Software Design Document

for a specific implementation of 'BCI2000'

Gerwin Schalk
Thilo Hinterberger
Dennis J. McFarland
Jürgen Mellinger

New York State Department of Health

Wadsworth Center
Laboratory of Nervous Systems Disorders

Eberhard–Karls–Universität Tübingen

Medizinische Fakultät
Institut für Medizinische Psychologie

Sponsors
Jonathan R. Wolpaw and Niels Birbaumer

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Chapter 1

Introduction

1.1 Purpose

All presently available augmentative communication systems depend in some measure on voluntary muscle control. Thus, they are useless to those who are totally paralyzed and to some others with severe motor disabilities. EEG–based communication, because it does not depend on voluntary muscle control, could provide a valuable new communication and control option for these individuals. Over the past decade, a number of laboratories have begun developing EEG–based Brain Computer Interfaces (i.e., BCIs) as a new augmentative technology for people with motor disabilities.

The BCI2000 standard (as described in the BCI2000 Project Outline) has been designed in a cooperation between the Laboratory of Nervous Systems Disorders at the Wadsworth Center in the New York State Department of Health and the Institut für Medizinische Psychologie at the Medizinische Fakultät at the Eberhard–Karls–Universität in Tübingen/Germany, in an effort to create a well documented and open system that is open for extensions; this document describes one particular implementation of this standard.

Not only does this document describe the software already in place, it is also intended to enforce compatibility of future modifications or add–ons.

1.2 Scope

This document is intended to give a detailed technical description of the BCI2000 software project. It does not, however, explain the BCI2000 standard itself, or the rationale behind the implementation or standard.

1.3 Intended Audience

The intended audience for this document are engineers or researchers, who want to modify and/or extend the existing reference implementation. As described software is implemented using Borland's C++ Builder, the reader should have some knowledge of the C/C++ programming language.

1.4 List of System Components

The software package consists of four Win32 executables:

Module Name	**Filename**	**Current Version**
Operator	Operat.exe	V1.31
EEG source	e.g., DT2000.exe	V0.30
Signal Processing	e.g., ARSignalProcessing.exe	V0.30
Application	e.g., RJB.exe	V0.30

Table 1.1: The four executables

For modules other than the operator module, executable file names vary, reflecting specializations of the generic modules.

1.5 References

The BCI2000 project homepage contains all relevant documentation, source code, and additional analysis tools:
http://www.bciresearch.org/BCI2000/bci2000.html

1.6 Content Summary

This document presents an overview of the system, the design considerations leading to the system architecture, describes the system architecture itself, and finally details the system design.

Chapter 2

System Overview

While BCIs can differ widely in the nature of the physiological components they use, in the signal processing they perform, in the feedback they provide, or in the underlying training and operation paradigm, they all need the same four elements: EEG data collection, signal processing, an output device and manual or automatic parameterization and configuration. Therefore, it seems to be a natural choice to partition the system into four modules with respective functionality. Figure 5.1 illustrates a high–level overview of this partitioning scheme.

It is conceivable that for certain BCIs, the chosen decomposition might be overkill, or even unfavorable, but still it seemed to be the most appropriate for a variety of systems.

Chapter 3

Design Considerations

3.1 Assumptions and Dependencies

3.1.1 Processing performance, definition of real time

This section is concerned with perfomance related issues, and the assumptions and dependencies that exist in the present system.

Processing performance

The existing system involves many components of a PC architecture:

- The microprocessor
- The graphic subsystem
- The I/O subsystem – hard drive storage
- The I/O subsystem – networking

The configuration of the system will determine the actual load on these components and therefore the software might run on low–end machines, or it might require more advanced hardware.

If processor speed becomes an issue, adding subsystems with bus–mastered hardware and dedicated processors (SCSI–controllers, good 100MBit networking cards), might be a more favorable (and cheaper) solution than using a faster processor.

Feasibility study

We evaluated the system behavior and processor load caused by the 'administrative' duties of the system, i.e., the communication between modules, under different scenarios (e.g., whether the modules reside on one or on seperate machines). In this study, all core modules not only transmitted all generated channels to the next core module (which is more than what the system would transmit in a real–world configuration), but also sent all channels as visualization data to the operator. However, neither was any data further processed in any module, nor was it visualized at the operator.

The results in Figure 3.1 clearly show that this inter–module communication only has a small impact on processor load, and that this impact is relatively independent on system configuration.

Machine:
Pentium III 450Mhz, 384Mb RAM, NT4.0

Data creation: **10/sec**
TransmitCh **16**
SampleBlockSize **16**

	CPU not busy		100% uniform CPU load 1 task 100%		100% uniform CPU load 2 tasks 100%	
	timer interval	roundtrip	timer interval	roundtrip	timer interval	roundtrip
mean	100.14	7.09	100.14	6.15	100.21	5.53
std dev	0.39	2.32	7.35	5.02	25.19	4.74
min	97.00	2.00	77.00	2.00	9	2
max	103.00	11.00	123.00	77.00	209	79
CPU load:	1%		N/A	N/A	N/A	N/A

Data creation: **10/sec**
TransmitCh **64**
SampleBlockSize **16**

	CPU not busy		100% uniform CPU load 1 task 100%		100% uniform CPU load 2 tasks 100%	
	timer interval	roundtrip	timer interval	roundtrip	timer interval	roundtrip
mean	100.19	4.09	100.14	3.75	100.18	3.67
std dev	3.07	3.61	7.89	3.91	27.60	0.63
min	96.00	2.00	78.00	2.00	10	3
max	311.00	47.00	122.00	84.00	200	22
CPU load:	1%		N/A		N/A	

