DESIGN AND IMPLEMENTATION OF AN ECG BASED EMERGENCY TELEDIAGNOSTIC SYSTEM

by

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ABSTRACT

DESIGN AND IMPLEMENTATION OF AN ECG BASED EMERGENCY TELEDIAGNOSTIC SYSTEM

This thesis aims for the design and implementation of a software system for distributed emergency diagnosis to be used in conjunction with ambulatory electrocardiography (ECG/EKG) devices. The software consists of a Digital Signal Processor (DSP) helper library for processing and conditioning the ECG signals, a database for central data storage, and an expert user interface for ECG data evaluation. The system primarily aims to reduce the gap between patients and experts (cardiologists) and allows for the rapid diagnosis of acute myocardial infarction (AMI), commonly known as heart attack. This will consequently decrease the time span between the onset of symptoms and treatment. However, this system can also be used for the diagnosis of other forms of cardiovascular diseases, as well as a means of routine monitoring of cardiac patients.

Keywords: Telemedicine, ECG/EKG, telecardiology, electrophysiology, AMI, MI, pre-hospital thrombolysis.

ÖZET

ECG TABANLI ACİL UZAKTAN TANI SİSTEMİNİN TASARIMI VE UYGULAMASI

Bu tez çalışması taşınabilir elektrokardiyografi (EKG) aygıtlarıyla beraber kullanılacak dağıtık bir acil tanı sistemi için gerekli yazılımın tasarlanması ve geliştirilmesini içermektedir. Geliştirilen yazılım alınan sinyallerin işlenmesi için bir yardımcı DSP kütüphanesi, verilerin toplanması için bir merkezi veritabanı ve EKG kayıtlarının uzmanlar tarafından değerlendirilebilmesi için bir görüntüleme arayüzünden oluşmaktadır. Sistemin başlıca amacı uzman hekimler (kardiyologlar) ile hastalar arasındaki uzaklığın en aza indirgenmesi ve bu sayede öncelikle akut miyokard infarktüsü (AMİ) tanı süresinin olabildiğince kısaltılmasıdır. Böylece semptomların başlangıcından tedaviye kadar geçen sürenin kısaltılması hedeflenmektedir. Bununla beraber, sistem başka kardiyolojik hastalıkların tanısında da kullanılabileceği gibi, kalp hastalarının rutin gözetimi amacıyla da kullanılabilir.

Anahtar Sözcükler: Teletıp, ECG/EKG, telekardiyoloji, elektrofizyoloji, AMI, MI, hastane öncesi tromboliz.

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LIST OF SYMBOLS

V_I	The voltage of EKG Lead I
V_{II}	The voltage of EKG Lead II
V_{III}	The voltage of EKG Lead III
V_{aV_R}	The voltage of EKG Lead aV_R
V_{aV_L}	The voltage of EKG Lead aV_L
V_{aV_F}	The voltage of EKG Lead aV_F
V_{V_n}	The voltage of EKG Lead $V_n, \quad n = 1 \ldots 6$
V_{RF}	The voltage between the right arm and the left foot
V_{LF}	The voltage between the left arm and the left foot
V_{V_nF}	The voltage between the chest location V_n and the left foot
Φ_L	The potential at the left arm
Φ_R	The potential at the right arm
Φ_F	The potential at the left foot
Φ_{V_n}	The potential at the chest location $V_n, \quad n = 1 \ldots 6$
Φ_{CT}	The potential of the Wilson central terminal

LIST OF ABBREVIATIONS

AMI	Acute Myocardial Infarction
MI	Myocardial Infarction
DSP	Digital Signal Processing
EKG/ECG	Electrocardiogram
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
CT	(Wilson) Central Terminal
API	Application Programming Interface
RDBMS	Relational Database Management System
SQL	Structured Query Language
XML	Extended Markup Language
SOAP	Simple Object Access Protocol
HTTP	Hyper Text Transfer Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
USB	Universal Serial Bus

1. INTRODUCTION

1.1 Motivation

Cardiovascular disease is the number one cause of death and disability in the United States and most European countries, including Turkey. Turkey has the highest rate of coronary mortality in Europe, with an increase of 5% every year. Currently, approximately 2 million people in Turkey live with chronic heart disease, and 100.000 more are added to the pool each year. Especially in the case of acute myocardial infarction (AMI), the time span between the onset of symptoms and treatment is critical. The most important time for the prevention of irreducible heart damage is the first 90 minutes, and no improvement can usually be achieved after six hours have passed. Currently, research shows that the median time between the onset of symptoms and treatment in Turkey is four hours. Consequently, approximately 30% of cardiac patients die after their first coronary event in life [1].

The electrocardiogram (ECG/EKG) is the primary tool for screening and diagnosis of cardiovascular diseases. The method is noninvasive, and electrodes can easily be placed by a paramedic, or even by the patient oneself. ECG data is compact enough to be transmitted via the widely available GSM/GPRS cellular network. All these factors make ECG a good candidate for telemedicine. With an ambulatory ECG device that acquires and sends signals over the widely available GSM/GPRS network, a cardiologist at a remote location could evaluate and even diagnose the patient. A similar device was developed by in a previous work [2].

ECG telemetry systems have already been developed and are being utilized with limited, but encouraging, success. A common aspect of these solutions is that they are built as an extension to what is already available - by modifying traditional ECG devices and standalone ECG software. A more specific approach may be required to achieve a truly successful ECG based telediagnostic system. Such a system should use diagnostic grade remote ECG devices and software specifically designed for telemetry, and should be deployed on a call center exclusively designated for continual delivery of telediagnostic services.

1.2 Objective

The objective of this thesis work was to design and develop software specifically for use in a call center for remote diagnosis of cardiac disorders using ECG telemetry. This software consists of a database that stores all ambulatory ECG recordings, an easy to use visualization platform, a rapid diagnosis interface for display, and a processing library for signal conditioning. The system can run both in store-and-forward mode and live-preview mode.

1.3 The EKGNET Project

The software developed is part of the EKGNET project for rapid diagnosis of acute myocardial infarction and remote monitoring of cardiac patients. The project is developed by Teknofil and sponsored by Ericsson. Most of the work is completed at Ericsson Mobility World Turkey. The EKGNET project also includes the development of a GSM based 12-lead mobile EKG device and an embedded communication framework[3]. The development process took nearly two years (from 2004 to 2006), and the project is entering the test phase in 2006.

1.4 Possible Uses of the System

There are three possible uses for such a central telediagnostic system:

1. **Emergency Pre-Hospital Thrombolysis**

The initial treatment of AMI is done by the use of *thrombolytics* to clear a blocked artery and avoid permanent damage to the perfused tissue. These drugs are most effective if administered immediately after it has been determined they are clinically appropriate. As mentioned earlier, the advantage of administration is highest within the first 90 minutes, but may extend up to six hours after the start of symptoms.

The clinical indication for the use of thrombolytics can be determined from ST segment elevations in the patients ECG. If this diagnosis is made before the patient reaches the hospital, valuable time (and heart muscle) can be saved. This is termed as pre-hospital thrombolysis, and recent studies in Europe show that it results in a significant improvement in mortality and morbidity rates of patients suffering from AMI. [4, 5]

2. **Remote Expert Evaluation Service for Medical Practitioners**

   Correctly interpreting ECG is a hard task that requires years of training and experience. Many patients, especially in rural areas, do not have immediate access to an expert cardiologist qualified for ECG interpretation. However, they usually do have access to a medical practitioner with another field of expertise. Such practitioners could benefit from this system to get immediate expert evaluation of their patients ECG.

3. **Monitoring Cardiac Patients Remotely**

   Many cardiac disorders can be diagnosed using ECG before they become symptomatic. If ECG telemetry devices were distributed directly to patients, such a system could also play an important function as a means of their routine monitoring.

A centralized database is also very useful for tracking patient history, and a large amount of accumulated ECG data could also be useful for research purposes.

2. BACKGROUND

2.1 The Human Heart

2.1.1 Anatomy and Physiology of the Heart

The walls of the heart are composed of cardiac muscle, called *myocardium*. It also has striations similar to skeletal muscle. It consists of four compartments: the right and left *atria* and *ventricles*. The heart is oriented so that the anterior aspect is the right ventricle while the posterior aspect shows the left atrium (see Figure 2.1). The atria form one unit and the ventricles another. This has a special importance to the electric function of the heart. The left ventricular free wall and the septum are much thicker than the right ventricular wall. The left ventricle pumps blood to the systemic circulation, where the pressure is considerably higher than that of the pulmonary circulation.

The cardiac muscle fibers are oriented spirally and are divided into four groups: Two groups of fibers wind around outside of both ventricles. Beneath these fibers a third group winds around both ventricles. Beneath these fibers a fourth group winds only around the left ventricle. The fact that cardiac muscle cells are oriented more tangentially than radially, and that the resistivity of the muscle is lower in the direction of the fiber has importance in *electrocardiography*.

The heart has four valves. Between the right atrium and ventricle lies the tricuspid valve, and between the left atrium and ventricle is the mitral valve. The pulmonary valve lies between the right ventricle and the pulmonary artery, while the aortic valve lies in the outflow tract of the left ventricle (controlling flow to the aorta).

The blood returns from the systemic circulation to the right atrium and from there goes through the tricuspid valve to the right ventricle. It is ejected from the

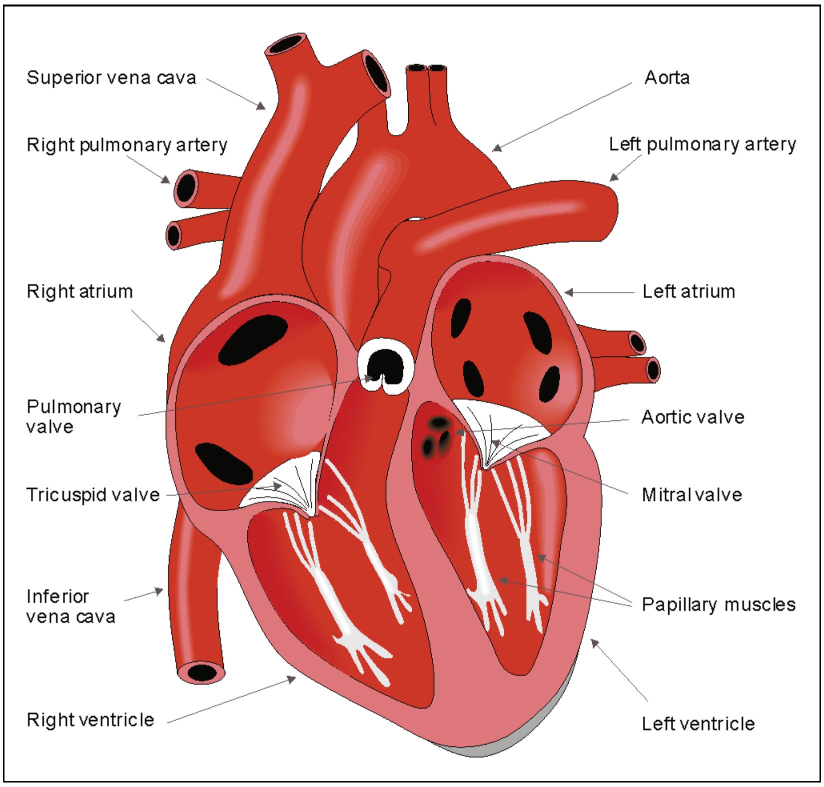


Figure 2.1 The anatomy of the heart.

right ventricle through the pulmonary valve to the lungs. Oxygenated blood returns from the lungs to the left atrium, and from there through the mitral valve to the left ventricle. Finally blood is pumped through the aortic valve to the aorta and to the systemic circulation.

2.1.2 The Conduction System of the Heart

The heart beats spontaneously. It shows an inherent rhythmicity which is independent of any external nerve supply. Located in the right atrium at the superior vena cava is the sinus node (*sinoatrial* or SA node) which consists of specialized muscle cells. The SA nodal cells are self-excitatory, pacemaker cells. They generate an action potential at the rate of about 70 per minute. From the sinus node, activation propagates throughout the atria, but cannot propagate directly across the boundary between atria and ventricles.

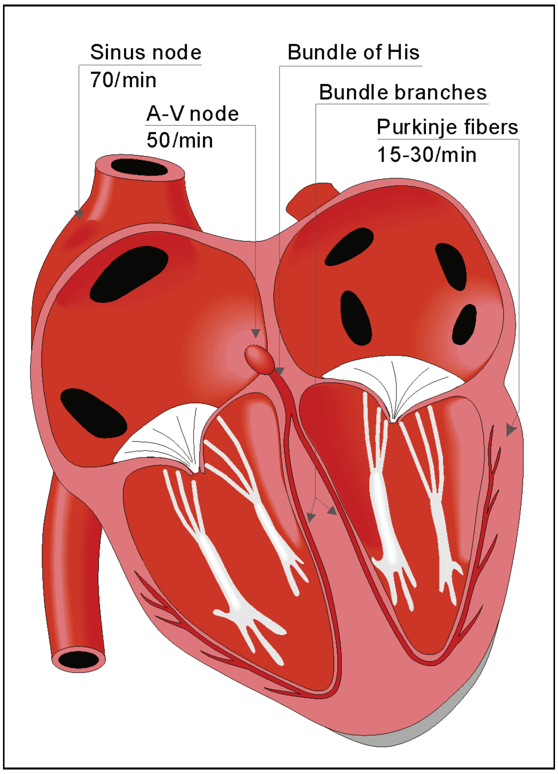


Figure 2.2 The conduction system of the heart.

The *atrioventricular* node (AV node) is located at the boundary between the atria and ventricles; it has an intrinsic frequency of about 50 pulses/min. However, if the AV node is triggered with a higher pulse frequency, it follows this higher frequency. In a normal heart, the AV node provides the only conducting path from the atria to the ventricles.

Propagation from the AV node to the ventricles is provided with a specialized conduction system. This system is composed of a bundle, called the bundle of His. More distally, it separates into the right and left bundle branches. The bundles finally form the *Purkinje* fibers that diverge to the inner sides of the ventricular walls. Propagation along the conduction system takes place at a relatively high speed once it is within the ventricular region, but prior to this the velocity is extremely slow.

From the inner side of the ventricular wall, the many activation sites cause the formation of a wavefront which propagates through the ventricular mass toward the outer wall. This process results from cell-to-cell activation. After each ventricular muscle region has depolarized, repolarization occurs. Repolarization is not a propagating phenomenon, and because the duration of the action impulse is much shorter at the *epicardium* (the outer side of the cardiac muscle) than at the *endocardium* (the inner side of the cardiac muscle), the termination of activity appears as if it were propagating from epicardium toward the endocardium.

2.2 The Electrocardiogram

An electrocardiogram is a graphic produced by an electrocardiograph, which records the electrical voltage of the heart in the form of a continuous strip graph. It is the prime tool in cardiac electrophysiology, and has a prime function in screening and diagnosis of cardiovascular diseases. The electrical measurements are made using electrodes connected to the patients limbs and chest. The standard 12-lead EKG consists of three *limb leads*, three *augmented leads*, and six *precordial leads*. These leads are summarized in Table 2.1

Table 2.1
List of Standard ECG Leads

Lead Name	Description
I	Limb lead I
II	Limb lead II
II	Limb lead III
aV_R	Augmented lead R
aV_L	Augmented lead L
aV_F	Augmented lead F
V_1	Precordial lead 1
V_2	Precordial lead 2
V_3	Precordial lead 3
V_4	Precordial lead 4
V_5	Precordial lead 5
V_6	Precordial lead 6

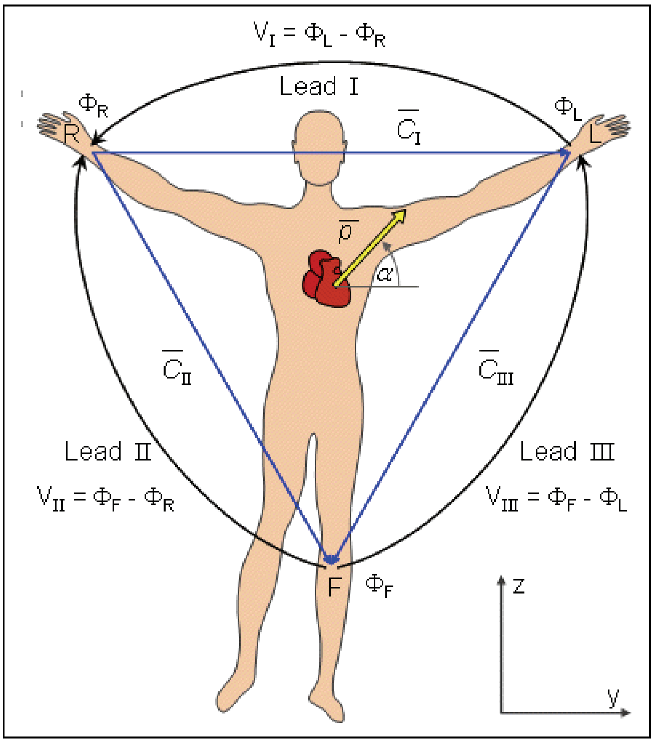


Figure 2.3 Einthoven limb leads and Einthoven triangle. The Einthoven triangle is an approximate description of the lead vectors associated with the limb leads.

