 53: External USB Cable Assembly

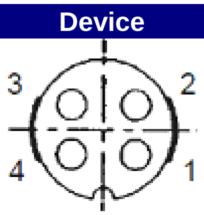
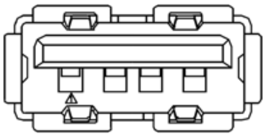
Device	Pin	Signal	Pin	Device
 MALE CONNECTOR	1	+5V	1	USB Type A Receptacle
	2	-DATA	2	
	3	+DATA	3	
	4	GND	4	
10 (3.9)				

Table 54: External Battery 1 Cable Assembly

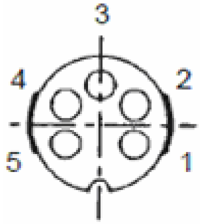
Device	Pin	Signal	Pin	Device
 MALE CONNECTOR	1	BAT+	1	6 5 4 3 2 1 Molex Connector
	2	BAT-	6	
	3	SDA	4	
	4	SCL	3	
	5	TH	2	
60 (23.4)				
Special Instructions: Bundle 3 wires together for the BAT+ and BAT-signals.				

Table 55: External Battery 2 Cable Assembly

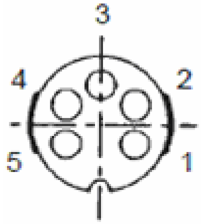
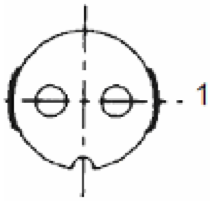
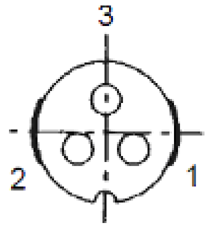
Device	Pin	Signal	Pin	Device
 MALE CONNECTOR	1	BAT+	1	6 5 4 3 2 1 Molex Connector
	2	BAT-	6	
	3	SDA	4	
	4	SCL	3	
	5	TH	2	
90 (35.1)				
Special Instructions: Bundle 3 wires together for the BAT+ and BAT-signals.				

Table 56: External Charger Cable Assembly

Device	Pin	Signal	Pin	Device
 MALE CONNECTOR	1	+24 V	1	 FEMALE INLINE CONNECTOR
	2	GND	2	
100 (39)				
Special Instructions: Bundle 4 wires together for each signal. The AC adapter must also be modified with the corresponding male inline connector.				

Appendix IV – Schematics

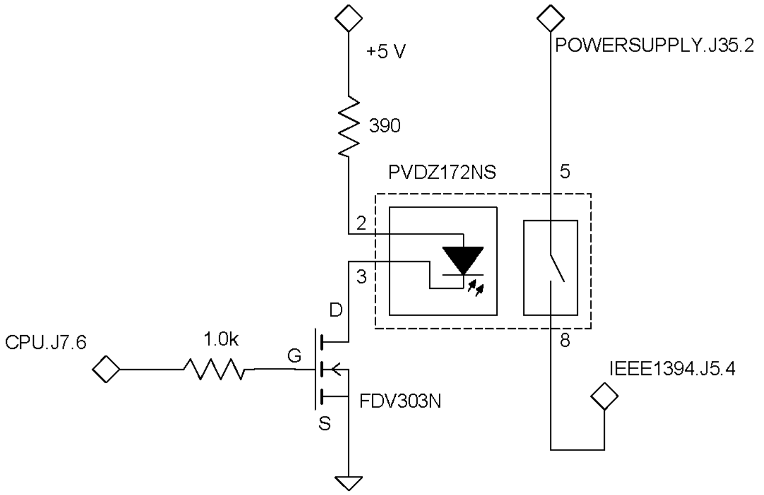
All components values are correctly specified in Appendix I – Bill of Materials. Where a discrepancy exists, the bill of materials should take precedence.

When modifying the 1394a interface board, the following components must be removed to isolate 1394a bus power from the interface board: F1, C1, F2, C4.

DWG. NO.	SH.	REV

REVISIONS

REV	DESCRIPTION	DATE	APPROVED



*Assembly Note:
Sever Pin J5.4 on IEEE 1394 board. Pin connects to power supply pin J35.2 and the photo relay switches this pin into the original J5.4 on IEEE 1394 board.

CONTRACT NO.