Machine:
Core Modules: Pentium III 450Mhz, NT 4.0 **3COM Etherlink (PCI), 10/100MBit**
Operator: Pentium III 550Mhz, Win 2000 **SMC EtherEZ (ISA), 10MBit**

Data creation: **10/sec** in this case, there were 61440+ bytes transferred over the network/sec
TransmitCh **64** (64 channels from each core module * 2 bytes * 16 samples * 10/sec)
SampleBlockSize **16** network traffic + networking card performance is becoming important

	CPU not busy		100% uniform CPU load 1 task 100%		100% uniform CPU load 2 tasks 100%	
	timer interval	roundtrip	timer interval	roundtrip	timer interval	roundtrip
mean	100.24	3.09				
std dev	5.13	1.70				
min	96.00	2.00				
max	354.00	36.00				
CPU load:	<10% for both					

Figure 3.1: Overview over the results of the feasibility study

Definition of real time

In the most general terms, *real time* means a reaction of a system to an event in an appropriate time period. However, the exact nature of this 'appropriate time period' depends on the application; for instance, the constraint could be maximal response time, or average response time, or a system could only be called a real–time system, if it responds in no more than x ms in y percent of the time. In a virtual surgery environment, for example, one unexpected delay per year of 20ms could be fatal.

In a Brain Computer Interface environment, the system usually has to

1. keep up with processing the EEG components over long time periods

2. on average provide feedback in a timely manner (e.g., less than 100ms)

Being able to keeping up with processing directly is a function of the system's overall performance. System response time is related to system performance, but also influenced by the operating system (i.e., OS) – simply because the communication involves the OS. As the feasibility study (figure 3.1) shows, system latency in absence of signal processing or graphical feedback is very low (i.e., a few ms). This latency marks the minimal latency the system will be able to achieve.

Most OSs on the market are not *real time* operating systems, that is, they don't guarantee a deterministic system response time. This includes the Microsoft Windows family of operating systems (except, Windows CE, under certain circumstances). This means that it is impossible to (at the application level) write code that operates under this definition. Time stamping data collection and feedback, and storing these in fields with the data recorded, can be used to accommodate for differences in latency. In addition, for a BCI, it is appropriate to say that it is sufficient, if it provides feedback on average (e.g., 99.9 percent of the time) in a timely manner.

3.1.2 Operating systems

The system is programmed using Borland's C++ Builder application development environment. The target platform of this environment is Win32 code for Intel CPUs. Therefore, the possible operating systems are Windows 95/98, Windows NT4.0, or Windows 2000/XP.

This system contains four processes with up to two threads each. Windows NT and its successors have built-in advanced priority based scheduling algorithms that are far superior than the simple context–switching based concepts in Windows 95 or 98. While neither the BCI2000 Project Outline nor this document excludes the use of any of these operating systems, it seems that described real time requirements can be met more easily under Windows NT and its successors.

3.1.3 End-user characteristics

3.1.4 Possible and/or probable changes in functionality

3.2 General Constraints

3.3 Goals and Guidelines

3.3.1 Module Independence

One of the goals of the system design is to generate modules that are as independent of each other as possible. The BCI2000 Project Outline defines the communication protocols between the modules, but not the content of the transmitted EEG signals, control signals, or the state vector. Ideally, all modules are totally independent of each other. Even in a real–world situation, both the Data Acquisition and Operator modules can be independent of all other modules. However, signal processing might often depend on the feedback provided.

In any case, the goal should be to minimize this interdepence. For example, different physiological phenomena (e.g., slow cortical potentials or the μ–rhythm) might result in control signals with different distribution characteristics. As we pass a derived control signal from Signal Processing to the Application, we could either do post–processing, e.g., normalizing the signal and making it zero mean, in either the Signal Processing or Application module. Following the aforementioned idea, it seems favorable to do these manipulations in the signal processing module. In this case, the application does not need to account for different signal processing techniques.

3.4 Development Methods

Chapter 4

Architectural Strategies

Chapter 5

System Architecture

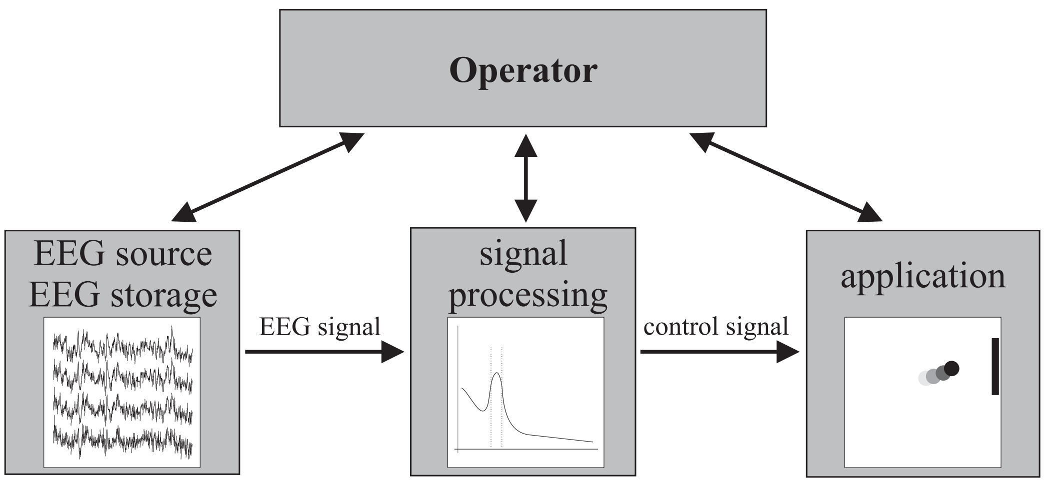


Figure 5.1: High–level overview of modules in BCI2000

This partitioning scheme and the used communication protocols are described in detail in the BCI2000 Project Outline.