2.2.1 Limb Leads

In 1908 Willem Einthoven published a description of the first clinically important ECG measuring system[6]. The Einthoven lead system is shown in Figure 2.3.

The Einthoven *limb leads* (standard leads) are defined in the following way:

$$\begin{aligned} \text{Lead I} &: V_I = \Phi_L - \Phi_R \\ \text{Lead II} &: V_{II} = \Phi_F - \Phi_R \\ \text{Lead III} &: V_{III} = \Phi_F - \Phi_L \end{aligned} \tag{2.1}$$

According to Kirchhoff's law these lead voltages have the following relationship:

$$V_I + V_{III} = V_{II} \tag{2.2}$$

hence only two of these three leads are independent.

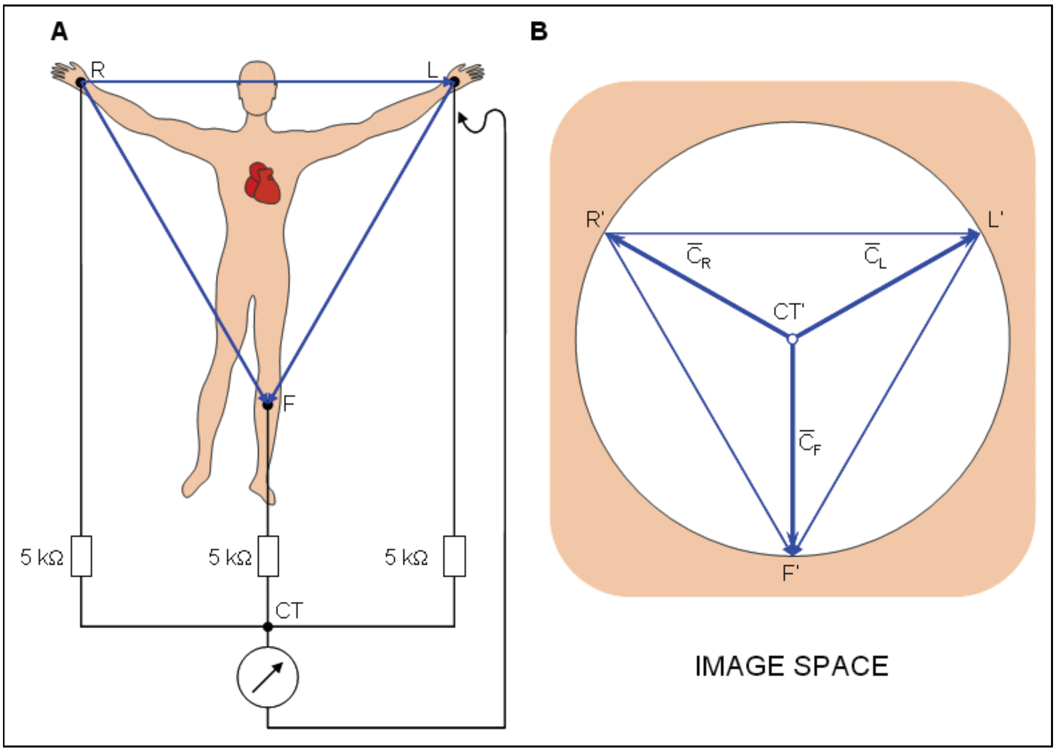


Figure 2.4 (A) The circuit of the Wilson central terminal (CT). (B) The Wilson central terminal is located in the center of the Einthoven triangle.

2.2.2 Wilson Central Terminal

To measure electrocardiographic unipolar potentials, the measurement must be made with respect to a remote reference (∞). To achieve this, Wilson et al. [7] suggested the use of the *central terminal* as this reference. This was formed by connecting a 5 kΩ resistor from each terminal of the limb leads to a common point called the central terminal (see Figure 2.4A). Wilson suggested that unipolar potentials should be measured with respect to this terminal which approximates the potential at infinity. The central terminal potential is the average of the extremity potentials, hence:

$$\Phi_{CT} = \frac{\Phi_R + \Phi_L + \Phi_F}{3} \tag{2.3}$$

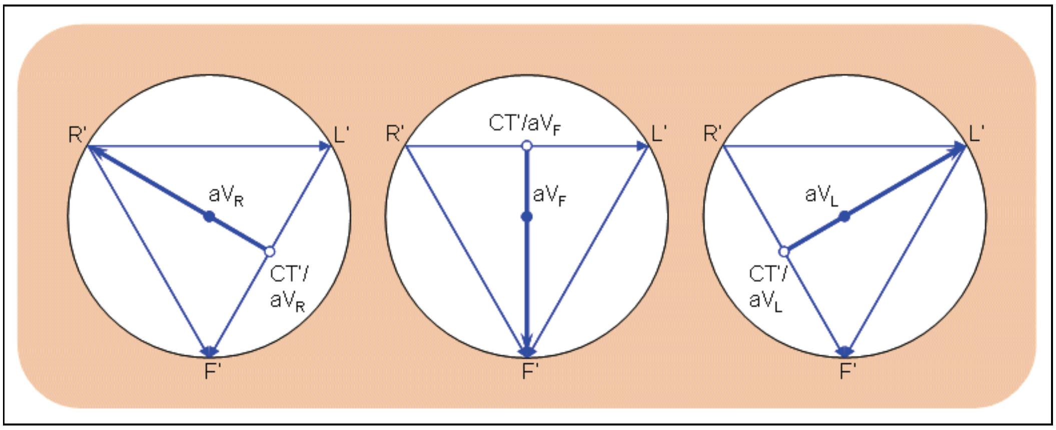


Figure 2.5 The location of the augmented lead vectors

2.2.3 Augmented Leads

Three additional limb potentials, V_R, V_L, and V_F are obtained by measuring the potential between each limb electrode and CT. These potentials are given by:

$$\begin{aligned} V_R = \Phi_R - \Phi_{CT} &= \frac{2\Phi_R - \Phi_L - \Phi_F}{3} \\ V_L = \Phi_L - \Phi_{CT} &= \frac{2\Phi_L - \Phi_R - \Phi_F}{3} \\ V_F = \Phi_F - \Phi_{CT} &= \frac{2\Phi_F - \Phi_R - \Phi_L}{3} \end{aligned} \tag{2.4}$$

These leads can be *augmented* by omitting the resistor on the corresponding limb electrode. This gives the set of augmented leads aV_R, aV_L, and aV_F:

$$\begin{aligned} V_{aV_R} = \Phi_R - \frac{\Phi_L + \Phi_F}{2} &= \frac{2\Phi_R - \Phi_L - \Phi_F}{2} \\ V_{aV_L} = \Phi_L - \frac{\Phi_R + \Phi_F}{2} &= \frac{2\Phi_L - \Phi_R - \Phi_F}{2} \\ V_{aV_F} = \Phi_F - \frac{\Phi_R + \Phi_L}{2} &= \frac{2\Phi_F - \Phi_R - \Phi_L}{2} \end{aligned} \tag{2.5}$$

Figure 2.5 gives the vector representations of the augmented leads.

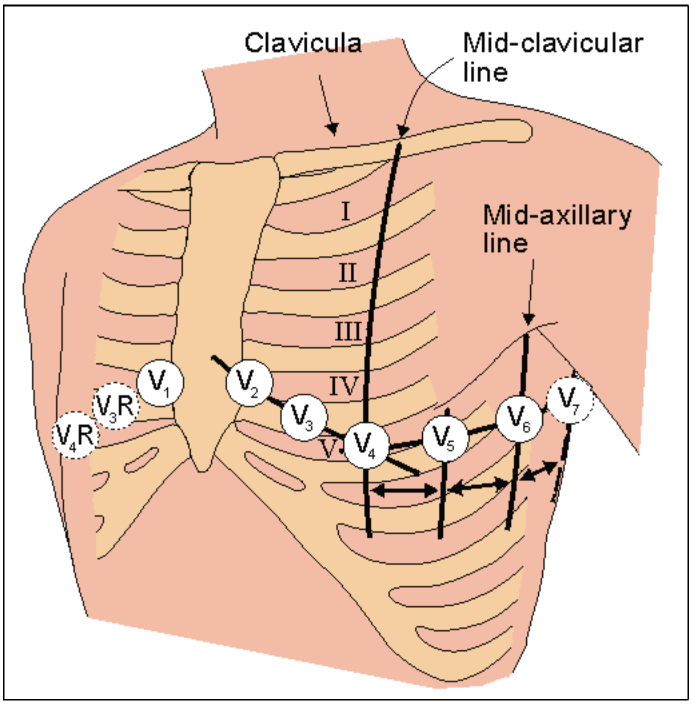


Figure 2.6 The placement of the precordial lead electrodes

2.2.4 Precordial Leads

To measure close-heart potentials, six additional electrodes are placed on the chest [8] as seen on Figure 2.6. The potential of these precordial leads, termed as V_1, V_2, V_4, V_5, and V_6, are measured with respect to the Wilson central terminal. Hence, the lead potential for precordial lead V_n is given by:

$$V_{V_n} = \Phi_{V_n} - \Phi_{CT}, \quad n = 1 \ldots 6 \tag{2.6}$$

2.2.5 Deriving the 12-lead EKG

There is a high level of redundancy in the first six leads of the 12-lead ECG. Any two of these leads can be used to calculate the other four. As a result, recording from eight different locations (two limb electrodes and six precordial electrodes) referenced to the left leg is sufficient derive the 12-lead ECG.

These eight leg-referenced potentials are given by:

$$\begin{aligned} V_{RF} &= \Phi_R - \Phi_F \\ V_{LF} &= \Phi_L - \Phi_F \\ V_{V_nF} &= \Phi_{V_n} - \Phi_F, \quad n = 1 \ldots 6 \end{aligned} \tag{2.7}$$

By using Equations 2.1, we get:

$$\begin{aligned} V_I &= V_{LF} - V_{RF} \\ V_{II} &= -V_{RF} \\ V_{III} &= -V_{LF} \end{aligned} \tag{2.8}$$

And the augmented leads are given by:

$$\begin{aligned} V_{aV_R} &= \frac{2V_{RF} - V_{LF}}{2} \\ V_{aV_L} &= \frac{2V_{LF} - V_{RF}}{2} \\ V_{aV_F} &= -\frac{V_{RF} + V_{LF}}{2} \end{aligned} \tag{2.9}$$

Finally, the precordial leads are given by:

$$V_{V_n} = V_{V_nF} - \frac{V_{RF} + V_{LF}}{3}, \quad n = 1 \ldots 6 \tag{2.10}$$

2.2.6 The Normal ECG

A typical ECG tracing of a normal heartbeat consists of a P wave, a QRS complex and a T wave (see figure 2.7). A small U wave is not normally visible.

The following short list is included to give an idea of various ECG measurements and corresponding diagnosis.

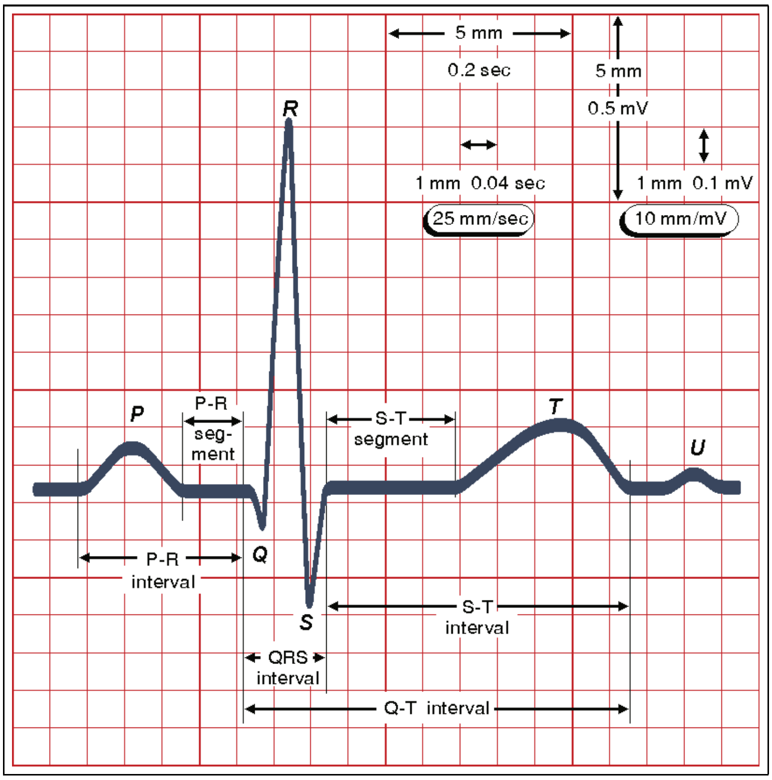


Figure 2.7 Schematic representation of normal ECG trace and standard ECG grid.

- **Axis**

  The axis is the general direction of the electrical impulse through the heart. It is usually directed to the bottom left (normal axis: -30^o to $+90^o$), although it can deviate to the right in very tall people and to the left in obesity.

  - Extreme deviation is abnormal and indicates a bundle branch block, ventricular hypertrophy or (if to the right) pulmonary embolism.
  - It also can diagnose dextrocardia or a reversal of the direction in which the heart faces, but this condition is very rare and often has already been diagnosed by something else (such as a chest X-ray).

- **P wave**

  The P wave is the electrical signature of the current that causes atrial contraction. Both the left and right atria contract simultaneously. Its relationship to QRS complexes determines the presence of a heart block.

  - Irregular or absent P waves may indicate arrhythmia.

  - The shape of the P waves may indicate atrial problems.

- **QRS**

  The QRS complex corresponds to the current that causes contraction of the left and right ventricles, which is much more forceful than that of the atria and involves more muscle mass, thus resulting in a greater ECG deflection. The duration of the QRS complex is normally less than or equal to 0.10 second. The Q wave, when present, represents the small horizontal (left to right) current as the action potential travels through the interventricular septum.

  - Very wide and deep Q waves do not have a septal origin, but indicate myocardial infarction that involves the full depth of the myocardium and has left a scar. The R and S waves indicate contraction of the myocardium itself.
  - Abnormalities in the QRS complex may indicate bundle branch block (when wide), ventricular origin of tachycardia, ventricular hypertrophy or other ventricular abnormalities.
  - The complexes are often small in pericarditis or pericardial effusion.

- **T wave**

  The T wave represents the repolarization of the ventricles. The QRS complex usually obscures the atrial repolarization wave so that it is not usually seen. Electrically, the cardiac muscle cells are like loaded springs. A small impulse sets them off, they depolarize and contract. Setting the spring up again is repolarization (more at action potential). In most leads, the T wave is positive.

  - Inverted (also described as negative) T waves can be a sign of disease, although an inverted T wave is normal in V_1 (and V_2 - V_3 in African-Americans/Afro-Caribbeans).
  - T wave abnormalities may indicate electrolyte disturbance, such as hyperkalemia or hypokalemia. The ST segment connects the QRS complex and the T wave.
  - This segment ordinarily lasts about 0.08 second and is usually level with the PR segment. Upward or downward displacement may indicate damage to

the cardiac muscle or strain on the ventricles. It can be depressed in ischemia and elevated in myocardial infarction, and upslopes in Digoxin use.

- **U Wave**

  The U wave is not always seen. It is quite small, and follows the T wave by definition. It is thought to represent repolarization of the papillary muscles or Purkinje fibers. Prominent U waves are most often seen in hypokalemia, but may be present in hypercalcemia, thyrotoxicosis, or exposure to digitalis, epinephrine, and Class 1A and 3 antiarrhythmics, as well as in congenital long QT syndrome and in the setting of intracranial hemorrhage. An inverted U wave may represent myocardial ischemia or left ventricular volume overload.

3. SYSTEM ARCHITECTURE

Before examining the individual parts of the system in more detail, the focus on the overall architecture of the system has to be given. As mentioned in Chapter 1, the primary aim of the system is to enable cardiologists to receive 12-lead ECG recordings from ambulatory devices and evaluate them. For maximum efficiency, a single cardiologist should be capable of easily handling multiple calls, while multiple cardiologists should be capable of working at the same call center without interference. A single database should contain all of the patient, recording, diagnosis, device and related information for the whole system. In the future, deployent of multiple call centers should also be possible.