APPROVALS		DATE
DRAWN	PJC	1/11/06
CHECKED		
ISSUED		

Photo Relay Driver

SIZE A
FSCM NO.
DWG. NO.
REV A
SCALE
SHEET 1 of 1

H=2LA; V=2LA

Appendix V – PCB Layout

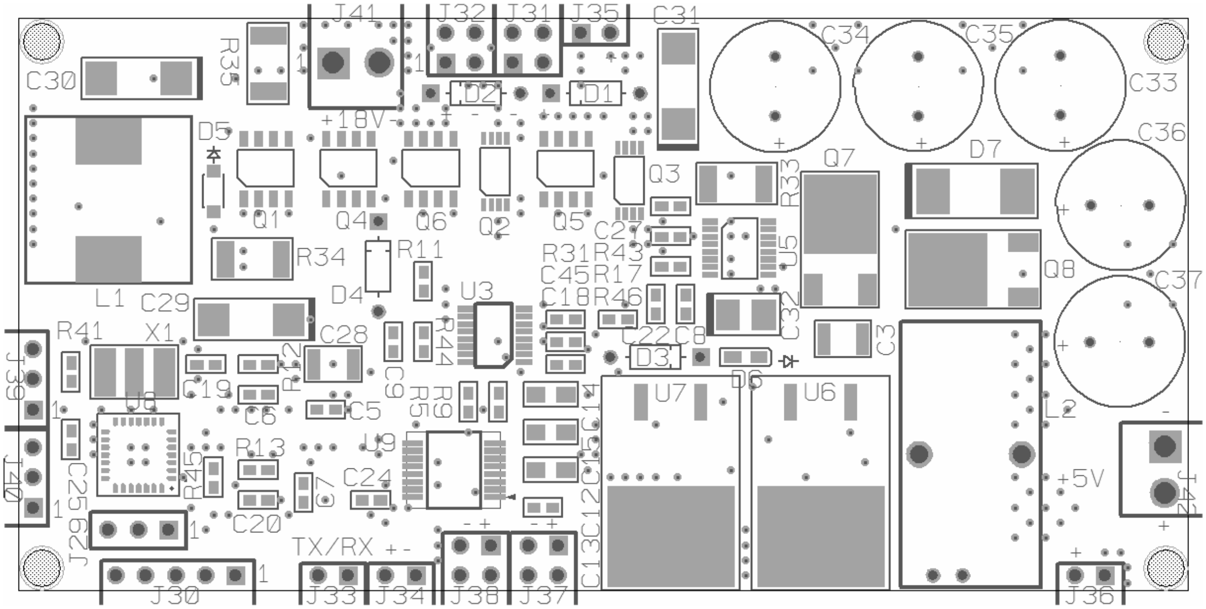