Chapter 6

Detailed System Design

6.1 Operator

6.2 Core Modules

6.2.1 Module Initialization

The initialization of each core module follows the procedure that is described in detail in chapter *System Initialization* in the BCI2000 Project Outline:

Each module publishes its requests for parameters and states to the Operator module, which configures those and sends them back. After Data Acquisition received all parameters and states, it tries to connect to Signal Processing and – upon successful connection – sends a positive status message to the Operator. In the same way, Signal Processing connects to the Application and the Application module connects to the Data Acquisition module. After the Operator received status messages from all three core modules, the system is fully initialized and is triggered to start, as soon as the Operator sends the state *Running* with a value of 1 to the Data Acquisition.

6.2.2 System Termination

To each of the three core modules, the operator module indicates system termination by closing the connection to that module.

When a core module loses connection to the two other core modules it is connected to, it will send an error message to the operator, and then quit. The operator module, in turn, will close the connections to the remaining core modules.

6.3 EEG Data Acquisition

The EEG Data Acquisition (or Source) module's role is to wait for data blocks coming in from the A/D hardware, and to send these blocks of data on to Signal Processing, thus acting as the on-line system's "metronome" synchronized to the A/D hardware clock. At the same time, it receives state vector information from the Application module, and saves this state vector information to a file in BCI2000 .dat format, together with the raw digitized data.

During normal operation (*Running* is 1), the EEG source module runs in a data acquisition loop that basically reads

```
1: While Running
2:   Save state vector to file
3:   Wait for A/D data
4:   Send A/D data to Signal Processing
5:   Wait for state vector from Application
6:   Save A/D data to file
```

Note that statement 3 as well as statement 5 are blocking operations, i.e. the module will wait for A/D data as well as for the state vector data coming in from the Application module.

This mode of operation requires a sufficiently fast system to work properly. For our purposes, a "fast" system is a system where

- synchronous I/O operations (2, 4, 5, and 6) require an execution time that is small compared to the duration of a data block (as given by the sampling rate and the sample block size), and

- the time required by the Signal Processing and Application modules for processing the data sent out in statement 4 is small compared to the duration of a data block.

In an on-line system, the time between sampling of a data block, and display of the resulting feedback information to the subject, is critical. Given a "sufficiently fast" system as defined above, only statement 4 will enter into this critical time path, while the time spent on execution of the remaining statements will reduce the waiting interval occurring in statement 3.

6.4 Signal Processing

6.4.1 Overview

Signal Processing acts like a black box to the rest of the system – it receives EEG signals from the Data Acquisition and sends control signals on to the Application. Figure 6.1 illustrates the data flow in this implementation. As layed out in Figure 6.1, there are basically 5 main filters (Calibration, Spatial Filter, Temporal Filter, Classifier, and Normalizer) and 6 different signals (A (EEG signal), B, C, D, E, F (control signal)). The dimensionality of each of these signals is described in their respective filter description.

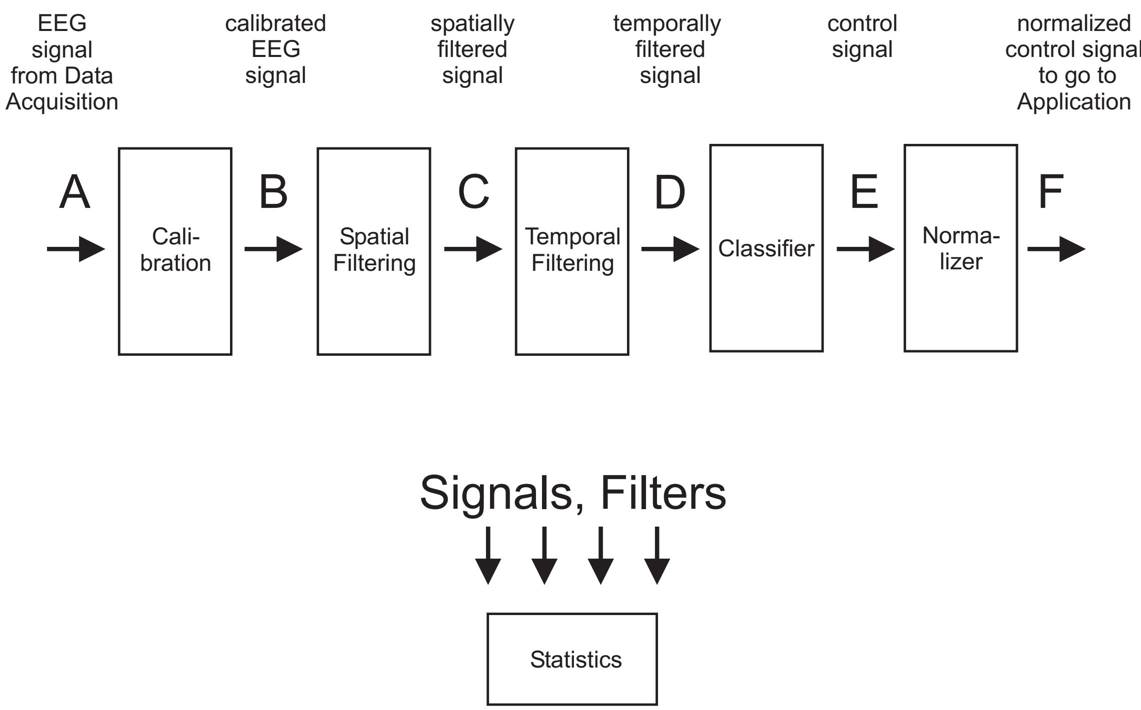


Figure 6.1: Data flow in the signal processing module

6.4.2 Goals

As described in chapter 3.3, one of the goals for this system is for each module to be as independent of the others as possible, e.g., Signal Processing should not have to take the type of data collection hardware into account. For the same reason, Application should (ideally) not have to know about the used signal processing method. While in real-world situations this will not be possible, control signals shall be normalized to the value range of short integers (-32767 to +32767), shall be zero mean (to the extent that this is possible), and each value shall be equally accessible by the user's EEG. In this fashion, the interdependence between Signal Processing and Application can be minimized.