3.1 Design Criteria

The design criteria for the whole system were laid out as follows:

- *Simplicity*: The system must fulfill all of the required functions with minimal complexity and maximal ease of use.
- *Scalability*: The system must easily scale according to needs.
- *Reliability*: The system must be very reliable, as it is an emergency healthcare system.
- *Manageability*: The system must be easily manageable by administrators.

3.2 System Overview

Figure 3.1 shows the general structure of the designed system. Mobile ECG devices connect using a GSM/GPRS network (or a 3G network in the near future) to

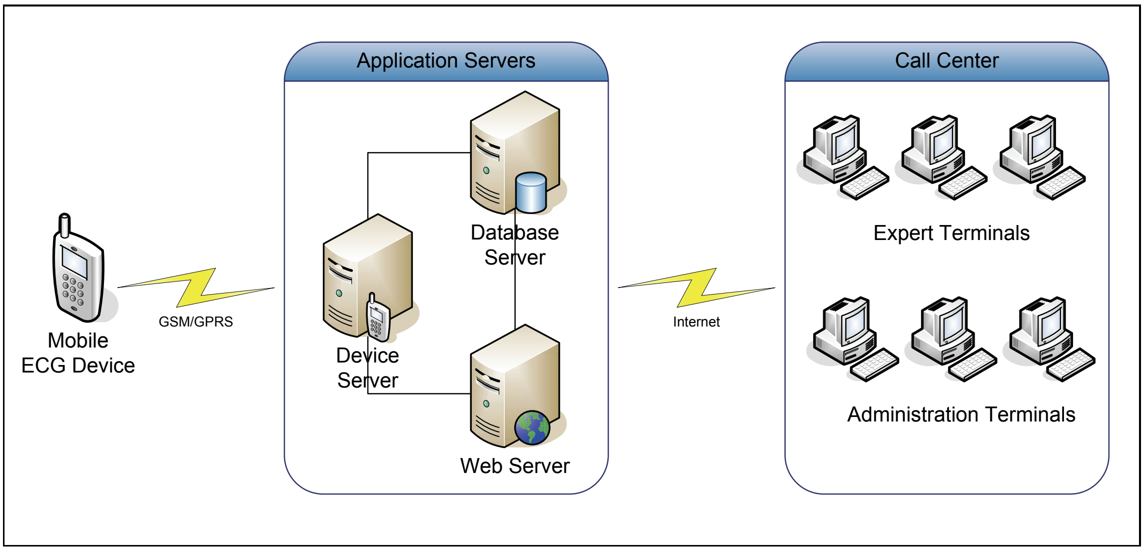


Figure 3.1 Schematic representation of the system.

a device server. The device server is directly connected to a database server and a web server that runs the web services (see the following section). The expert visualization terminals, which are used by cardiologists to evaluate the ECG signals, directly connect to the device server and the web services. The device server acts as a router between ECG device and expert terminals. The administration terminals, which are used to administer the system, use web services to communicate with the database.

The system is thus divided into two distinct application zones (Figure 3.2): the server zone and the call center zone. The device server, database server, and the web server reside within the server zone. These servers may be running on the same physical machine or separate ones. The expert and administration terminals reside within the call center zone. The system allows for an unlimited number of terminals within a call center zone, and multiple call centers can connect to the same server zone. Multiple server zones are not allowed. The server and call center zones can be located at different sites, as long as they are both connected to the internet. Nationwide coverage can be achieved by deploying a single server zone and multiple call centers across different cities.

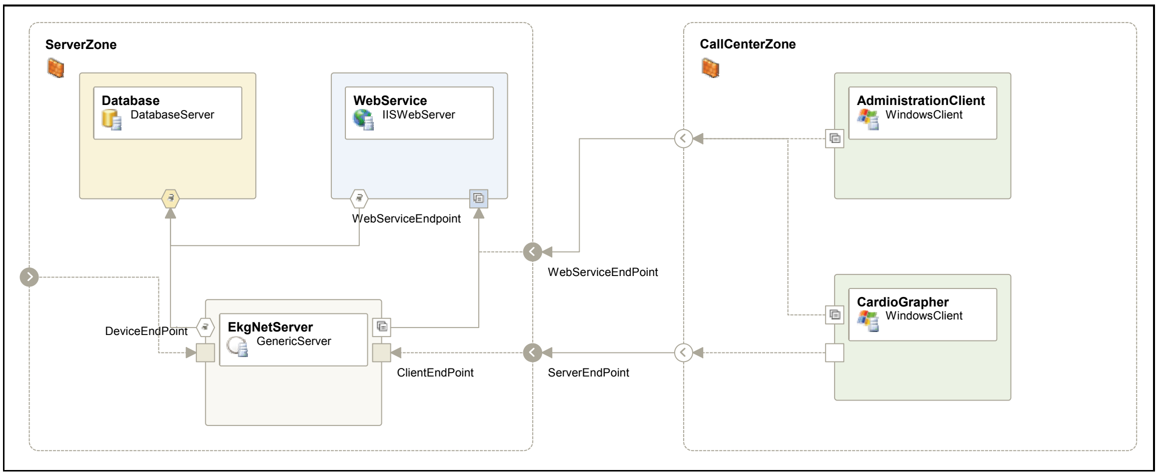


Figure 3.2 Application Zones.

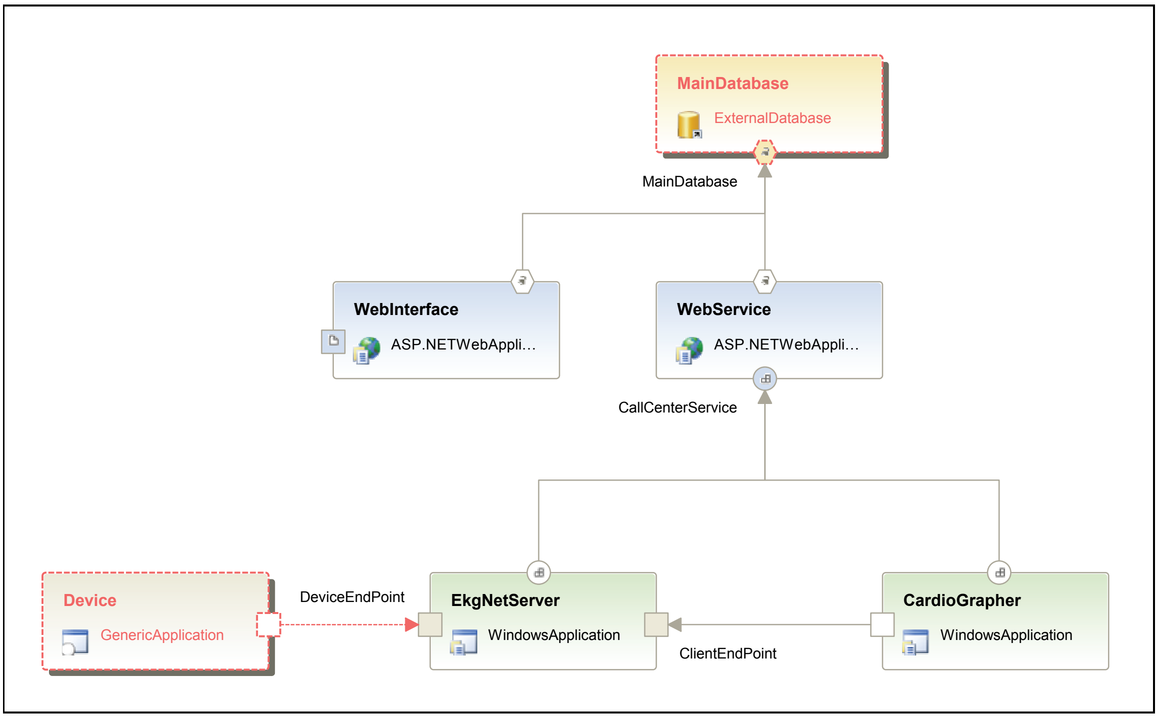


Figure 3.3 Application Diagram.

3.3 Web Services

In this system, web services are used for communication across application zones. Web services utilize the SOAP protocol for machine to machine communication. They provide an easy and secure way of connecting applications over the internet. Since it can be accessed through the web service, the database is not directly open to the internet and stays secure.

3.4 Development Platform and Tools

The software was developed using *Microsoft Visual Studio 2005* and *.Net Framework 2.0*. The programming language used was *C#*, which is a fully object oriented-language similar to *Java* and *C++*. The server software will run on Windows Server 2003, and the client on Windows XP. Microsoft's *SQL Server 2005* was used as an RDBMS (Relational Database Management System). For signal processing and plotting, National Instruments *Measurement Studio 8.01* was used. Measurement Studio is a collection of libraries that can be directly called form a .Net application.

3.5 Software Architecture

Different software components of the system and their relationships (dependencies) are outlined in Figure 3.4 although some of its components are not within the scope of this thesis. The most important of these are: the DSP helper library, the database, and the visualization (expert) application. These components are described in more detail in Chapters 4, 5, and 6.

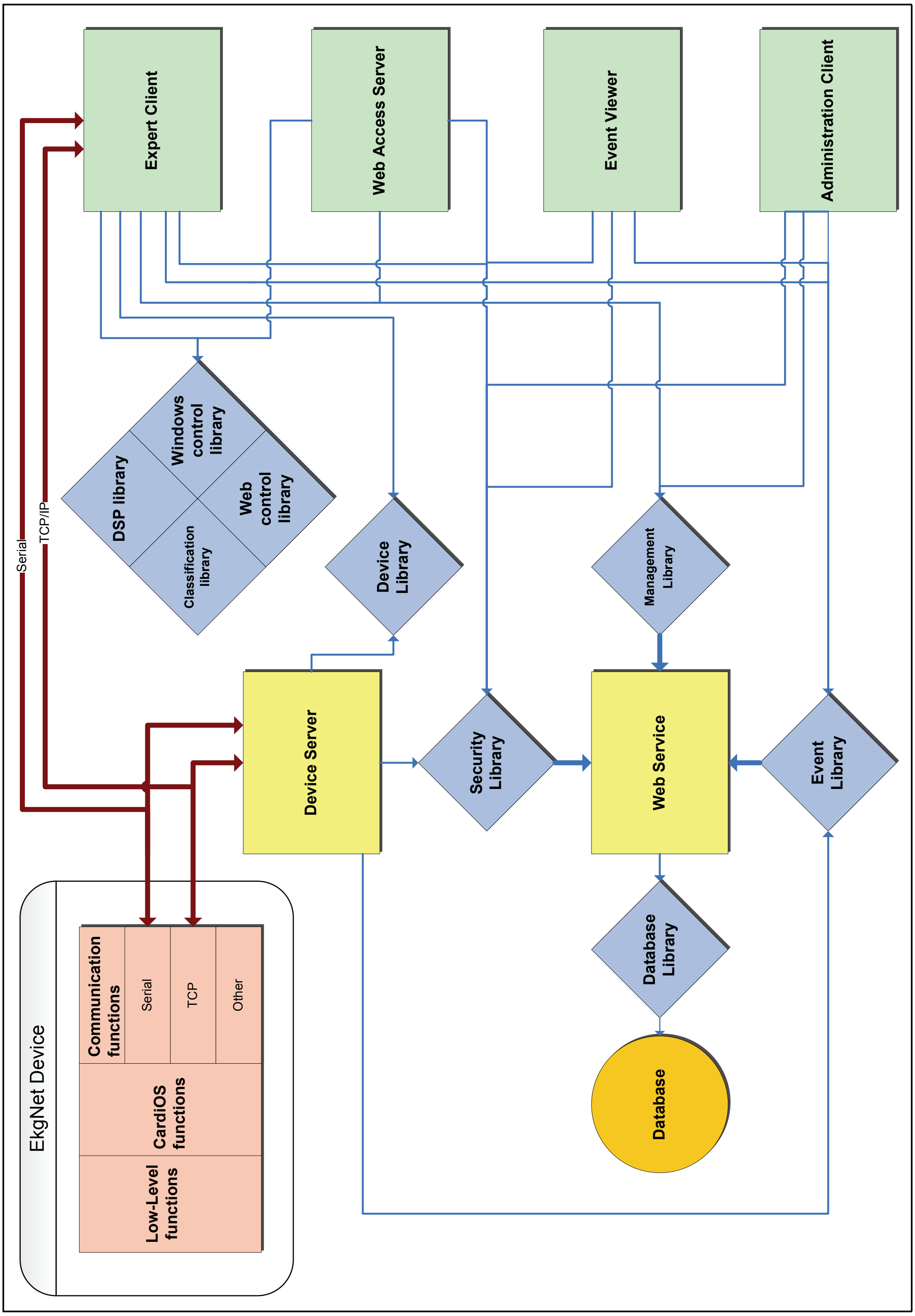


Figure 3.4 General architecture of the software components and their dependencies.

4. DSP HELPER LIBRARY

National Instruments Measurement Studio software was used to process and to visualize signals in this application. This package contains powerful tools for analysis and display of signals. The DSP helper library is designed to provide a framework around Measurement Studio, to build complex signal processing trees in which every unit automatically adapts to changing signal parameters. The library defines signal sources, which generate signals, signal sinks, which consume signals, and filters, which allow signals to pass through them. Only real-valued signals can be processed by this library. Signals are divided into three categories: one dimensional, multidimensional, and multi-channel. Table 4.1 summarizes the namespaces within this library and their functions.

Table 4.1
Namespaces within the DSP library

Namespace	Function
Exvivo.Dsp	Foundation for processing of one dimensional signals
Exvivo.Dsp.Filters	Filter classes classes for one dimensional signals
Exvivo.Dsp.MultiChannel	Foundation for processing of multi channel signals
Exvivo.Dsp.MultiChannel.Filters	Filter classes for multi channel signals
Exvivo.Dsp.MultiDimensional	Foundation for processing of multidimensional signals
Exvivo.Dsp.MultiDimensional.Filters	Filter classes for multidimensional signals
Exvivo.Dsp.Windows.Controls	Windows control wrappers for plotting and charting

4.1 One Dimensional Signals

4.1.1 Signal Interface Definition

The core definition of the DSP helper library is the *ISignal* interface. This interface defines the common properties of a one dimensional signal. Classes that implement this interface (and therefore have all of these properties) will be treated

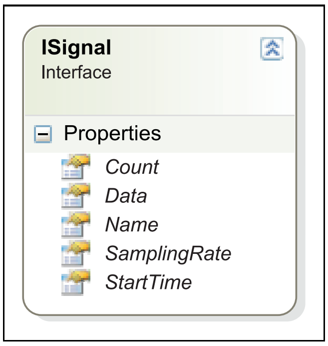


Figure 4.1 ISignal Interface.

as a signal by the other classes within the library. These common properties (see Figure 4.1) include the number of samples within the signal (Count), the time value corresponding to the first sample of the signal (StartTime), the sampling frequency of the signal (SamplingRate), the name of the signal (Name), and the data of the signal as an array of double precision floating point numbers (Data).

Different implementations of the ISignal interface are possible depending on the need. The *BasicSignal* class, for example, provides the most compact and least flexible implementation. The *DynamicSignal*, on the other hand, allows appending signals, signal insertions and removals, and direct manipulation of each sample. Details about these classes can be found in the Appendix A.

4.1.2 Signal Sources and Sinks

Defining a signal is not enough for processing. In any signal processing setup, there is at least one source that (usually periodically) generates signals. The *ISignal-Source* interface defines such signal sources. It exposes two events: *SignalReady* and *Reset*. The SignalReady event is fired whenever the signal source is ready to generate another signal. Signals generated from a source are usually part of a larger continuous signal. Therefore, whenever there is a discontinuity, the Reset event is fired to notify the listeners. Classes that listen to signals from a signal source must implement the *ISignalSink* interface. ISignalSink defines two methods, *Connect()* and *Disconnect()*

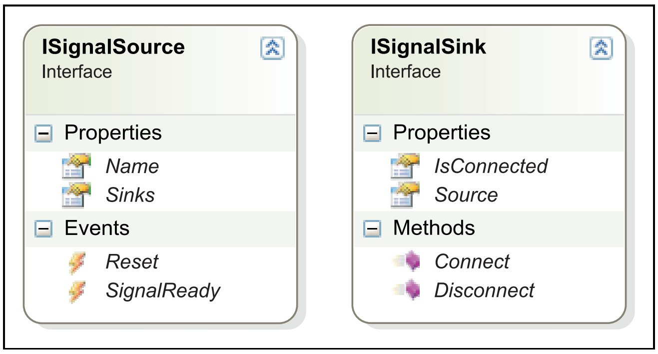


Figure 4.2 ISignalSource and ISignalSink Interfaces.