Fig. 126: Top Silkscreen

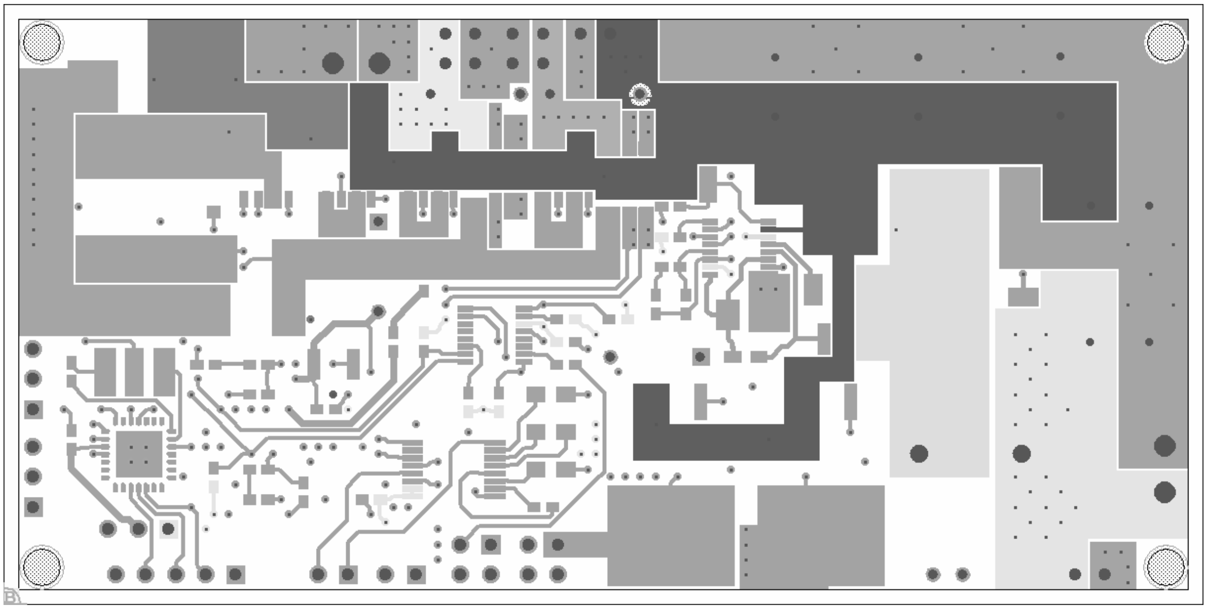


Fig. 127: Top Copper

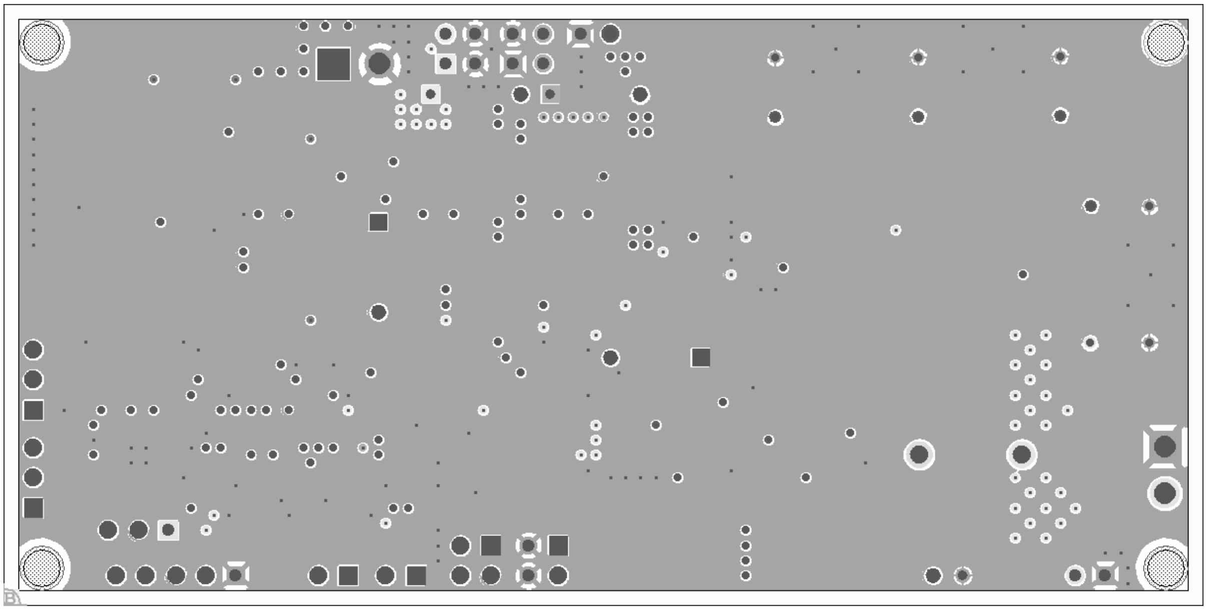


Fig. 128: Layer 2 Copper

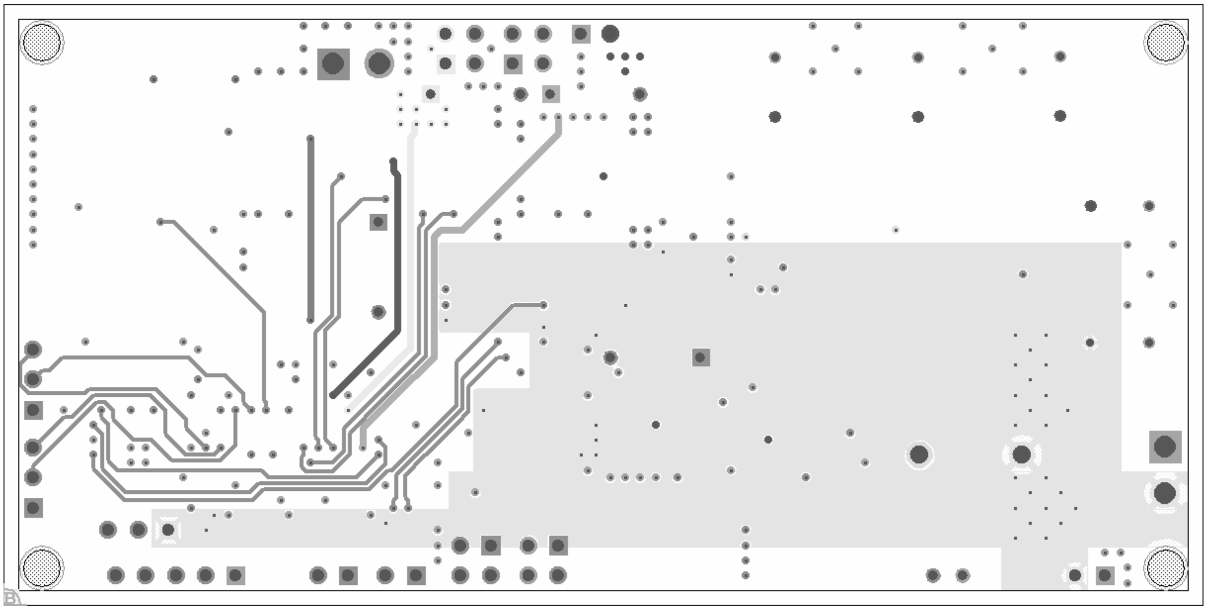