6.4.3 Assumptions and Dependencies

Signal Processing can contain instances of multiple filter classes. These filter classes cannot assume any specific values for *SampleBlockSize*, *SamplingRate*, or *TransmitCh*. They have to be able to adapt their functionality according to these three parameters – they might not only be used in scenarios with varying parameters, but also they might have to work together with other filters. Therefore, hard coded assumptions about these three parameters have to be avoided.

6.5 User Application

As described in chapter 3.3.1, one major goal for system design is the independence between modules. In most BCI systems, however, some parts of the signal processing applied (i.e., the device-dependent part of signal processing) depend on the feedback to the user – a feature provided by the user application.

This inter-dependence between signal processing and the user application poses severe problems to the system design, because it is not possible to completely encapsulate each module and separate it from others.

In order to minimize inter-dependence, duties should be performed by the module that is conceptually defining it, e.g., task paradigm and timing are conceptually parts of a task and should therefore be handled by the user application module.

Section 7.3.1 describes a particular implementation of a user task – a simple cursor task – that complies with this motivation.

6.6 Understanding and Writing BCI2000 Code

This section provides background information which you need in order to understand, modify, or create code that depends on the specific BCI2000 framework presented in this document. You should read it before writing your own BCI2000 module, or modifying an existing one as presented in the examples of sections 6.6.7 and 6.6.8 below.

6.6.1 Reporting errors and warnings

There are two output channels available to any code inside a BCI2000 module. Technically, these channels are global objects derived from the STL's `std::ostream` class. As such, they work much like the global `std::cout` and `std::cerr` output streams available inside a C++ command line program, except that their output will be sent to the operator module's log window rather than a terminal window. The names of these output streams are `bciout` and `bcierr`, declared in `shared/UBCIError.h`, and while writing output to `bciout` has no side effects, writing to `bcierr` has side effects that depend on the system's phase of operation: In preflight phase, the side effect will be a preflight failure, and the system will refuse to be started unless reconfigured with correct parameters; otherwise, the side effect will be system termination after error display.

For the `Preflight` function, there is also a macro `PreflightCondition` available that is intended to make checking for conditions more convenient:

```
PreflightCondition( Parameter( "MyFirstParam" ) >= 3 );
```

will result in a message

```
"A necessary condition is violated: Parameter( "MyFirstParam" ) >= 3"
```

in the operator window if `MyFirstParam`'s value is below 3.

Finally, in case of a non-recoverable error, you may also throw an exception of type `const char*` in order to report an error in the operator window, and to terminate the BCI2000 system after the error has been displayed:

```
throw __FUNC__ ": Disk space is exhausted";
```

A more detailed discussion of these error reporting facilities, and the overall error handling concept in this BCI2000 implementation is available at `Documentation/errorhandling`.

6.6.2 Your code's `Environment`

In each BCI2000 module, there exist system wide parameters and states as described in the project outline document. In this implementation, access to parameters and states is mediated through a class `Environment`. This class provides functions for convenient access to parameters and states, and transparently handles a number of error conditions that might occur. The services provided by the `Environment` class interface are available to all classes that inherit from it. For `GenericFilter` descendants, this is automatically the case; for other classes, you need to explicitly state the inheritance as in

```
#include "UEnvironment.h"
...
MyClass : private Environment
{
  ...
};
```

From any code inside `MyClass`, you may then read or set parameter and state values simply by writing

```
int numberOfItems = Parameter( "NumberOfItems" );
float matrixValue = Parameter( "MatrixParam", index1, index2 );
short feedbackState = State( "Feedback" );
State( "Feedback" ) = 0;
```

If you try accessing a parameter or state that does not exist, an appropriate error message will be sent to `bcierr`, so you don't need to handle this type of error explicitly.

For a greater independence between modules, it is sometimes desirable to read a parameter or state if it exists, and use a default value otherwise. You achieve this behavior by writing

```
int numberOfItems = OptionalParameter( defaultValue, "NumberOfItems" );
short itiState = OptionalState( 0, "IntertrialInterval" );
```

Note: Due to some non-standard conventions in Borland's VCL library, you cannot create a VCL class such as a `TForm` descendant that also inherits from `Environment` – the compiler will report an error if you try. As a work-around, you might declare an `Environment` subclass *inside* your VCL `TForm` child declaration, and create a single instance `mEnv` of this subclass as a member of your class, using it to access the `Environment` functions as in

```
MyForm : public TForm
{
  ...
  private:
    class MyFormEnvironment : private Environment
    {
      public:
        MyFormEnvironment( MyForm& parent );
        void Preflight() const;
        void Initialize();
    } mEnv;
};

...

MyForm::MyFormEnvironment( MyForm& parent )
: mParent( parent )
{
  BEGIN_PARAMETER_DEFINITIONS
    "UsrTask int MyParam= 1 1 0 5 // my parameter",
  END_PARAMETER_DEFINITIONS
}

...
```

```
void
MyForm::Initialize()
{
  mEnv.Initialize();
}

void
MyForm::MyFormEnvironment::Initialize()
{
  mParent.mMyParam = Parameter( "MyParam" );
}
```

This should work in situations where your code's class model is centered around VCL form classes. When writing new code, you might consider basing your class model on functionality, and use VCL forms merely for input and output – instantiating populating, and deleting them as you need them, such that the BCI2000 `Environment` interfacing is done from your own classes, independently of the VCL's special needs.