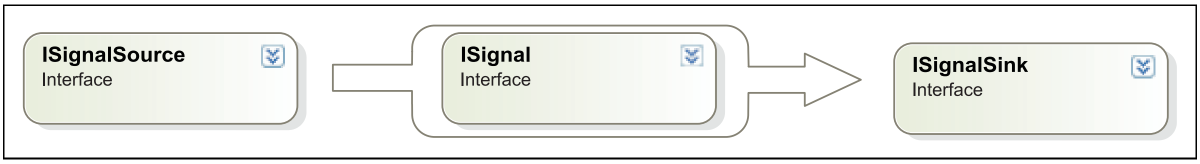


Figure 4.3 Connected Signal Source and Signal Sink.

that allows it to connect to and disconnect from signal sources (see Figures 4.2 and 4.3). Multiple signal sinks can connect to a single signal source, but the inverse is not possible.

In a real signal processing setup, the signal source could be a class that communicates with the data acquisition hardware, and a signal sink could be a class that plots the signal on screen. Another signal sink connected to the same signal source could be responsible for storing the signal data on disk for later use.

4.1.3 Filters

Signal sources and sinks make up the two ends of a processing tree. Without mid-tier units that actually do the processing, such a tree is not complete. Since they connect to signal sources and also produce output signals, such units act both as signal sinks and sources. Therefore the *IFilter* interface encapsulates ISignalSink and ISignalSource interfaces, as shown in Figure 4.4.

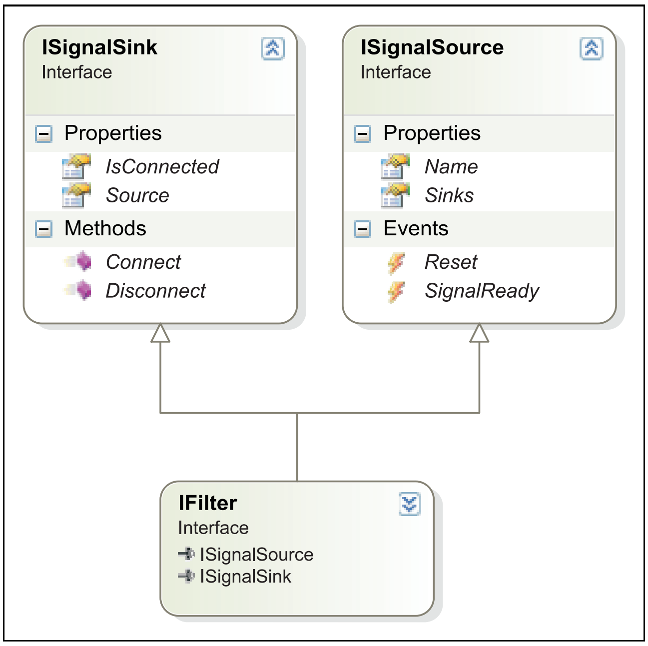


Figure 4.4 IFilter interface.

According to this definition, any class that both consumes and generates signals can act as a filter, including standard IIR or FIR filters, adaptive filters, neural network filters, or wavelet filters. Some filters do not modify the signal, but analyze and annotate it using *Markers*.

The DSP library includes wrapper classes for IIR and FIR filters found in the Measurement Studio. Additional filters can be easily created and integrated into an existing DSP setup.

4.1.4 Special Classes

- **IirFilter and FirFilter Classes**

  These classes automatically design FIR and IIR filters according to requested parameters. Filter type (e.g. Butterworth, Chebyshev, elliptic), filter band type (lowpass, highpass, bandpass, or bandstop), order and other parameters can be specified. The filter is designed when the first signal is received and redesigned whenever the sampling rate of incoming signals changes. Internal filter state is preserved until a reset event occurs. If for some reason the filter cannot be designed, an error event is fired and the filter is disabled until parameters are modified. The filters can also be manually disabled, in which case they just forward the incoming signals to their output.

- **SignalClipper Class**

  The SignalClipper class can clip a signals both length and amplitude if they exceed pre-determined thresholds. Amplitude values exceeding the threshold will be replaced by the threshold value. Time clip behavior can be set to first block or last block, depending on which part of the signal should be clipped if its duration exceeds the threshold value.

- **SignalCounter Class**

  The SignalCounter class can be used to monitor signals generated by a signal source. Once connected, the counter will automatically store and update its *SignalInformation* property whenever new signals are received. The StartTime, Name, and the SamplingRate in the SignalInformation structure will contain the corresponding values of the first signal received after a counter reset, while the Duration and Count values will be the sum of all signals received after a reset.

  Events for automatically resetting the counter can be set using the AutoResetEvent property. By default, the SignalCounter resets on SamplingRateChanged and NameChanged events. A manual reset can also be issued by calling the Reset() method.

- **SignalBuffer Class**

  The signalBuffer class automatically stores multiple signals received from a signal source and combines them in a single signal. The buffer contains an internal SignalCounter, which can be set to reset at a combination of events to retrieve the contents of the buffer.

- **SignalInformation Class**

  The SignalInformation structure is used to store all of the information of a signal except the actual signal data.

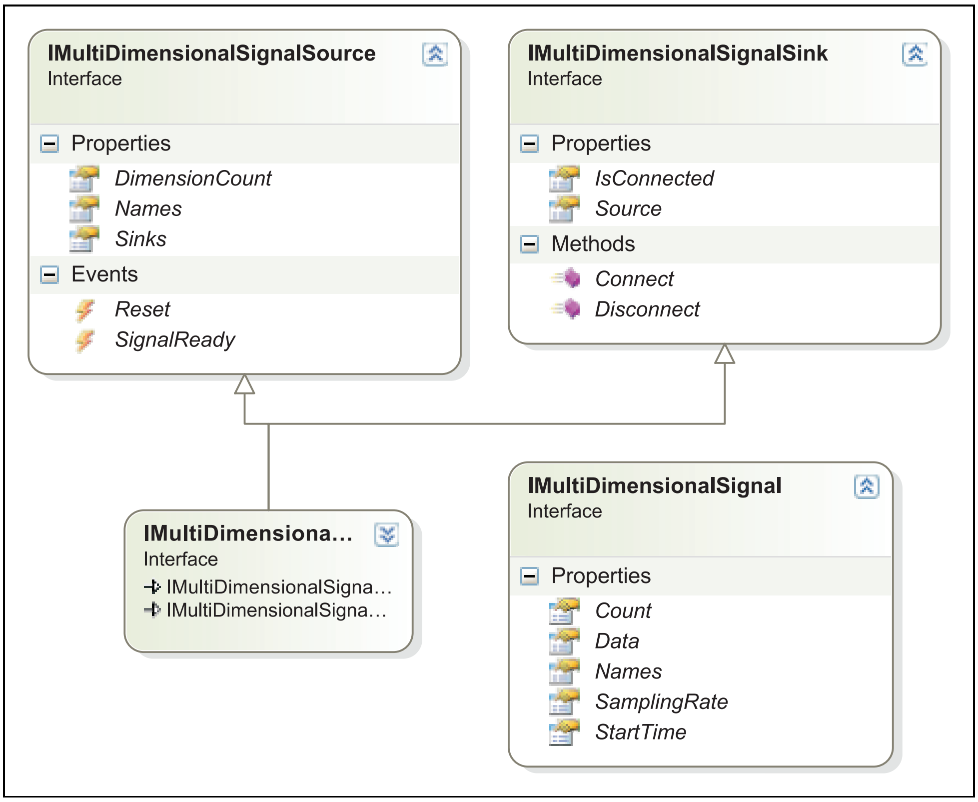


Figure 4.5 Multidimensional Interfaces.

- **SignalOperations Class**

  The SignalOperations class provides static methods for performing certain operations, such as add, subtract, convolve or combine, on one or more signals.

4.2 Multidimensional Signals

Multidimensional signals are similar to one dimensional signals, but they contain multidimensional vectors at each sampling point. 12-lead ECG is an example, where each lead corresponds to a signal dimension. Multidimensional filters operate the same way as one dimensional filters.

4.2.1 Special Classes

- **Transformer Class**

  The *Transformer* class can be used to perform a matrix transformation on a multidimensional signal. Every sample vector is multiplied by a transformation matrix to obtain the output vector. As a result, every output dimension is a linear combination of all input dimensions. An 8 by 12 matrix can be used to transform recorded raw ECG information into 12-lead ECG as described in Chapter 2. Montages in EEG is another example for matrix transformations.

- **TransformationMatrix Class**

  The *TransformationMatrix* class represents the transformation matrices to be used by the Transformer class.

- **BasicMultiDimensionalBuffer**

  The *BasicMultiDimensionalBuffer* class is similar to the SignalBuffer class in its function. It stores incoming multidimensional signals until a reset condition is met, at which time it appends these signals to produce a single signal.

4.3 Multi-channel Signals

Multi-channel Signals are bundles of single dimensional signals. They must not share the same properties as long as they are related and acquired roughly at the same time. An example would be the output of a patient monitor, which includes pulse oximeter, blood pressure, and ECG signals. Multidimensional signals can be converted to multi-channel signals, but not vice-versa.

Use of multi-channel signals and filters help in performing the same processing operations on a series of signals.

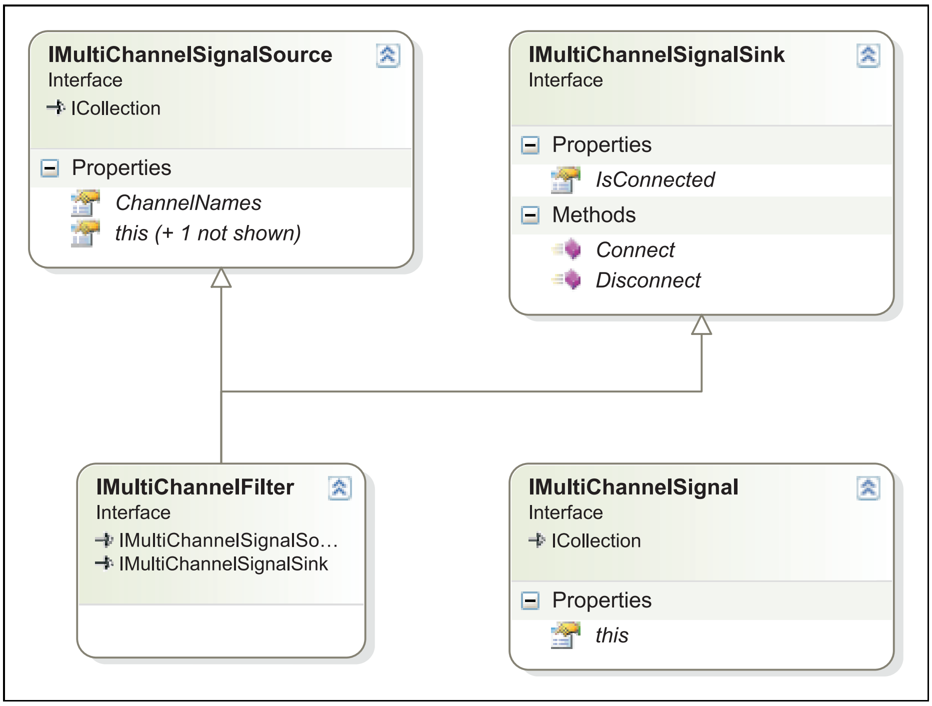


Figure 4.6 Multi-channel interfaces.

4.3.1 Special Classes

- **Demuxer Class**

  The *Demuxer* class converts Multi-dimensional signals into multi-channel signals. Each dimension is converted into a one dimensional signal, and then bundled together to form a multi-channel signal.

- **IirMultiChannelFilter Class**

  The *IirMultiChannelFilter* class creates multiple IirFilter objects using the same parameters and connects them to a multi-channel signal.

5. DATABASE

Storing only ECG data, patient data, and diagnosis results is not sufficient to maintain a remote diagnosis service. Device information, user information (experts and administrators), server information and settings should also be kept in the database. Database tables are summarized in Table 5.1. Details about certain table groups are given in the following sections.

5.1 Table Structure

5.1.1 Device Related Tables

Tracking device status is important for maintaining the system. The location and current status is every device is stored. Faulty devices that have to be serviced can be tracked using the service table.

5.1.2 Patient and ECG Related Tables

General information regarding a patient, such as name and gender, is stored within the Patients table. Specific information, such as past surgical operations, is stored within PatientData. Every patient have multiple associated PatientData entries. Diagnosis results of each session is also associated with PatientData.

ECG recordings are stored as binary information within the Recordings table. Multiple recordings received from the same device in the same session are grouped as recording sessions in the Sessions table. Every recording session has one or more related diagnosis reports, associated with a single patient. All related information such as the user who made the diagnosis and the device that was used, is also recorded.

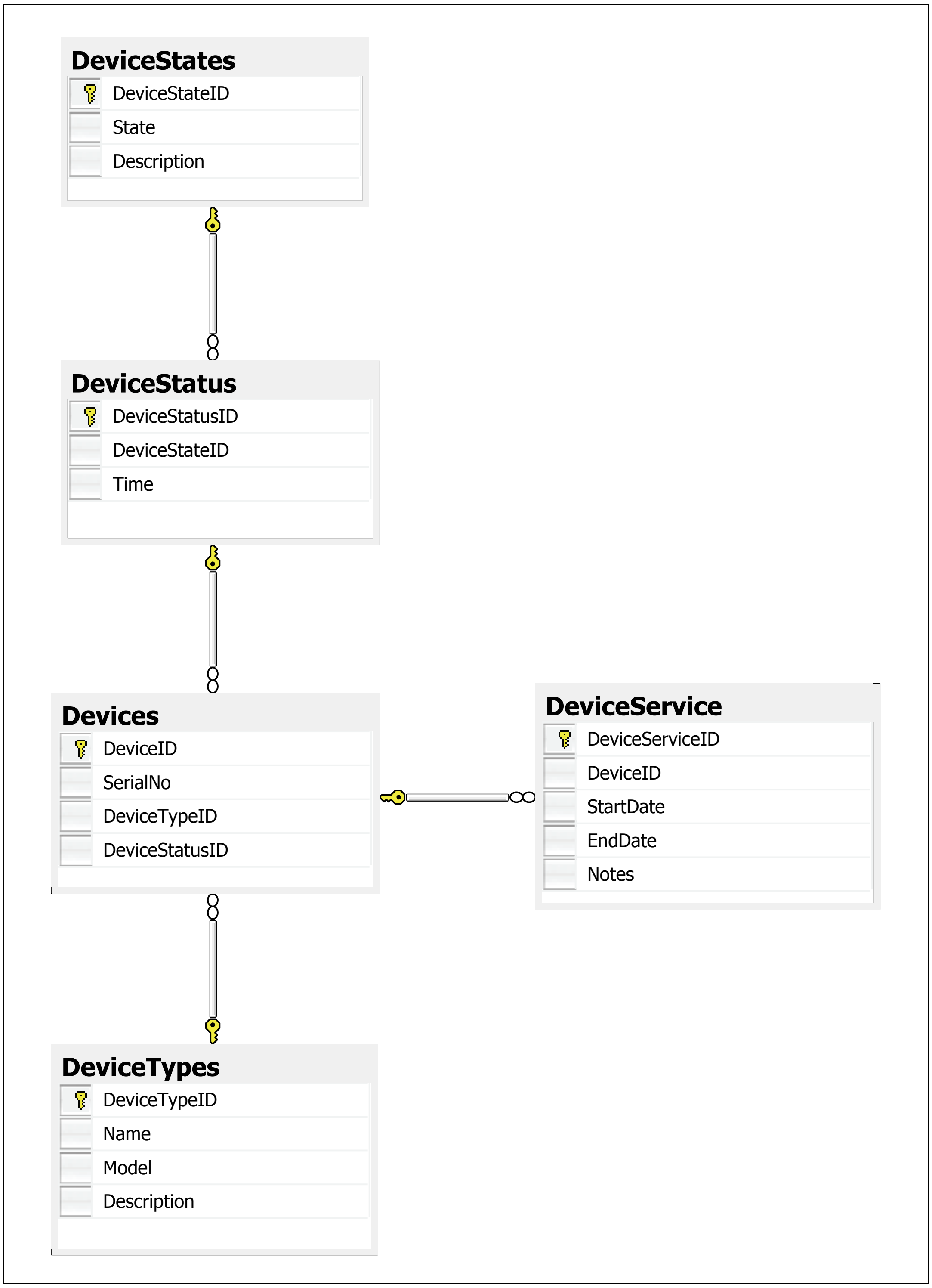


Figure 5.1 Device Related Tables.