Fig. 129: Layer 3 Copper

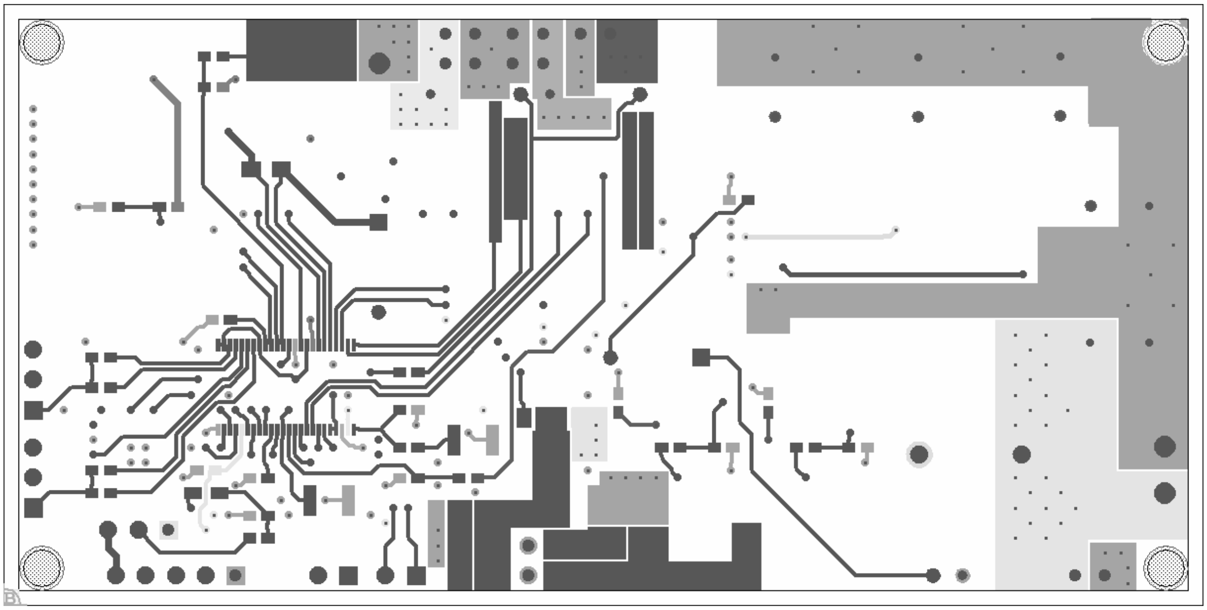


Fig. 130: Bottom Copper

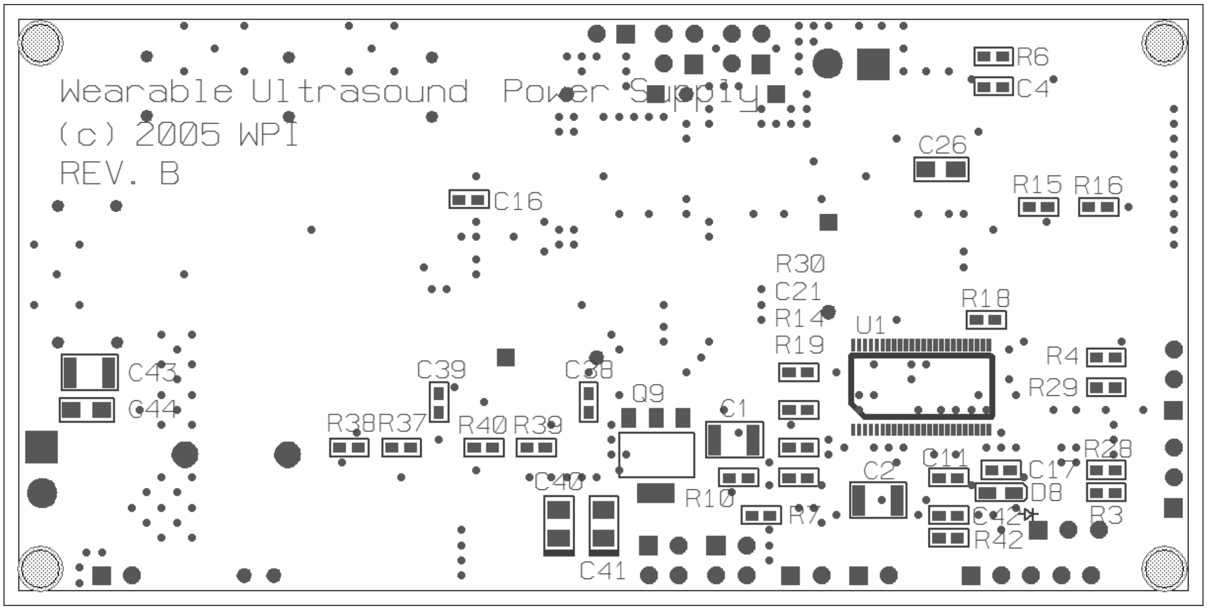


Fig. 131: Bottom Silkscreen (horizontally mirrored)