For a detailed description of the `Environment` facilities, see the `Environment` section of the BCI2000 error handling document.

6.6.3 Signals and Signal Properties

Many classes in both Data Acquisition and Signal Processing work on signals. The `GenericSignal` class contains floating point data organized as a matrix of channels and "elements" (a generalized notion of samples – e.g., spectrally analyzed data might contain the spectrum of each channel as a list of "elements").

Sometimes, the number of channels, elements, and the number of bytes required for storing values, are referred to as "Signal Properties". There is a separate class, `SignalProperties`, for expressing those values, and determining whether a given signal "fits" into another one, i.e. whether the values contained in one signal may be copied into another signal without loss of information. `GenericSignal` uses a `SignalProperties` member to maintain information about its properties.

6.6.4 The `GenericFilter` class

`GenericFilter` is a base class that provides a programming interface for all user code inside the core modules of this BCI2000 implementation. Programming your own data acquisition module, your own filter inside Signal Processing, or your own application, all implies deriving your own class from `GenericFilter`.

`GenericFilter`'s member functions represent the various initialization and processing events that occur during system startup and operation (cf. the *System Initializa-*

tion chapter in the BCI2000 project outline). Your own filter code *must* implement its own versions of some of these member functions:

- The *Constructor*, besides its general purpose of initializing member data, declares the parameters and states your filter wants to introduce into the system (the `BEGIN_...` and `END_...` macros handle the actual function calls):

```
MyFilter::MyFilter()
: mMyParam( 1 ),
  mMyOtherParam( 0.1 ),
  mCount( 0 )
{
  BEGIN_PARAMETER_DEFINITIONS
    "MySection int MyParam= 1 "
      "0 0 3 // This is range-checked between 0 and 3",
    "MySection float MyOtherParam= 0.1 "
      "0 0 0 // This is not automatically range-checked",
  END_PARAMETER_DEFINITIONS

  BEGIN_STATE_DEFINITIONS
    "MyState 1 0 0 0",
  END_STATE_DEFINITIONS
}
```

- The `Preflight` function checks whether the preconditions for successful operation are met. This function is called whenever parameter values are re-applied, i.e. whenever the user presses “Set Config”, “Start”, or “Resume” in the operator window. If `Preflight` does not report an error via `bcierr`, this is considered a promise that `Initialize` and `Process` will work properly with the current parameters.

  The first argument to `Preflight` will inform you about what kind of input signal your filter is going to receive, and your filter is expected to report the properties of its output signal via the second parameter:

```
void
MyFilter::Preflight( const SignalProperties& inputProperties,
                                  SignalProperties& outputProperties ) const
{
  PreflightCondition( Parameter( "MyOtherParam" ) > 0.0 );
  PreflightCondition( inputProperties.Channels() > 0 );
  PreflightCondition( inputProperties.MaxElements( 0 ) > 0 );
  outputProperties = inputProperties;
}
```

  Note that the `const` keyword following the function argument list forbids to alter any data member of your filter object. This avoids diffusion of initialization code from `Initialize` into `Preflight`. If you have your own sub-objects instantiated and maintained by your filter, you should provide them with their own `Preflight() const` member functions, and call these from your filter's `Preflight`.

- `Initialize` is called after a successful `Preflight`. Thus, it may safely omit all checks related to parameter consistency. In `Initialize`, your filter's data members are set to the values implied by the user's choices, or to the initial values required for the filter's operation:

```
void
MyFilter::Initialize()
{
  mMyParam = Parameter( "MyParam" );
  mMyOtherParam = Parameter( "MyOtherParam" );
  mCount = 0;
}
```

- The `Process` function is called once for each block of EEG data. It receives an input in its first argument, and sets the output signal to values resulting from the filter operation. In the current BCI2000 implementation, there is a single chain of filters; one filter's output signal is the next filter's input. A filter which does not perform any modification to the signal (e.g., a statistics filter) needs to copy its input signal into the output signal, as in the example:

```
void
MyFilter::Process( const GenericSignal* inputSignal,
                                GenericSignal* outputSignal )
{
  if( ( *inputSignal )( 0, 0 ) > mMyOtherParam )
    ++mCount;
  *outputSignal = *inputSignal;
}
```

  The `Process` function should not acquire or release resources (opening/closing files, allocating memory, etc). Natural places for such operations are the `Initialize`, `StartRun`, and `StopRun` member functions.

Other member functions are *optional;* you may decide whether you override their default implementation with your own version, depending on what your filter needs to do:

- `StartRun` is called when the system enters the running state. As opposed to `Initialize` – which is the place for tasks that need to be performed on each parameter change –, `StartRun` is provided for tasks that need to be performed each time the user clicks "Run" or "Resume" in the operator window. As a canonical example, the `DataIOFilter` opens a new `.dat` file from its `StartRun` member function.

By default, `StartRun` calls `Initialize` to make sure that intermittent parameter changes are applied. If you provide your own `StartRun` function, you will probably want to call `Initialize` from there as well.

- `StopRun` is called each time the system leaves the running state, entering the suspended state. Typically, this happens whenever the user clicks "Suspend" in the operator window. The `DataIOFilter` provides an example for its usage: This filter closes the current `.dat` file from its `StopRun` member function.

  `StopRun` is also the only function from which a filter may change a parameter value. Any parameter changes inside `StopRun` will propagate to the other modules without any explicit request from your side.

- `Resting` is called instead of `Process` while the system is in suspended state.

- The `Halt` function is called before any re-configuration of the system takes place. If your filter initiates asynchronous operations such as playing a sound file, acquiring EEG data, or executing threads, its `Halt` member function should terminate all such operations immediately. Failure to do so might result in a non-responding module, or in other errors difficult to track down. For descendants of `GenericADC`, implementing the `Halt` function is mandatory.