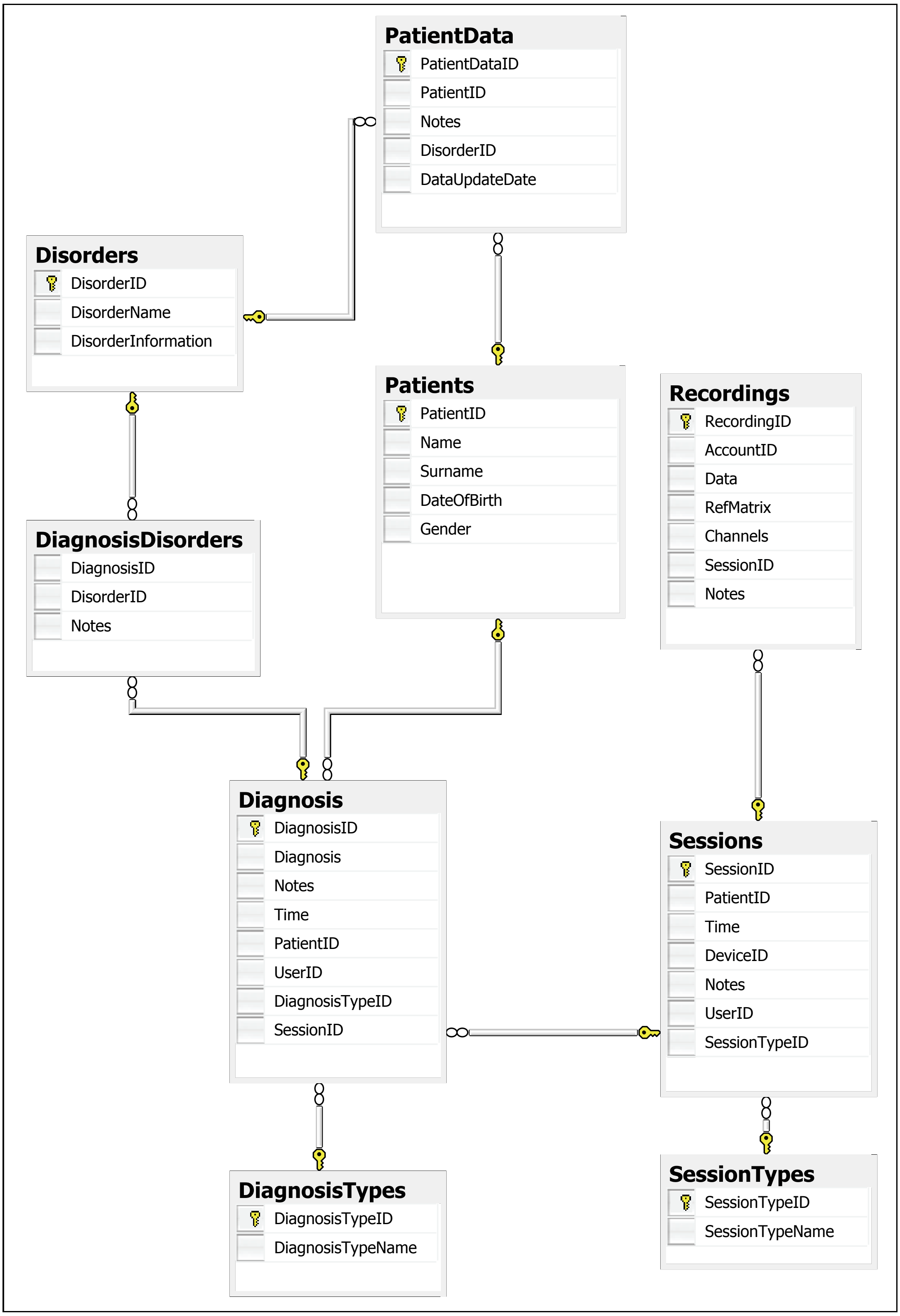


Figure 5.2 Patient Related Tables.

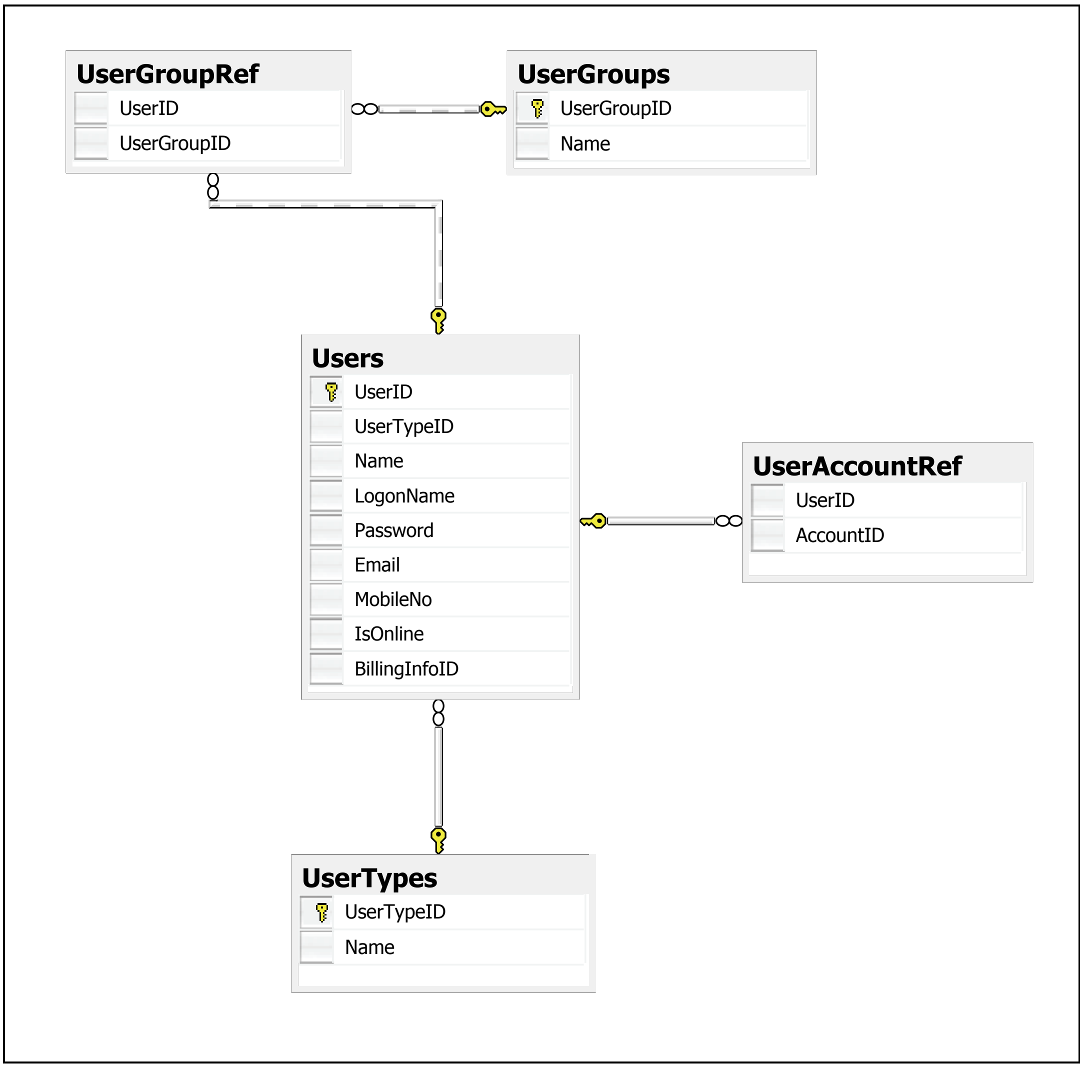


Figure 5.3 User Related Tables.

5.1.3 User Related Tables

Users of the system will be administrators responsible for maintenance, and experts responsible for handling calls. UserGroups table is used to group these user in different categories. Users can be member of multiple groups. Role-based security can later be implemented based on these tables.

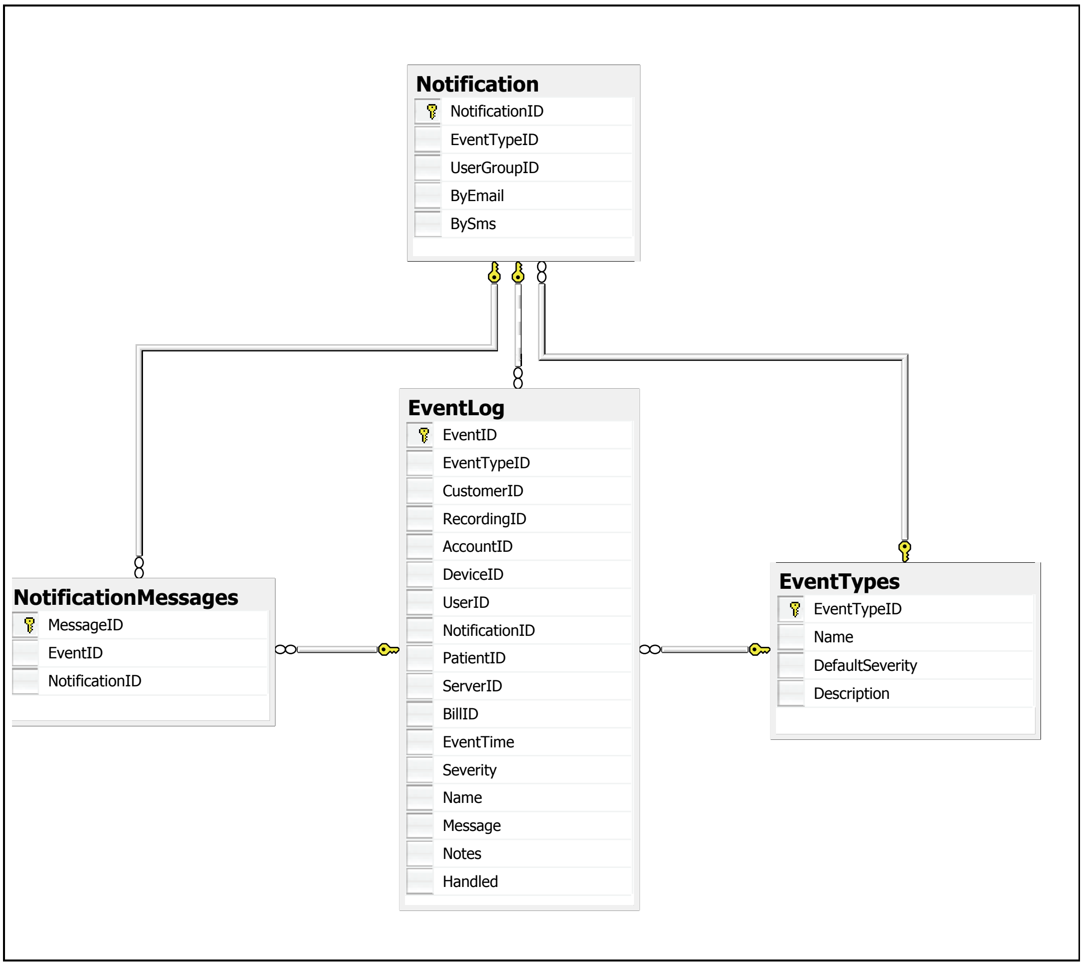


Figure 5.4 Eventlog and Notification Related Tables.

5.1.4 Eventlog and Notification System

The eventlog and the notification system is a crucial part of the database. Every event in the systems life cycle, including incoming device calls or new ECG recordings, user logons, or software failure, is stored in the event log. According to event types and severity, users or user groups can be subscribed to receive notifications. These notification subscriptions are stored in the notification table. Notification messages could be sent as email or SMS messages. This system can be used to alert administrators of a critical system failure.

5.2 Data Access Layer

The data access layer provides necessary classes and methods for the application to access and manipulate the data stored in the database. For this system, the classes within the Teknofil.EkgNet.Data namespace and the web service constitute the data access layer. All of the query codes are within the data access layer. If for some reason the RDBMS is to be changed, only the data access layer has to be rewritten.

Table 5.1
List of Tables Within the Database

Table Name	Content
Devices	Device information
DeviceService	Device servicing information
DeviceStates	List of possible device states
DeviceStatus	List of possible device statuses
DeviceTypes	List of possible device types
Diagnosis	Diagnosis information
DiagnosisDisorders	Diagnosis - disorder relationship
DiagnosisTypes	List of possible diagnosis types
Disorders	List of cardiac disorders
EventLog	Main event log
EventTypes	List of possible event types
Notification	Notification membership table
NotificationMessages	Notification messages
PatientData	Specific patient information
Patients	General patient information
Recordings	ECG recording information
Servers	List of application servers
ServerStates	List of possible server states
ServerStatus	List of possible server statuses
Sessions	ECG recording sessions
SessionTypes	List of possible session types
UserGroupRef	User - user group relationship
UserGroups	List of user groups
Users	User information
UserTypes	User types

6. VISUALIZATION APPLICATION

The visualization application is composed of two main interfaces: the call center interface and the grapher interface. The application is fully configurable using XML configuration files, and stores each users personal preferences separately. The code for the complete application spans several namespaces, as summarized in Table 6.1. Details regarding each namespace is given in the following sections.

Table 6.1
Namespaces within the Visualization Application

Namespace	Function
Teknofil.EkgNet.Application	Classes that make up the main application logic.
Teknofil.EkgNet.Device	Classes and interfaces for controlling remote ECG devices
Teknofil.EkgNet.Dsp	ECG specific extensions to the DSP library
Teknofil.EkgNet.Settings	Classes for managing application settings
Teknofil.EkgNet.Windows.Controls	ECG specific windows controls
Teknofil.EkgNet.Windows.CardioGrapher	The actual application

6.1 Device Namespace

The Device namespace contains the *Device* class, which sends commands to the actual ECG device, and interprets its responses. The Device class communicates using the IChannel interface. An instance of this interface, the RemoteChannel class, enables TCP/IP based communication. Other implementations of this interface could be used for different communication methods, such as USB or RS-232. This namespace also contains other device specific classes and enumerations.

6.2 Dsp Namespace

The DSP namespace contains the *IEkgDecoder* interface and implementing classes for decoding data received from a device into proper multidimensional signals. It also contains the *IEkgSignalSource* interface required by the EkgGraph control.

6.3 Settings Namespace

The settings namespace contains classes for storing and retrieving application settings. It also handles the serialization and deserialization of these settings to and from XML files.

6.4 Windows Controls Namespace

6.4.1 EkgPlot Control

The *EkgPlot* control inherits from the SignalPlot control in the DSP helper library. Its function is to draw a single ECG trace on a specific area of the graph. It has ECG specific properties, such as lead name and plot settings. It contains an internal SignalCounter for displaying signal duration, an internal filter socket for optionally filtering the signal, and a SignalClipper to keep the drawn signal within its boundaries.

6.4.2 EkgGraph Control

The *EkgGraph* control is the main control of the grapher interface. It collects the data from the signal source, arranges the EkgPlot objects according to the selected layout settings, applies the style, handles printing, and manages zooming, panning and measurement.

IChannel

↓

Device

↓

IEkgDecoder

⇓

BasicMultiDimensionalBuffer

⇓

Transformer

⇓

Demuxer

↓↓↓

IEkgSignalSource

↓↓↓

EkgGraph

Figure 6.1 Flow of Signals in the CardioGrapher Application.

6.5 Application Namespace

This namespace contains the *SessionManager* class, which creates the necessary classes and connections, and runs the application logic. Figure 6.1 shows the individual classes that are connected and arranged by SessionManager. The data is first received through a class that implements the IChannel interface (in the case of a TCP/IP connection, this class is RemoteChannel), then it passes through the device class, which is sent to an appropriate IEkgDecoder. The SessionManager determines the correct decoder from the device configuration. For example, an ECG device configured to use 16-bit simple differential encoding (the differences between samples, instead of the actual sample values are sent as 16-bit integers), would require an instance of the DifferentialEkgDecoder class. The decoder outputs multidimensional signals, which are stored in a buffer and passed on to a matrix transformer to be converted into 12-lead ECG. The demuxer converts the multidimensional signal into a multi-channel signal, which is then filtered and plotted by the EkgGraph class.