Appendix VI – Speech Recognition Grammar

```
#BNF+EM V1.0;
!grammar "Terason Grammar";
!language "American English";
!start <Terason> <NATO> <YesNoRules>;

<Terason>: <TerasonRules> |
<SystemRules>;
<NATO>: <NATORules> | <SystemRules>;

<SystemRules>:
shutdown !id(1000) |
"patient information" !id(1003) |
ultrasound !id(1004);

<YesNoRules>:
yes !id(1001) |
no !id(1002);

<TerasonRules>:
"freeze image" !id(1) |
"live image" !id(2) |
"small size" !id(3) |
"medium size" !id(4) |
"large size" !id(5) |
"depth two" !id(6) |
"depth three" !id(7) |
"depth four" !id(8) |
"depth five" !id(9) |
"depth six" !id(10) |
"depth seven" !id(11) |
"depth eight" !id(12) |
"depth nine" !id(13) |
"depth ten" !id(14) |
"depth eleven" !id(15) |
"depth twelve" !id(16) |
"depth thirteen" !id(17) |
"depth fourteen" !id(18) |
"depth fifteen" !id(19) |
"depth sixteen" !id(20) |
"depth seventeen" !id(21) |
"depth eighteen" !id(22) |
"depth nineteen" !id(23) |
"depth twenty" !id(24) |
"depth twenty one" !id(25) |
"depth twenty two" !id(26) |
"depth twenty three" !id(27) |
"depth twenty four" !id(28) |
"focus zero point six" !id(29) |
"focus one" !id(30) |
"focus one point three" !id(31) |
"focus two" !id(32) |
"focus two point five" !id(33) |
"focus two point eight" !id(34) |
```

```
<NATORules>:
zero !id(2000) |
one !id(2001) |
two !id(2002) |
three !id(2003) |
four !id(2004) |
five !id(2005) |
six !id(2006) |
seven !id(2007) |
eight !id(2008) |
niner !id(2009) |
alpha !id(2017) |
bravo !id(2018) |
charlie !id(2019) |
delta !id(2020) |
echo !id(2021) |
foxtrot !id(2022) |
golf !id(2023) |
hotel !id(2024) |
india !id(2025) |
juliet !id(2026) |
kilo !id(2027) |
lima !id(2028) |
mike !id(2029) |
november !id(2030) |
oscar !id(2031) |
papa !id(2032) |
quebec !id(2033) |
romeo !id(2034) |
sierra !id(2035) |
tango !id(2036) |
uniform !id(2037) |
victor !id(2038) |
whiskey !id(2039) |
x-ray !id(2040) |
yankee !id(2041) |
zulu !id(2042) |
backspace !id(2043) |
"switch fields" !id(2044) |
space !id(2045) |
ok !id(1005) |
cancel !id(1006);
```