- Your filter's *Destructor* should free all resources acquired in the Constructor or in `Initialize`. In many cases, freeing of resources will be done automatically if you use direct members instead of pointers, removing the need of a destructor.

  However, if your filter has a non-empty `Halt` function, it needs a destructor that calls `Halt`:[1]

```
MyFilter::~MyFilter()
{
  Halt();
}
```

6.6.5 The filter chain

As noted in the discussion of the `GenericFilter::Process` function, all `GenericFilter` descendants inside a BCI2000 module form a single chain of filters. Each filter's

[1] This can not be done from the base class destructor because overridden virtual functions cannot be called from base class constructors or destructors.

output forms the input of the subsequent filter. Creating instances of all filter classes inside a module, and building the filter chain, is handled by the framework. However, it needs a hint to determine the sequence in which filters are to be arranged. In general, this hint consists of a single statement placed inside your filter's .cpp file:

```
RegisterFilter( MyFilter, 2.C );
```

The first argument to this statement is your filter's class name; the second argument is a string value (given without quotes) that determines the relative position of your filter in the filter chain. This is done applying the simple rule that the filter positions in the chain match the alphanumeric sorting order of the filters' associated position strings. This scheme allows you to place an additional filter between existing ones without changing the position strings of the existing filters.

In principle, this allows to add filters to a module's filter chain without modification to existing source code, simply by adding a .cpp file with a `RegisterFilter` statement to the project.

However for Signal Processing modules, it appears more desirable to have an explicit representation of the entire filter chain centralized in one file. So there is, for each individual Signal Processing module, one file `UFilterHandling.cpp` that defines the filter chain as a sequence of `Filter` statements (see Section 6.6.8 for an example).

6.6.6 Presenting data to the operator user

Your filter may have information that it wants to present to the user – e.g., the EEG signal might appear graphically in a window, or an application task log should be presented. Packaging this information into core messages, and sending these to the operator module, is handled by the `GenericVisualization` class.

Typically, to visualize data this way, you will add a data member of type `GenericVisualization` to your filter class – see Section 6.6.8 for an example.

6.6.7 Tutorial: Implementing Your Own Data Acquisition

Data acquisition modules are factored into code required for any hardware, and code required to access a specific hardware. What you need to do is provide a function that waits for and reads A/D data (line 3 in the EEG source pseudo code of section 6.3), together with some helper functions that perform initialization and cleanup tasks. Together these functions form a class derived from `GenericADC`.

In this tutorial, we consider this scenario: Your *Tachyon Corporation* A/D card comes with a C-style software interface declared in a header file `"TachyonLib.h"` that consists of three functions

```
#define TACHYON_NO_ERROR 0
int TachyonStart( int inSamplingRate, int inNumberOfChannels );
int TachyonStop( void );
int TachyonWaitForData( short** outBuffer, int inCount );
```

From the library help file, you learn that `TachyonStart` configures the card and starts acquisition to some internal buffer; that `TachyonStop` stops acquisition to the buffer, and that `TachyonWaitForData` will block execution until the specified amount of data has been acquired, and that it will return a pointer to a buffer containing the data in its first argument. Each of the functions will return zero if everything went well, and some error value otherwise.

Luckily (and somewhat unrealistic), *Tachyon Corporation* gives you just what you need for a BCI2000 source module, so implementing the ADC class is quite straightforward. In your class' header file, `"TachyonADC.h"`, you write

```
#ifndef TachyonAdcH
#define TachyonAdcH

#include "GenericADC.h"

class TachyonADC : public GenericADC
{
 public:
   TachyonADC();
   ~TachyonADC();

   void Preflight( const SignalProperties&, SignalProperties& ) const;
   void Initialize();
   void Process( const GenericSignal*, GenericSignal* );
   void Halt();

 private:
   int  mSoftwareCh,
        mSampleBlockSize,
        mSamplingRate;
};
#endif // TachyonAdcH
```

In the .cpp file, you will need some `#includes`, and a filter registration:

```
#include "TachyonADC.h"
#include "Tachyon/TachyonLib.h"
#include "UBCIError.h"

using namespace std;

RegisterFilter( TachyonADC, 1 );
```

From the constructor, you request parameters and states that your ADC needs; from the destructor, you call `Halt` to make sure that your board stops acquiring data whenever your class instance gets destructed:

```
TachyonADC::TachyonADC()
: mSoftwareCh( 0 ),
  mSampleBlockSize( 0 ),
  mSamplingRate( 0 )
{
  BEGIN_PARAMETER_DEFINITIONS
    "Source int SoftwareCh=      64 64 1 128 "
        "// this is the number of digitized channels",
    "Source int SampleBlockSize= 16 5 1 128 "
        "// this is the number of samples transmitted at a time",
    "Source int SamplingRate=    128 128 1 4000 "
        "// this is the sample rate",
  END_PARAMETER_DEFINITIONS
}

TachyonADC::~TachyonADC()
{
  Halt();
}
```

Your `Preflight` function will check whether the board works with the parameters requested, and communicate the dimensions of its output signal:

```
void TachyonADC::Preflight( const SignalProperties&,
                              SignalProperties& outputProperties ) const
{
  if( TachyonStart( Parameter( "SamplingRate" ), Parameter( "SoftwareCh" ) )
      != TACHYON_NO_ERROR )
    bcierr << "SamplingRate and/or SoftwareCh parameters are not compatible"
           << " with the A/D card"
           << endl;
  TachyonStop();
  outputProperties = SignalProperties( Parameter( "SoftwareCh" ),
                          Parameter( "SampleBlockSize" ), SignalType::int16 );
}
```

Here, the last argument of the `SignalProperties` constructor determines not only the type of the signal propagated to the BCI2000 filters but also the format of the `dat` file written by the source module.