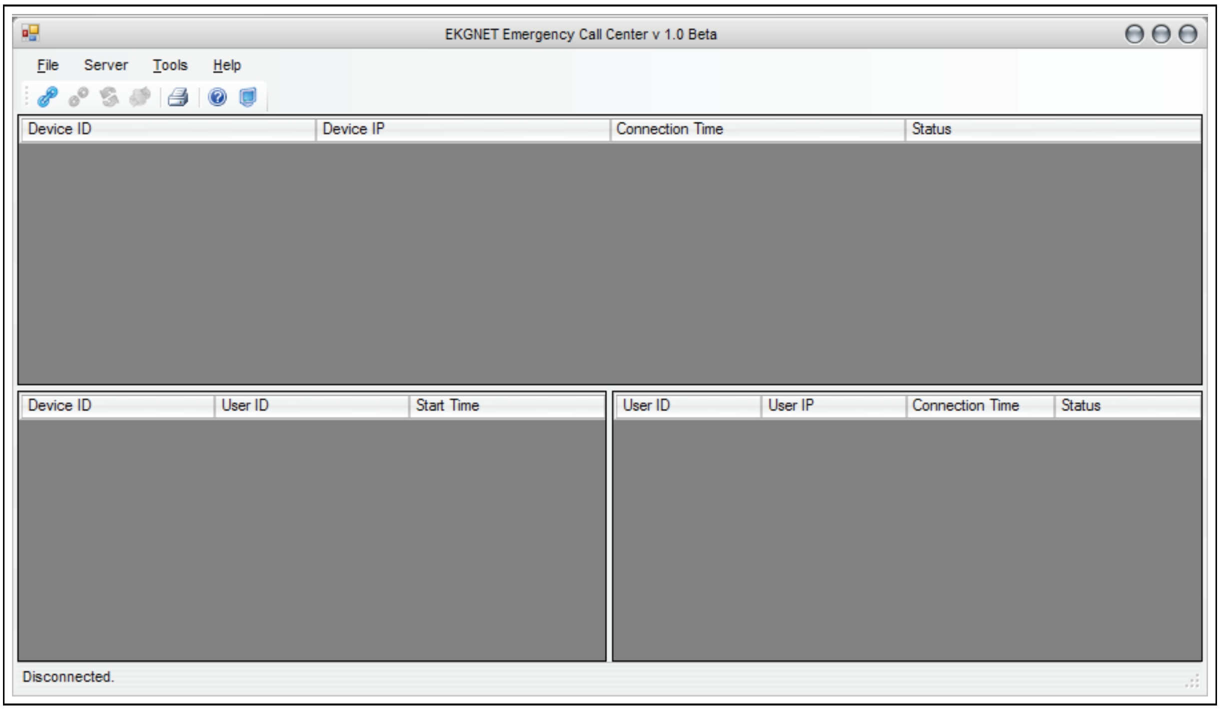


Figure 6.2 Screenshot of the Call Center Interface.

6.6 CardioGrapher Namespace

6.6.1 Call Center User Interface

The call center user interface is the starting point for the application. The interface is separated into three fields (see Figure 6.2). The larger field shows currently connected devices awaiting evaluation. The smaller lists show currently ongoing recording sessions and connected users (cardiologists). Using the toolbar or the menu, the user can choose to connect to or disconnect from the web service. While connected, the form periodically polls the web service to update its lists. The user can also choose to manually refresh the lists. The web service address and port are user configurable.

The main component of the call center interface is the *ServerStatusGrid* Control. It is a databound Windows.Forms control that accepts server status information (devices, sessions, and users) as a typed dataset, formats it, and displays it accordingly.

The CardioGrapher interface can be launched by double-clicking on one of the available devices in the device list, in which case it is automatically connected to the device. CardioGrapher can also be directly launched using the appropriate button on the toolbar.

6.6.2 CardioGrapher User Interface

This is the main ECG evaluation interface. The majority of the form is dedicated to the graphing area (see Figure 6.3). The interface contains remote control buttons for the ECG device. Using these buttons and menus, the user can request an ECG recording from the connected device by specifying a signal duration, sampling rate, and recording delay. The recording delay is used to signal the device to wait before starting acquisition, which may be required to prevent EM noise from the GSM antenna from interfering with the signal.

The layout of the graph can be fully customized. Any row - column combination of any duration can be chosen to display the ECG data. Individual cells can be arranged in any fashion, and can span multiple rows. The same ECG lead can be displayed on multiple cells, and some leads can be omitted. The user can choose one of the preset layout options anytime.

As with layout, every aspect of the style of the graph can also be customized. Some options include graph background color, line style, color and width for individual leads, major and minor grid styles and intervals, font, color, size and position of lead labels, and lead boundaries. The interface also gives the user the ability to choose one of the preset graph styles.

The user also has the ability to enable or disable the filters, zoom in and pan on any area of the graph and use the ruler to make measurements (see Figure 6.4).

When a new recording is started, the form automatically switches to on line mode, and the ECG signal is shown on screen gradually as it is received. Once the recording is complete, the form switches to review mode, and the user can scroll back to see the complete recording. The recording can then be stored or printed in high-resolution mode.

The user can also choose to open the evaluation form, through which patient and related diagnosis information can be entered (see Figure 6.5).

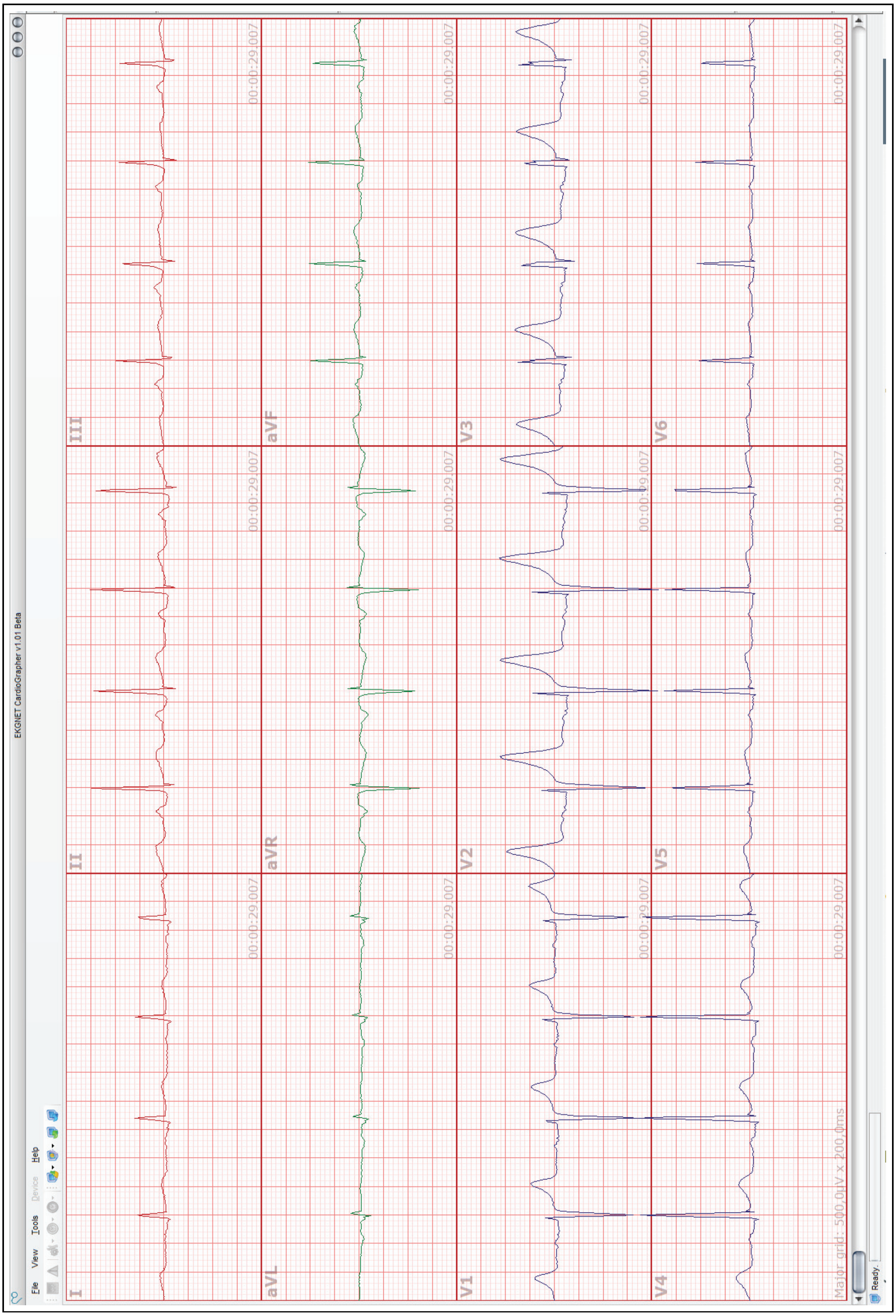


Figure 6.3 Screenshot of the CardioGrapher Interface.

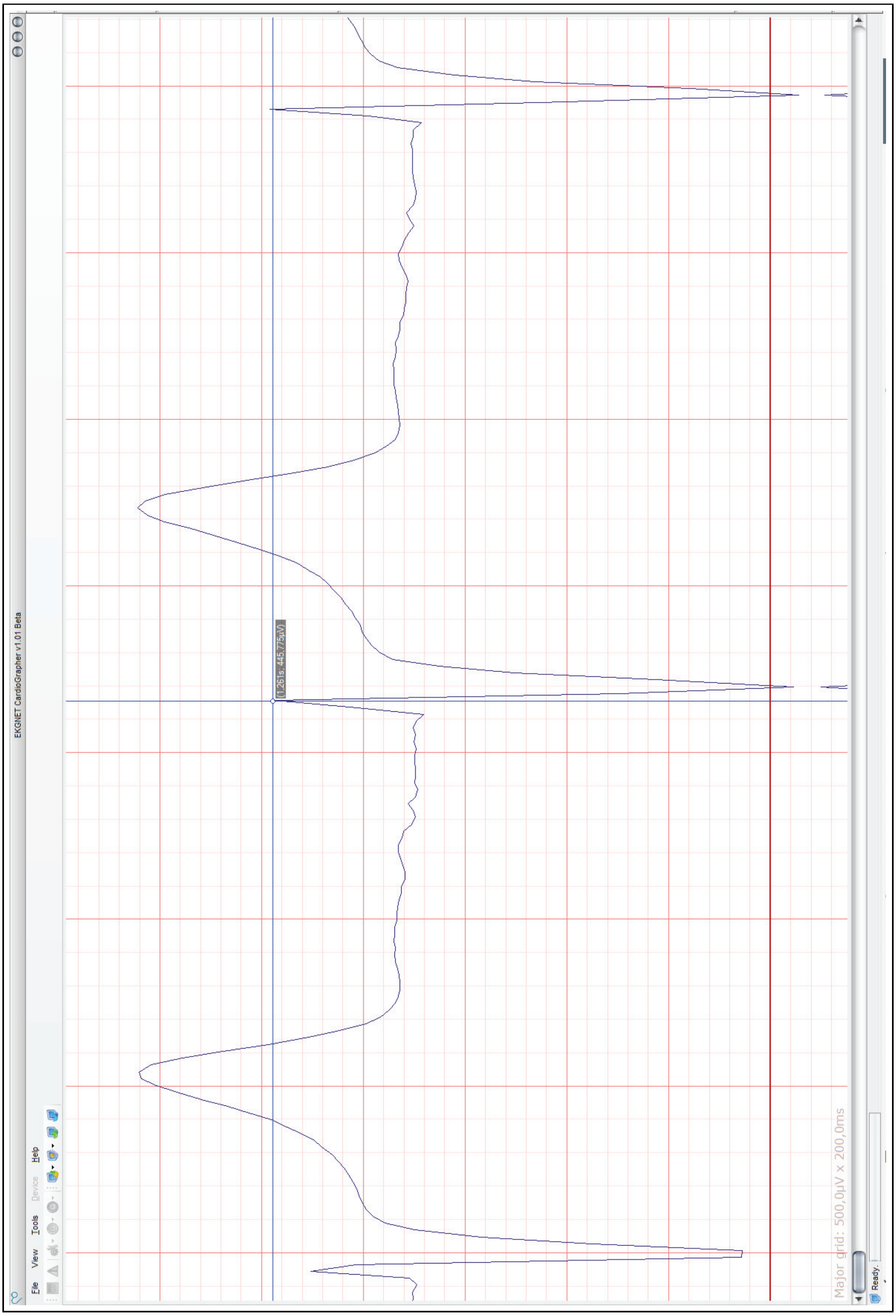


Figure 6.4 Screenshot of the CardioGrapher Interface (Zoomed in on Signal).

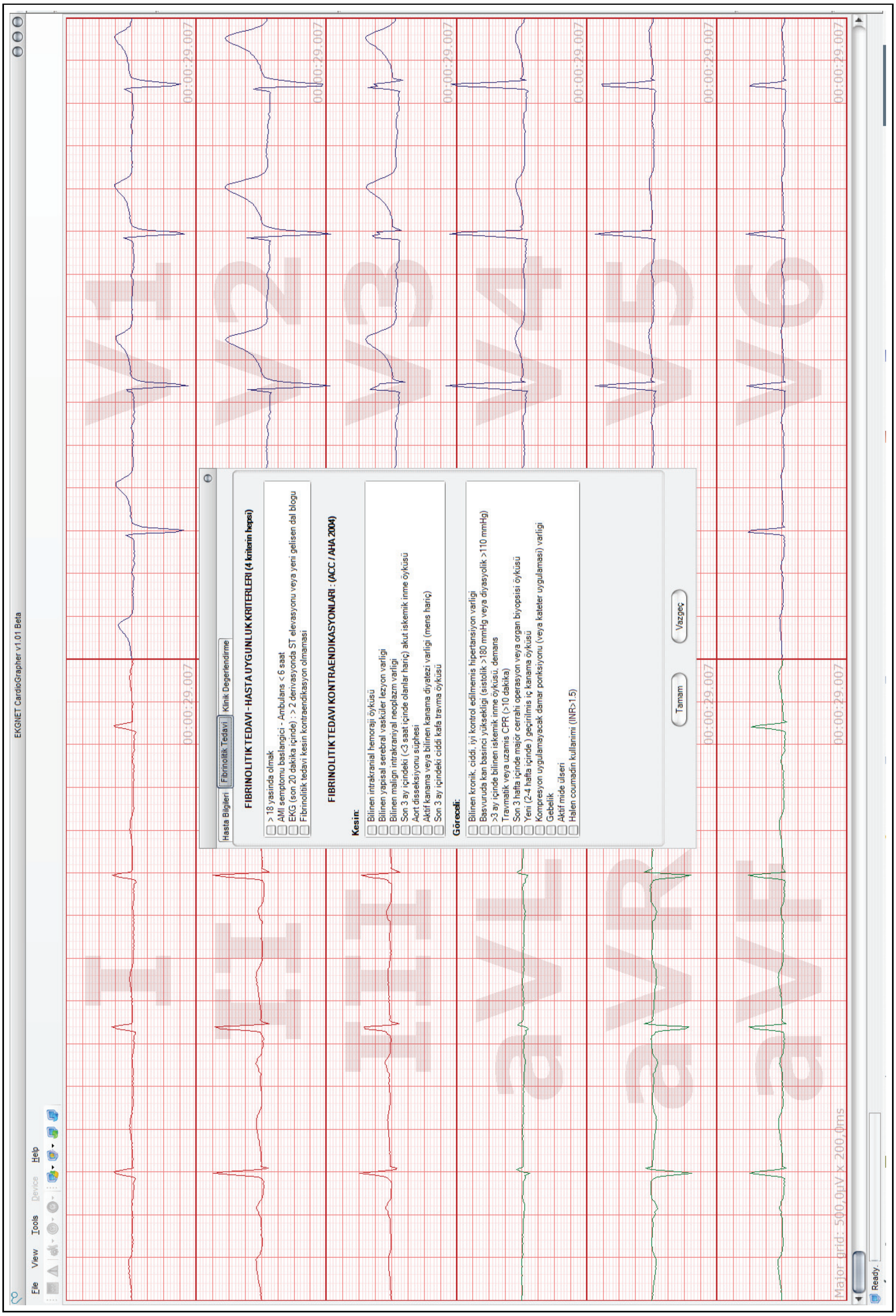


Figure 6.5 Screenshot of the CardioGrapher Interface (With the evaluation form).

7. DISCUSSIONS and CONCLUSIONS

Combined with the mobile ECG devices of the EKGNET project, the software performs very well in retrieving ECG signals and displaying them for evaluation. Several cardiologists were shown the application asked for their opinion. They found the signal quality and the interface highly sufficient for diagnosis. In fact, EKGNET delivers higher quality electrocardiograms than most of the currently available clinical ECG systems.