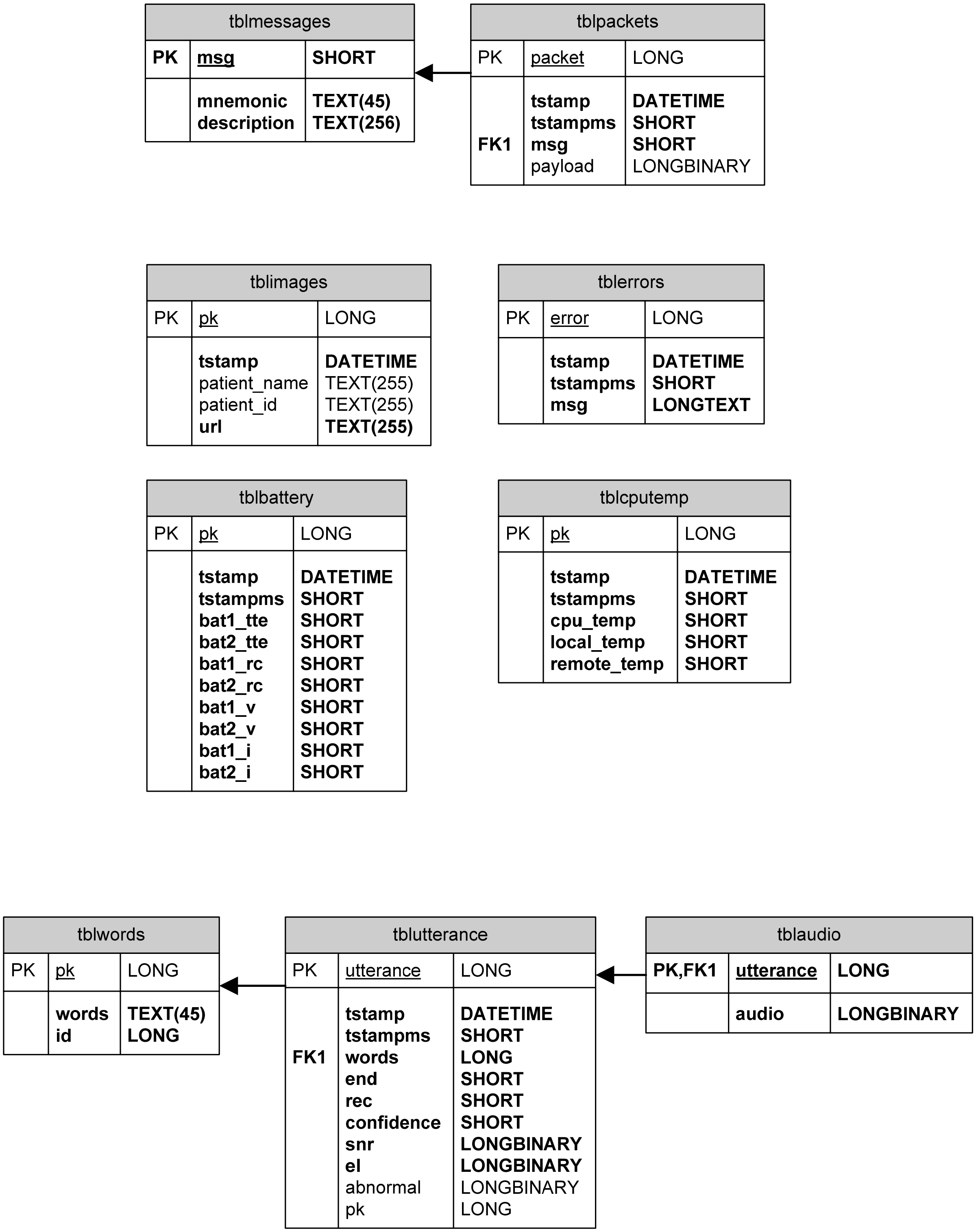
```
"focus three" !id(35) |
"focus three point five" !id(36) |
"focus four" !id(37) |
"focus four point five" !id(38) |
"focus five point five" !id(39) |
"focus six" !id(40) |
"focus six point five" !id(41) |
"focus seven" !id(42) |
"focus eight" !id(43) |
"focus eight point five" !id(44) |
"focus ten" !id(45) |
"focus thirteen" !id(46) |
"focus sixteen" !id(47) |
"focus sixteen point five" !id(48) |
gray !id(49) |
tan !id(50) |
flame !id(51) |
sepia !id(52) |
magenta !id(53) |
sage !id(54) |
rainbow !id(55) |
cobalt !id(56) |
"smoothing alpha" !id(57) |
"smoothing bravo" !id(58) |
"smoothing charlie" !id(59) |
"smoothing delta" !id(60) |
"smoothing echo" !id(61) |
"persistence zero" !id(62) |
"persistence one" !id(63) |
"persistence two" !id(64) |
"persistence three" !id(65) |
"persistence four" !id(66) |
"persistence five" !id(67) |
"persistence six" !id(68) |
"persistence seven" !id(69) |
"map alpha" !id(70) |
"map bravo" !id(71) |
"map charlie" !id(72) |
"map delta" !id(73) |
"map echo" !id(74) |
"map foxtrot" !id(75) |
"invert horizontal" !id(76) |
"invert vertical" !id(77) |
"b mode" !id(78) |
"m mode" !id(79) |
"pulsed wave doppler" !id(80) |
"color doppler " !id(81) |
"directional power doppler" !id(82) |
"power doppler" !id(83) |
"save image" !id(84) |
"brightness increase" !id(85) |
"contrast increase" !id(86) |
"brightness decrease" !id(87) |
"contrast decrease" !id(88) |
"full screen" !id(89);
```

Appendix VII – Database Schema

The following table shows the data type mappings between MySQL and ODBC. Fig. 132 shows a graphical representation of the database schema using ODBC data types.

Table 57: MySQL and ODBC Data Type Mappings

MySQL Data Type	ODBC Data Type
TINYINT	SHORT
SMALLINT	SHORT
INT	LONG
TINYBLOB	LONGBINARY
BLOB	LONGBINARY
MEDIUMBLOB	LONGBINARY
VARCHAR(M)	TEXT
TEXT	LONGTEXT
TIMESTAMP	DATETIME



tblmessages		
PK	**msg**	**SHORT**

	mnemonic
	description
		TEXT(45)
		TEXT(256)

tblpackets		
PK	packet	LONG
  FK1	**tstamp** **tstampms** **msg** payload	**DATETIME** **SHORT** **SHORT** LONGBINARY

tblimages		
PK	pk	LONG

	tstamp
	patient_name
	patient_id
	url
		DATETIME
		TEXT(255)
		TEXT(255)
		TEXT(255)

tblerrors		
PK	error	LONG
	tstamp **tstampms** **msg**	**DATETIME** **SHORT** **LONGTEXT**

tblbattery		
PK	pk	LONG
	tstamp **tstampms** **bat1_tte** **bat2_tte** **bat1_rc** **bat2_rc** **bat1_v** **bat2_v** **bat1_i** **bat2_i**	**DATETIME** **SHORT** **SHORT** **SHORT** **SHORT** **SHORT** **SHORT** **SHORT** **SHORT** **SHORT**