For the `Initialize` function, you know that it will only be called if `Preflight` did not report any errors. So everything will work fine with the parameters, and you may skip any checks, writing

```
void TachyonADC::Initialize()
{
  mSoftwareCh = Parameter( "SoftwareCh" );
  mSampleBlockSize = Parameter( "SampleBlockSize" );
  mSamplingRate = Parameter( "SamplingRate" );
  TachyonStart( mSamplingRate, mSoftwareCh );
}
```

Your `Halt` function should stop all asynchronous activity that your ADC code initiates:

```
void TachyonADC::Halt()
{
  TachyonStop();
}
```

And now, finally, the actual meat of your class – note that the function may not return unless the output signal is filled with data, so it is crucial that `TachyonWaitForData` is a blocking function. (If your card does not provide such a function, and you need to poll for data, don't forget to call `Sleep( 0 )` inside your polling loop to avoid hogging the CPU.)

```
void TachyonADC::Process( const GenericSignal*, GenericSignal* outputSignal )
{
  int valuesToRead = mSampleBlockSize * mSoftwareCh;
  short* buffer;
  if( TachyonWaitForData( &buffer, valuesToRead ) == TACHYON_NO_ERROR )
  {
    int i = 0;
    for( int channel = 0; channel < mSoftwareCh; ++channel )
      for( int sample = 0; sample < mSampleBlockSize; ++sample )
        ( *outputSignal )( channel, sample ) = buffer[ i++ ];
  }
  else
    bcierr << "Error reading data" << endl;
}
```

You are done! Use your `TachyonADC.cpp` to replace the `GenericADC` descendant in an existing source module, add the `TachyonADC.lib` shipped with your card to the project, compile, link, and find the bugs...

6.6.8 Tutorial: Implementing Your Own Signal Processing Filter

This tutorial shows you how to derive a new filter class from `GenericFilter`, how to check preconditions, initialize your filter, and process data. It will also show you how to visualize a filter's output signal, presenting it to the operator user.

A simple low pass filter

We want to implement a low pass filter with a time constant T (given in units of a sample's duration), a sequence $S_{in,t}$ as input and a sequence $S_{out,t}$ as output (where t is an sample index proportional to time), and obeying

$$\begin{aligned} S_{out,0} &= \left(1 - e^{-1/T}\right) S_{in,0} \\ S_{out,t} &= e^{-1/T} S_{out,t-1} + \left(1 - e^{-1/T}\right) S_{in,t} \end{aligned} \tag{6.1}$$

The filter skeleton

The resulting filter class is to be called `LPFilter`. We create two new files, `LPFilter.h`, and `LPFilter.cpp`, and put a minimal filter declaration into `LPFilter.h`:

```
#ifndef LPFilterH
#define LPFilterH

#include "UGenericFilter.h"

class LPFilter : public GenericFilter
{
 public:
   LPFilter();
   ~LPFilter();

   void Preflight( const SignalProperties&, SignalProperties& ) const;
   void Initialize();
   void Process( const GenericSignal*, GenericSignal* );
};
#endif // LPFilterH
```

Into `LPFilter.cpp` we put the lines

```
#include "PCHIncludes.h" // Make the compiler's Pre-Compiled Headers feature happy
#pragma hdrstop

#include "LPFilter.h"

#include "MeasurementUnits.h"
#include "UBCIError.h"
#include <vector>
#include <cmath>

using namespace std;
```

The `Process` function

When implementing a filter, a good strategy is to begin with the `Process` function, and to consider the remaining class member functions mere helpers, mainly determined by the code of `Process`. So we convert (6.1) into the `Process` code, introducing member variables *ad hoc*, ignoring possible error conditions, and postponing efficiency considerations:

```
void LPFilter::Process( const GenericSignal* input, GenericSignal* output )
{
  // This will initialize additional elements with 0,
  // implementing the first line of the filter prescription:
  mPreviousOutput.resize( input->Channels(), 0 );
  // This implements the second line for all channels:
  for( size_t channel = 0; channel < input->Channels(); ++channel )
  {
    for( size_t sample = 0; sample < input->Elements(); ++sample )
    {
      mPreviousOutput[ channel ] *= mDecayFactor;
      mPreviousOutput[ channel ] +=
           ( *input )( channel, sample ) * ( 1.0 - mDecayFactor );
      ( *output )( channel, sample ) = mPreviousOutput[ channel ];
    }
  }
}
```

The `Initialize` member function

As you will notice when comparing `Process` to equation (6.1), we introduced member variables representing these sub-expressions:

$$\begin{aligned} \texttt{mPreviousOutput[ ]} &= S_{out,t-1} \\ \texttt{mDecayFactor} &= e^{-1/T} \end{aligned}$$

We introduce these members into the class declaration, adding the following lines after the `Process` declaration:

```
  private:
    float              mDecayFactor;
    std::vector<float> mPreviousOutput;
```

The next step is to initialize these member variables, introducing filter parameters as needed. This is done in the `Initialize` member function – we write it down without considering possible error conditions:

```
void LPFilter::Initialize()
{
  float timeConstant = Parameter( "LPTimeConstant" );
  mDecayFactor = ::exp( -1.0 / timeConstant );
  mPreviousOutput.clear();
}
```