However, in order to become a complete tele health care system, crucial additions have to be made to the software that were left outside the scope of this thesis. These additions can be summarized as:

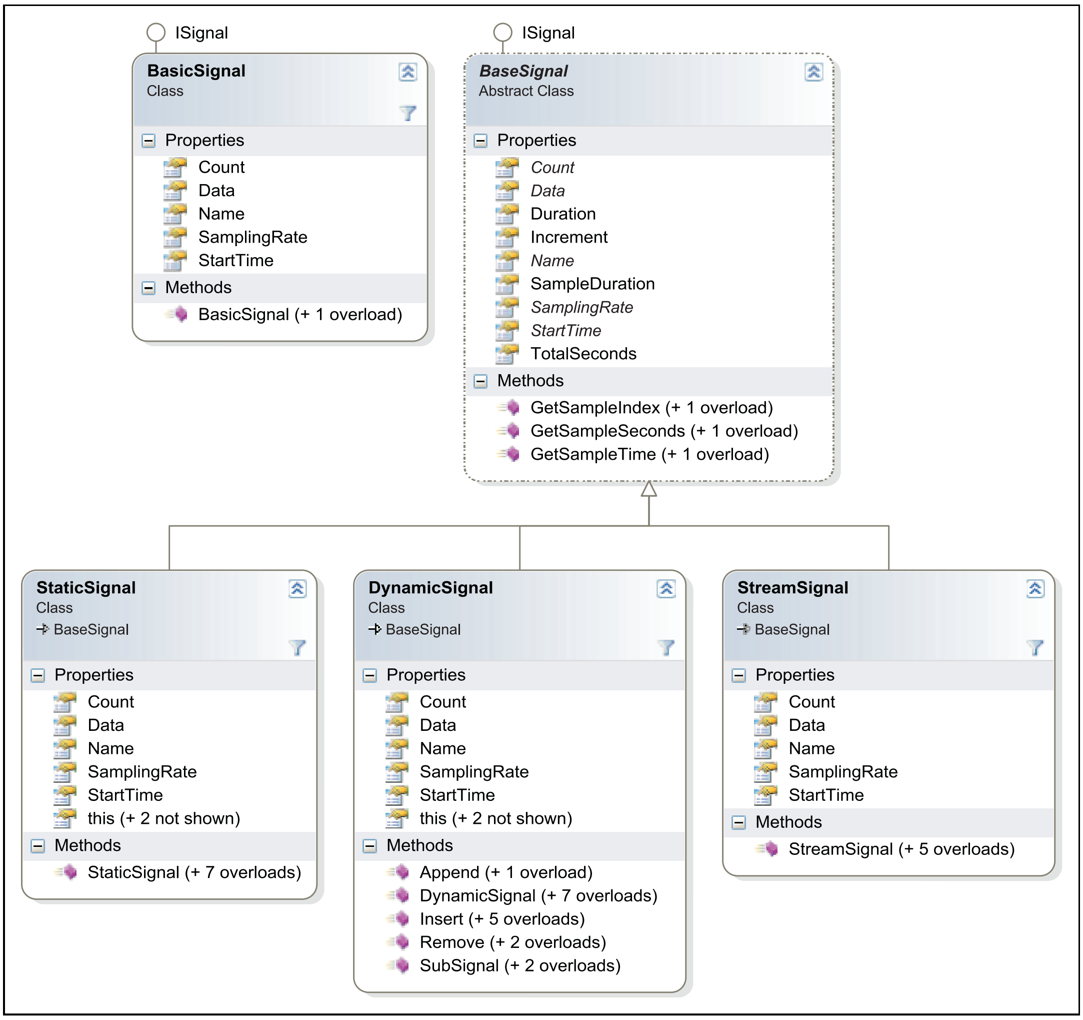
- **Security**: Currently, there is no user authentication system. The database is designed to incorporate role-based security, but it was not implemented on the user interface. Full user authentication and authorization is required to ensure system security.
- **User Interfaces**: Although many parts of the application is customizable, these settings can only be manipulated by editing XML files. Full visual user interfaces are required for changing graph settings, filters and other settings.
- **More Sophisticated Filters**: Currently, certain factors, especially muscle movement artifacts, seriously degrade the signal quality. Considering that the system will be used frequently in non-ideal recording conditions, this could become a severe obstacle in diagnosis. More sophisticated filtering methods, such as adaptive filters, should be implemented to increase signal quality.
- **Automatic Measurement and Diagnosis**: The software could be extended for detecting certain disorders and abnormalities, such as arrhythmia or ST segment elevation. Although these functions are not necessary, they could play an important role in assisting the experts in making a rapid diagnosis.

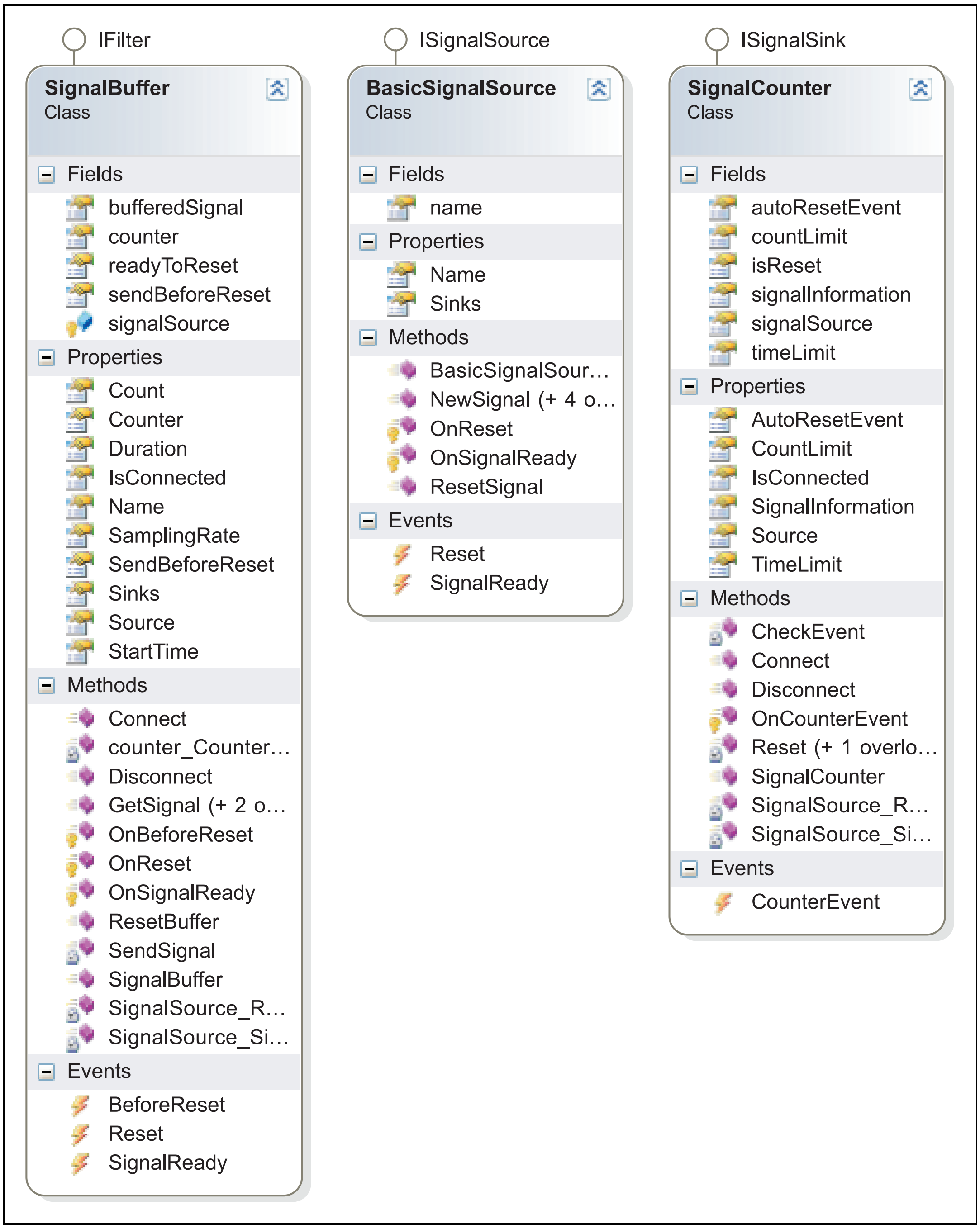
With these additions, the system will fill a very important gap in the current health care infrastructure and a significant improvement in reducing the mortality and morbidity rates especially for AMI patients will be expected with its wide use.

APPENDIX A. CLASS DIAGRAMS

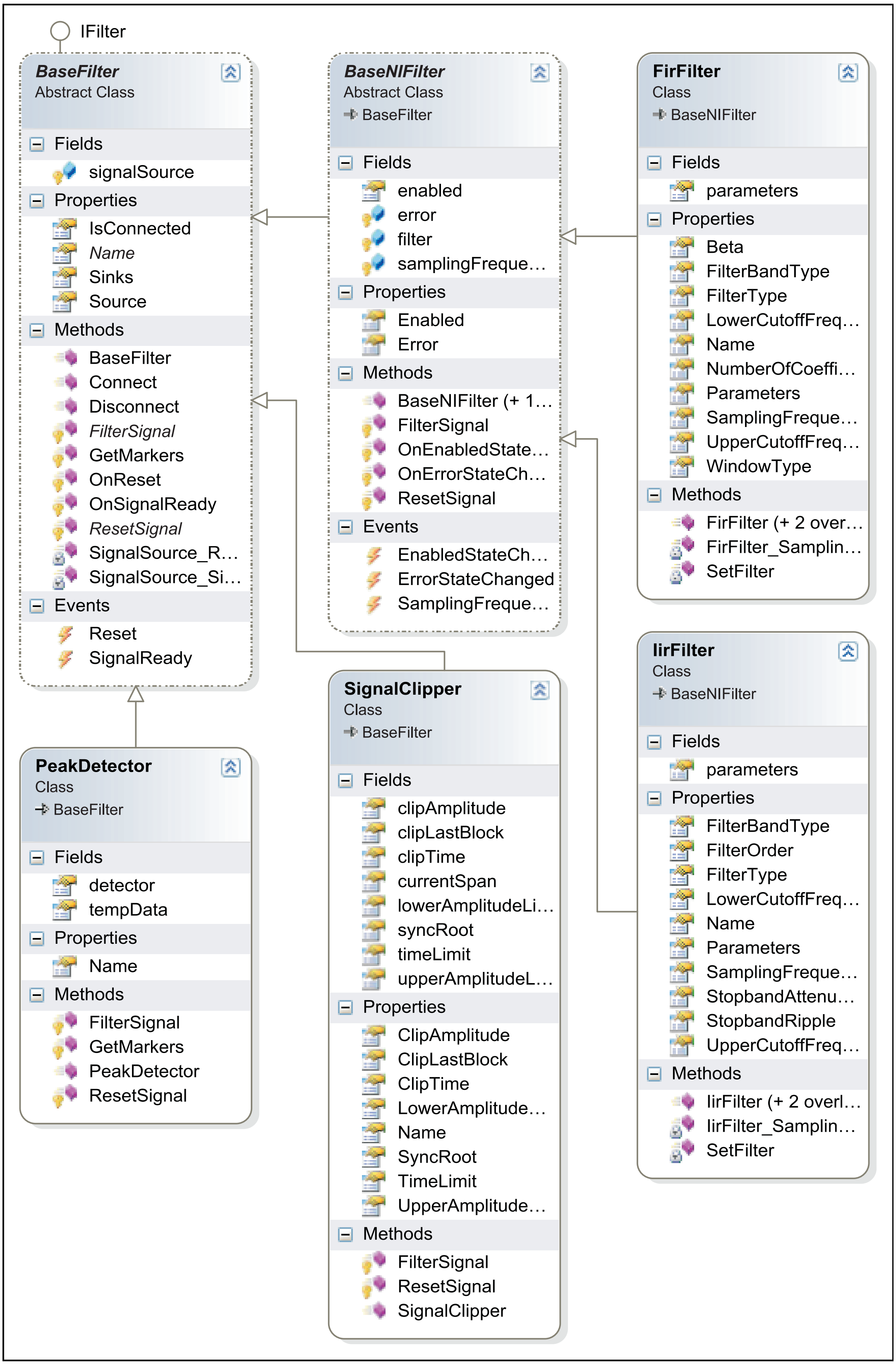
The following class diagrams show the organization and members of important classes within the project.

A.1 Exvivo.Dsp Namespace

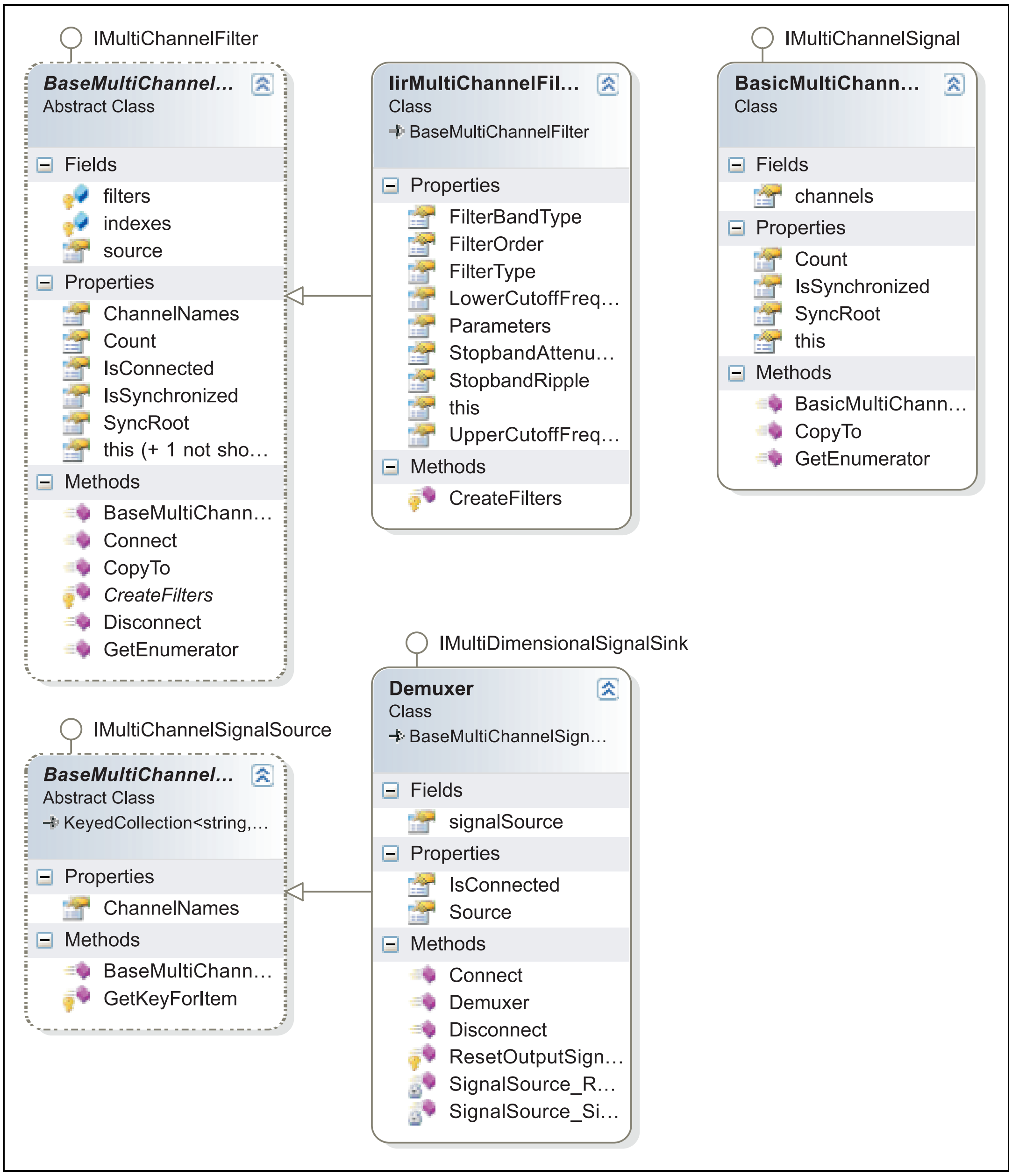



IFilter
SignalBuffer
Class
Fields
bufferedSignal
counter
readyToReset
sendBeforeReset
signalSource
Properties
Count
Counter
Duration
IsConnected
Name
SamplingRate
SendBeforeReset
Sinks
Source
StartTime
Methods
Connect
counter_Counter…
Disconnect
GetSignal (+ 2 o…
OnBeforeReset
OnReset
OnSignalReady
ResetBuffer
SendSignal
SignalBuffer
SignalSource_R…
SignalSource_Si…
Events
BeforeReset
Reset
SignalReady
ISignalSource
BasicSignalSource
Class
Fields
name
Properties
Name
Sinks
Methods
BasicSignalSour…
NewSignal (+ 4 o…
OnReset
OnSignalReady
ResetSignal
Events
Reset
SignalReady
ISignalSink
SignalCounter
Class
Fields
autoResetEvent
countLimit
isReset
signalInformation
signalSource
timeLimit
Properties
AutoResetEvent
CountLimit
IsConnected
SignalInformation
Source
TimeLimit
Methods
CheckEvent
Connect
Disconnect
OnCounterEvent
Reset (+ 1 overlo…
SignalCounter
SignalSource_R…
SignalSource_Si…
Events
CounterEvent