tblcputemp		
PK	pk	LONG
	tstamp **tstampms** **cpu_temp** **local_temp** **remote_temp**	**DATETIME** **SHORT** **SHORT** **SHORT** **SHORT**

tblwords		
PK	pk	LONG
	words **id**	**TEXT(45)** **LONG**

tblutterance		
PK	utterance	LONG
  FK1	**tstamp** **tstampms** **words** **end** **rec** **confidence** **snr** **el** abnormal pk	**DATETIME** **SHORT** **LONG** **SHORT** **SHORT** **SHORT** **LONGBINARY** **LONGBINARY** LONGBINARY LONG

tblaudio		
PK,FK1	**utterance**	**LONG**
	audio	**LONGBINARY**

Fig. 132: Database Schema

Appendix VIII – Training Video Scripts

WEARABLE ULTRASOUND SYSTEM TUTORIAL

OPERATOR
NARRATOR

INT.

OPERATOR IS STANDING NEAR THE VEST WHICH SITS ON A CHAIR. THE BACKSIDE OF THE VEST IS VISIBLE.

VOICE OVER:
Hello and welcome to the Wearable Ultrasound System tutorial video. This video is a short introduction to the Wearable Ultrasound System and will demonstrate some basic skills required to use the system. The same information, and much more, is contained in two manuals that accompany the system. The first manual, titled Terason User's Guide, contains information about using the Terason 2000 ultrasound transducer. The second manual, titled WPI Wearable Ultrasound System User's Guide, contains information specific to the Wearable Ultrasound System, including tutorials. We strongly suggest that you go through all of the tutorials before attempting to use the system with patients.

OPERATOR IS WEARING THE VEST AND POINTING OUT THE VARIOUS COMPONENTS IN THE VEST.

VOICE OVER:
Let's begin with an overview of the components in the vest. In each of the breast pockets, there is a rechargeable battery. Each battery can be recharged while still in the vest. In the lower right-hand pocket is the ultrasound transducer. It can be stored in this pocket when not in use. Above the ultrasound transducer is a mouse that can be operated with one hand. In the back pocket of the vest, is the embedded computer. The power button is located on the upper right hand side of the embedded computer. Sitting in the lower left hand pocket, is the head-mounted display. Finally, there is a microphone contained in the mesh near the left shoulder. Now, let's put the vest on and also show a different head-mounted display.

OPERATOR PUTS ON THE VEST

VOICE OVER:
Ultrasound images are viewed using a head-mounted display. The next step in putting on the vest is to put on the head-mounted display.

OPERATOR PUTS ON THE HMD. CUT TO SHOWING THE HMD BEING FLIPPED UP, CONNECTED TO ITS CABLE, AND POWERED ON AND OFF.

VOICE OVER:
The head mounted display may be flipped up and down by pressing a plunger above the display. Connect the cable and ensure that the display is on before powering on the system. Now the system is ready to be powered-up. The power button is located in the upper right hand corner of the embedded computer, located in the back pocket.

OPERATOR TURNS AROUND, ALLOWING THE CAMERA TO ZOOM IN TO THE BACK POCKET. OPERATOR TURNS ON THE EMBEDDED COMPUTER. WHILE TURNING BACK AROUND, THE CAMERA ZOOMS BACK OUT TO THE FULL SCENE.

VOICE OVER:
The system is now coming up. After approximately one minute, you should be able to see the ultrasound application.

CUT TO THE VIDEO DISPLAY. IT SHOWS A STATIC IMAGE REPRESENTING A SAMPLE OF WHAT THE USER MAY SEE.

VOICE OVER:
Let’s now go over the main graphical elements on the screen. On the left side of the screen is the image control bar.

HIGHLIGHT THE IMAGE CONTROL BAR ON THE STATIC IMAGE.

VOICE OVER:
The image control bar is used to control various aspects of the image. It is context-sensitive, meaning that it will show different controls based on factors such as the current scan mode and whether the image is moving or frozen.

ADDITIONALLY HIGHLIGHT THE TAB CONTROLS AT THE BOTTOM OF THE IMAGE CONTROL BAR. PAUSE. THE VIDEO DISPLAY SHOWS A STATIC IMAGE OF THE DEFAULT APPLICATION STATE.

VOICE OVER:
The tab controls at the bottom of the image control bar can be

used to access different groups of controls. For instance, the initial default control is the 2D control. Selecting the image quality tab will display another group of image controls that provide various image quality settings.

THE VIDEO DISPLAY SHOWS A STATIC IMAGE OF THE DEFAULT APPLICATION STATE AFTER SELECTING THE IMAGE I.Q. TAB.

VOICE OVER:
Above the image control bar, across the top of the screen, is the menu bar.

HIGHLIGHT THE MENU BAR ON THE STATIC IMAGE.

VOICE OVER:
The menu bar provides further controls that are fully explained in the Terason User’s Guide included with the system. Many of these commands are also implemented as voice commands. The Terason User’s guide also explains how to interpret the various graphics that overlay the ultrasound image. The final graphical element to look at is called the dashboard.