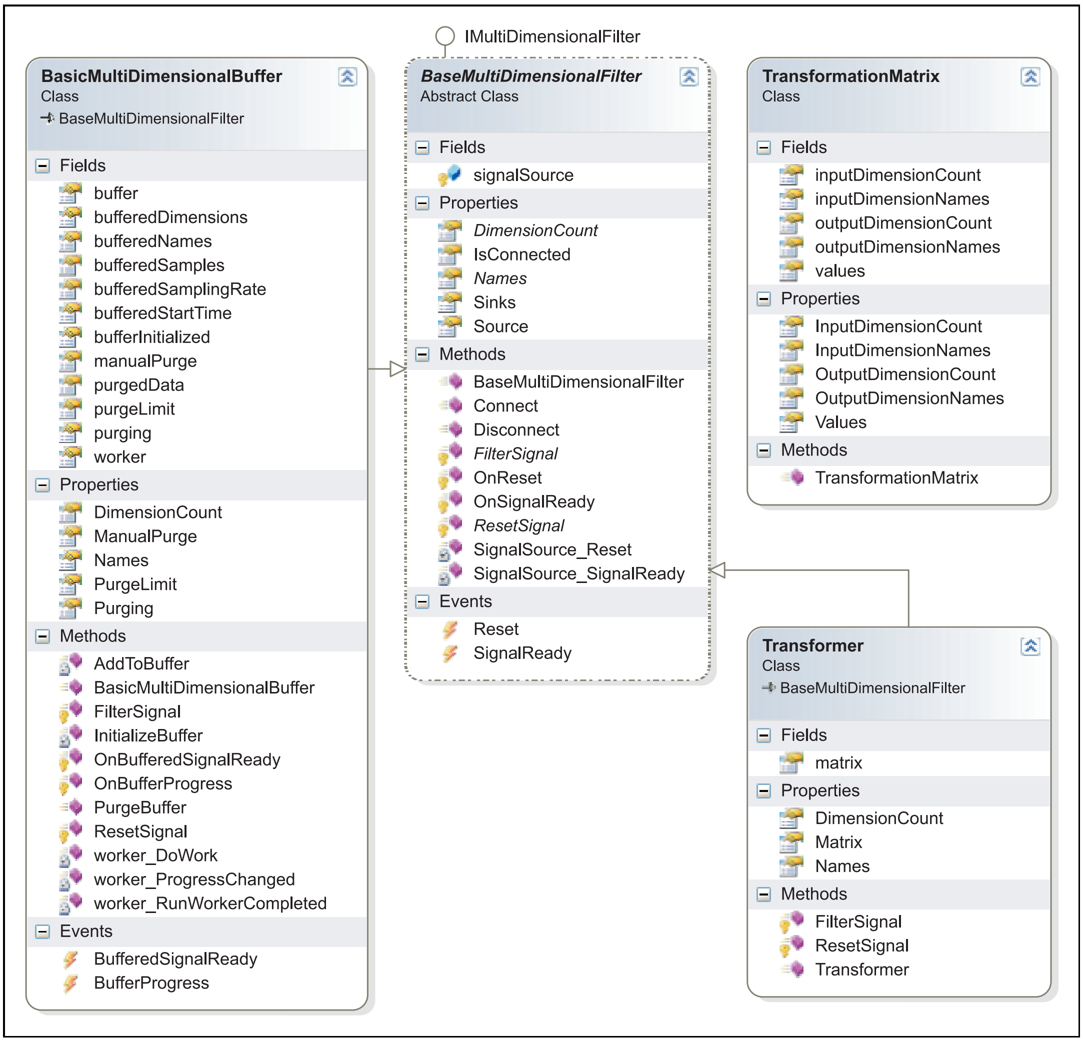
A.2 Exvivo.Dsp.Filters Namespace

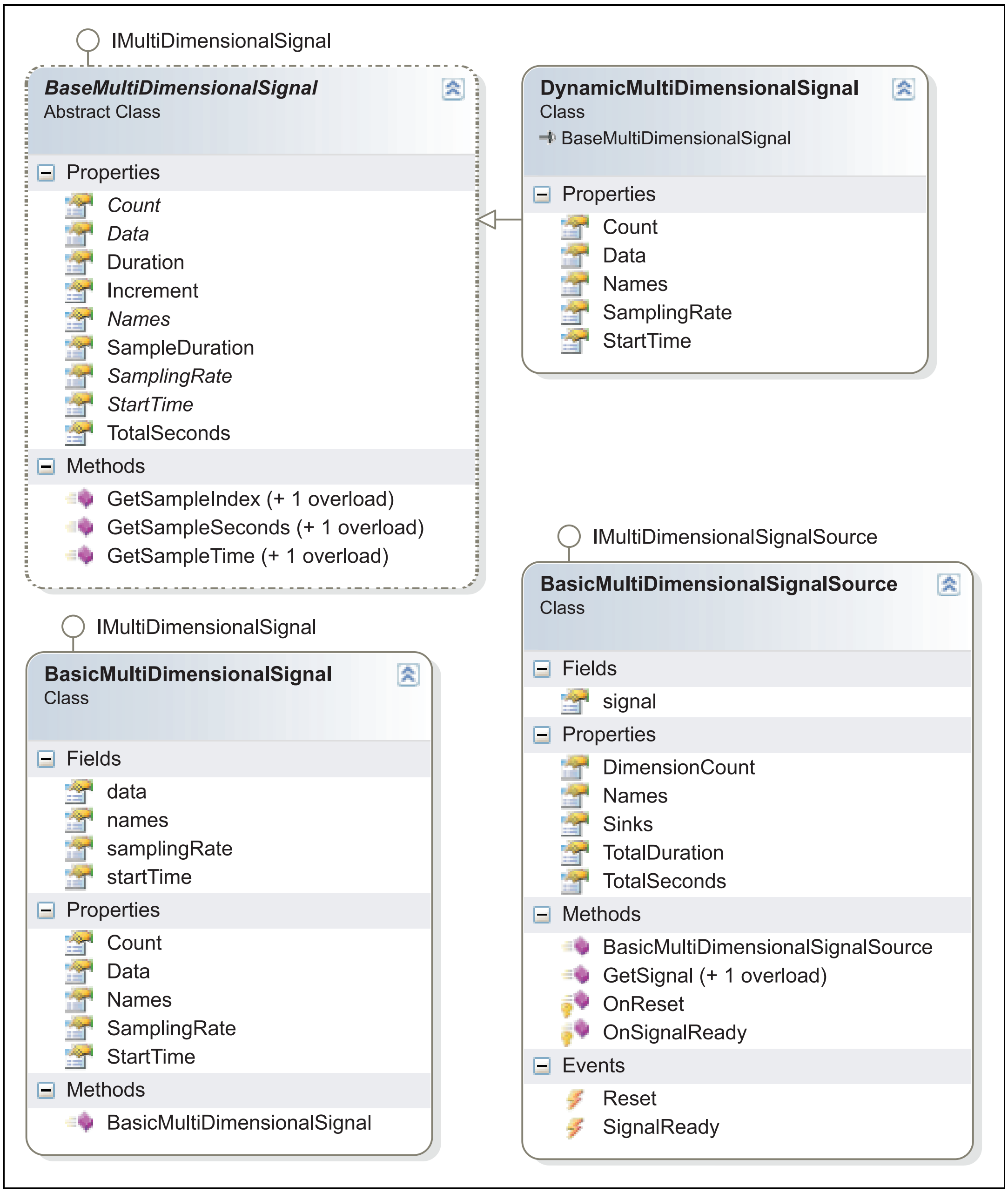


A.3 Exvivo.Dsp.MultiChannel Namespace

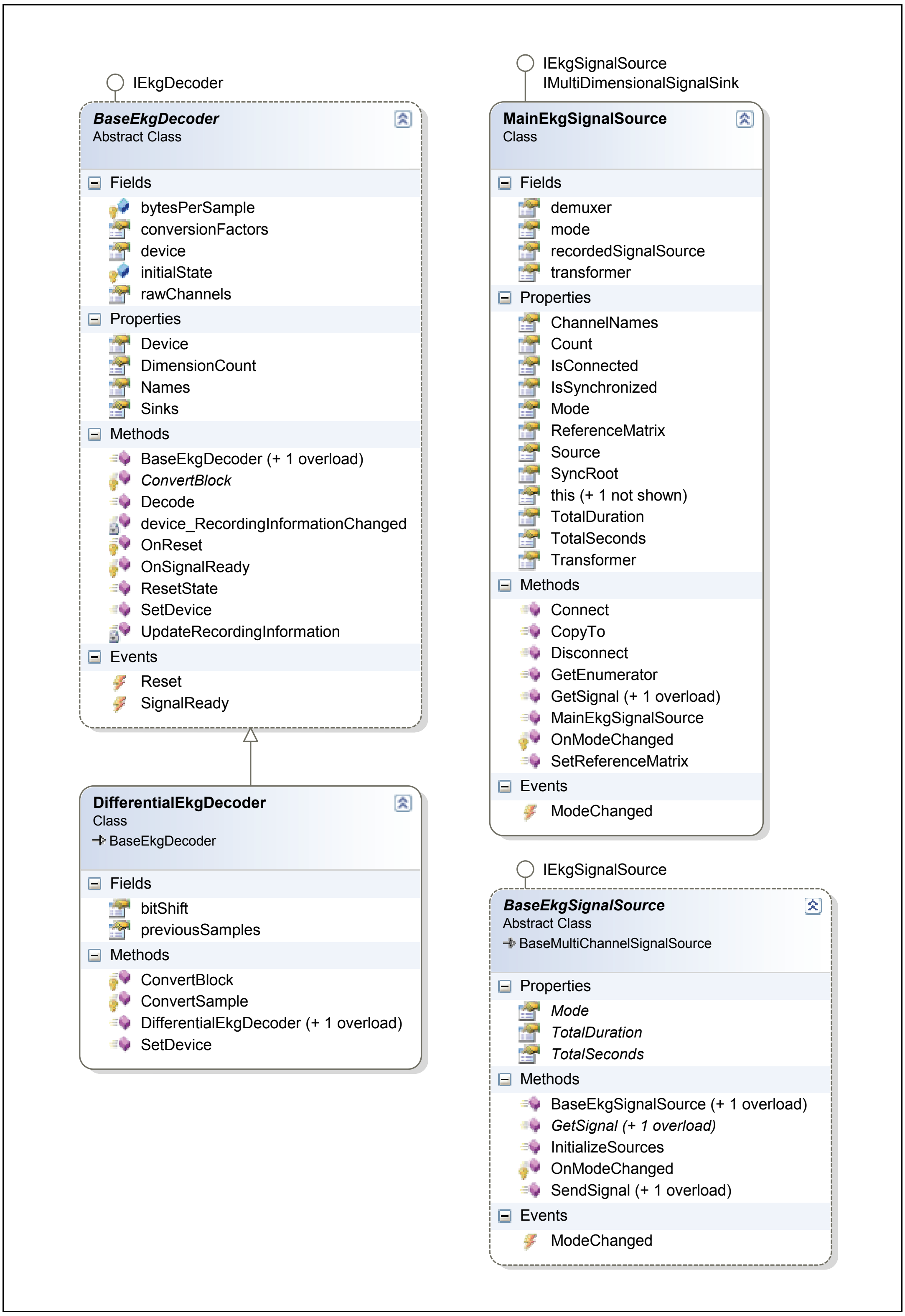


A.4 Exvivo.Dsp.MultiDimensional Namespace

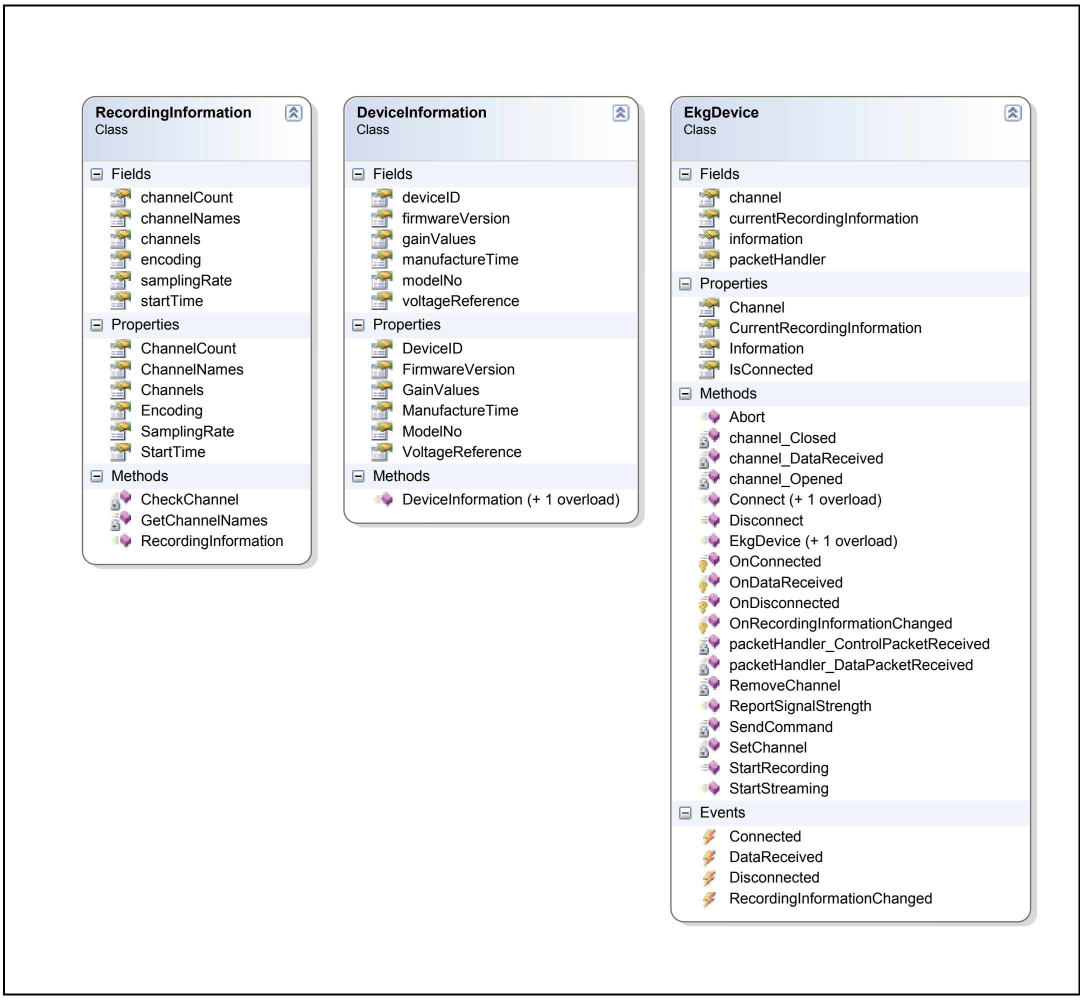



IMultiDimensionalSignal
BaseMultiDimensionalSignal
Abstract Class
Properties
Count
Data
Duration
Increment
Names
SampleDuration
SamplingRate
StartTime
TotalSeconds
Methods
GetSampleIndex (+ 1 overload)
GetSampleSeconds (+ 1 overload)
GetSampleTime (+ 1 overload)
DynamicMultiDimensionalSignal
Class
BaseMultiDimensionalSignal
Properties
Count
Data
Names
SamplingRate
StartTime
IMultiDimensionalSignal
BasicMultiDimensionalSignal
Class
Fields
data
names
samplingRate
startTime
Properties
Count
Data
Names
SamplingRate
StartTime
Methods
BasicMultiDimensionalSignal
IMultiDimensionalSignalSource
BasicMultiDimensionalSignalSource
Class
Fields
signal
Properties
DimensionCount
Names
Sinks
TotalDuration
TotalSeconds
Methods
BasicMultiDimensionalSignalSource
GetSignal (+ 1 overload)
OnReset
OnSignalReady
Events
Reset
SignalReady

A.5 Teknofil.EkgNet.Dsp Namespace



A.6 Teknofil.EkgNet.Device Namespace



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