HIGHLIGHT THE DASHBOARD ON THE STATIC IMAGE.

VOICE OVER:
The dashboard, developed by WPI, augments the Terason application with information pertaining to speech recognition and system power status.

SHOW THE ZOOMED DASHBOARD ONLY ON THE STATIC IMAGE.

VOICE OVER:
At the top of the dashboard is a line of text that indicates the current status of the speech recognition system.

HIGHLIGHT THE ASR TEXT IN THE DASHBOARD.

VOICE OVER:
Another name for speech recognition is ASR, which stands for automated speech recognition. The first line of text will always indicate the current status of the speech recognition system.

HIGHLIGHT THE BATTERY STATUS INDICATORS AND TIME REMAINING.

VOICE OVER:

Below this are two indicators, one for each battery, that show the remaining capacity of each battery. Finally, below the battery indicators, is the estimated remaining operating time. The time is represented in hours and minutes.

CUT TO THE OPERATOR'S HAND HOLDING THE TRANSDUCER.

VOICE OVER:
Issuing a command, using speech recognition, is a three step process. First, depress the push-to-talk button on the transducer…

OPERATOR PRESSES THE PTT BUTTON.

VOICE OVER:
…, say the command, then release the button.

OPERATOR RELEASES THE PTT BUTTON. PAUSE. CUT TO THE VIDEO DISPLAY SHOWING THE ZOOMED DASHBOARD ONLY AS A STATIC IMAGE.

VOICE OVER:
Before issuing a command, verify that the dashboard says "ASR Ready". When the push-to-talk button is depressed, the text will change to "Listening…"

UPDATE THE STATIC IMAGE.

VOICE OVER:
Once the system is listening, the command can be issued. When you are finished speaking the command, remember to release the push-to-talk button.

UPDATE THE STATIC IMAGE.

VOICE OVER:
Once the command has been interpreted, the dashboard should again say "ASR Ready". In addition, you should now see the interpretation of the command you just gave.

HIGHLIGHT THE LAST RECOGNIZED TEXT. PAUSE. UPDATE THE STATIC IMAGE TO SHOW A POOR RECOGNITION RESULT.

VOICE OVER:
If the speech recognition system had trouble recognizing the command, it will be displayed in yellow. Don't worry, the command will still be executed. Please refer to the included WPI Wearable Ultrasound System User's Guide for a complete

listing of the available commands.

When you are finished scanning, two voice commands should be issued to power off the system. The first command is “shutdown”. This has to be followed by “yes” to initiate the shutdown sequence.

OPERATOR ISSUES COMMANDS.

VOICE OVER:
Once the shutdown commands have been issued, you can take off the vest. Whenever the vest is not in operation, it should be plugged in to ensure that the batteries are always fully charged.

OPERATOR REMOVES THE VEST AND PLACES IT ON A CHAIR WITH THE BACKSIDE VISIBLE.

VOICE OVER:
The charging cable is located in the back pocket of the vest. Remove it and plug it into the AC adapter as illustrated.

ZOOM IN TO THE BACK POCKET AS THE OPERATOR PULLS OUT THE CHARGER CABLE. OPERATOR SHOWS THE CHARGER CABLE BEING PLUGGED INTO THE AC ADAPTER.

VOICE OVER:
Thank you for your attention and this concludes the introductory training video. For further help, the WPI Wearable Ultrasound System User’s Guide includes contact information.

END.

WEARABLE ULTRASOUND SYSTEM PATIENT INFORMATION TUTORIAL

NARRATOR

SCREEN.

VOICE OVER:
Welcome to the patient information tutorial. This tutorial will cover the use of the patient information dialog. To enter patient information mode, use the command “patient information”.

ISSUE THE COMMAND “PATIENT INFORMATION”.

VOICE OVER:
A dialog box will be displayed, showing the current patient information. To enter information, the NATO phonetic alphabet is used. Let’s start by entering some initials.

ISSUE THE COMMANDS: “PAPA”, “JULIET”, “CHARLIE”.

VOICE OVER:
Please note that each letter is a separate recognition event. Now, use the command “switch fields” to move to the Patient ID line.

ISSUE THE COMMAND “SWITCH FIELDS”.

VOICE OVER:
Notice that the Patient ID field is now highlighted. Now enter some numbers, again using the NATO phonetic alphabet.

ISSUE THE COMMANDS: “ZERO”, “ONE”, “TWO”, “NINER”.

VOICE OVER:
OK, now suppose a mistake was made. You can always erase the last character by using the command “backspace”.

ISSUE THE COMMAND “BACKSPACE”.

VOICE OVER:
When you have finished entering the patient information, issue the command “OK” to accept the information or “cancel” to reject the information.

ISSUE THE COMMAND “OK”.

VOICE OVER:
You should now be able to see the patient information at the top of the screen. This concludes the patient information tutorial.

END.