Now this version is quite inconvenient for a user going to configure our filter – the time constant is given in units of a sample's duration, resulting in a need to re-configure each time the sampling rate is changed. Wouldn't it be a nice idea to let the user choose whether to give the time constant in seconds or in sample blocks? To achieve this, there is a utility class `MeasurementUnits` that has a member `ReadAsTime()`, returning values in units of sample blocks which is the natural time unit in a BCI2000 system. Writing a number followed by an "s" will allow the user to specify a time value in seconds; writing an naked number will be interpreted as sample blocks. Thus, our user friendly version of `Initialize` reads

```
void LPFilter::Initialize()
{
  // Get the time constant in units of a sample block's duration:
  float timeConstant = MeasurementUnits::ReadAsTime( Parameter( "LPTimeConstant" ) );
  // Convert it into units of a sample's duration:
  timeConstant *= Parameter( "SampleBlockSize" );

  mDecayFactor = ::exp( -1.0 / timeConstant );
  mPreviousOutput.clear();
}
```

The `Preflight` function

Up to now, we didn't consider any error conditions that might occur during execution of our filter code. Scanning through the `Process` and `Initialize` code, we identify a number of implicit assumptions:

1. The time constant is not zero – otherwise, a division by zero will occur.

2. The time constant is not negative – otherwise, the output signal is no longer guaranteed to be finite, and a numeric overflow may occur.

3. Input and output signal pointers are assumed to point to valid locations in memory.

4. The output signal is assumed to hold at least as much data as the input signal contains.

The first two assumptions may be violated if a user enters an illegal value into the LPTimeConstant parameter; we need to make sure that an error is reported, and no code is executed that depends on these two assumptions. The third assumption will hold if the framework code does what it is supposed to do, so we don't need to check for it. For the last assumption, we request an appropriate output signal from the `Preflight` function. Thus, the `Preflight` code reads

```
void LPFilter::Preflight( const SignalProperties& inputProperties,
                            SignalProperties& outputProperties ) const
{
  float LPTimeConstant = MeasurementUnits::ReadAsTime(
                                            Parameter( "LPTimeConstant" ) );
  LPTimeConstant *= Parameter( "SampleBlockSize" );
  // The PreflightCondition macro will automatically generate an error
  // message if its argument evaluates to false.
  // However, we need to make sure that its argument is user-readable
  // -- this is why we chose a variable name that matches the parameter
  // name.
  PreflightCondition( LPTimeConstant > 0 );
  // Alternatively, we might write:
  if( LPTimeConstant <= 0 )
    bcierr << "The LPTimeConstant parameter must be greater 0" << endl;

  // Request output signal properties:
  outputProperties = inputProperties;
}
```

Constructor and destructor

Because we don't explicitly acquire resources, nor perform asynchronous operations, there is nothing to be done inside the `LPFilter` *destructor*. Our *constructor* will contain initializers for the members we declared, and a BCI2000 parameter definition for LPTimeConstant:

```
LPFilter::LPFilter()
: mDecayFactor( 0 ),
  mPreviousOutput( 0 )
{
  BEGIN_PARAMETER_DEFINITIONS
    "Filtering float LPTimeConstant= 16s"
      " 16s 0 0 // time constant for the low pass filter in blocks or seconds",
  END_PARAMETER_DEFINITIONS
}

LPFilter::~LPFilter()
{
}
```

Filter instantiation

To have our filter instantiated in a signal processing module, we add a line containing a `Filter` statement to the module's `UFilterHandling.cpp`. This statement expects a string parameter which is used to determine the filter's position in the filter chain. If we want to use the filter in the AR Signal Processing module, and place it after the `SpatialFilter`, we add

```
#include "LPFilter.h"
...
Filter( LPFilter, 2.B1 );
```

to the file `SignalProcessing/AR/UFilterHandling.cpp`.

Now, if we compile and link the AR Signal Processing module, we get an "unresolved external" linker error that reminds us to add our `LPFilter.cpp` to that module's project.

Visualizing filter output

We would like to present the LPFilter's output signal in an operator window. To accomplish this, we introduce a member of type `GenericVisualization` into our filter class, adding

```
#include "UGenericVisualization.h"
...
class LPFilter : public GenericFilter
{
...
  private:
...
    GenericVisualization  mSignalVis;
};
...
```

`GenericVisualization`'s constructor takes a one-byte visualization ID as a parameter; we need to get a unique ID in order to get our data routed to the correct operator window. This can be done by adding an entry `LowPass` at the end of the `SOURCEID` enumeration in the file `shared/defines.h`.

Then, in our `.cpp` file, we add

```
#include "defines.h"
```

and change the `LPFilter` constructor to read

```
LPFilter::LPFilter()
: mDecayFactor( 0 ),
  mPreviousOutput( 0 ),
  mSignalVis( SOURCEID::LowPass )
{
  BEGIN_PARAMETER_DEFINITIONS
    "Filtering float LPTimeConstant= 16s"
      " 16s 0 0 // time constant for the low pass filter in blocks or seconds",
    "Visualize int VisualizeLowPass= 1"
      " 1 0 1 // visualize low pass output signal (0=no, 1=yes)",
    "Visualize int LPVisMin= -100 0 0 0 "
      "// low pass visualization min value",
    "Visualize int LPVisMax= 100 0 0 0 "
      "// low pass visualization max value",
  END_PARAMETER_DEFINITIONS
}
```

where LPVisMin and LPVisMax parameters determine the default scaling of the displayed signal; these parameters may even be reverted, resulting in an inversion of the displayed signal, so there is no need to check these parameters from `Preflight`.

In `Initialize`, we add

```
  mSignalVis.Send( CFGID::WINDOWTITLE, "Low Pass" );
  mSignalVis.Send( CFGID::graphType, CFGID::polyline );
  mSignalVis.Send( CFGID::MINVALUE, Parameter( "LPVisMin" ) );
  mSignalVis.Send( CFGID::MAXVALUE, Parameter( "LPVisMax" ) );
  mSignalVis.Send( CFGID::NUMSAMPLES, 2 * Parameter( "SamplingRate" ) );
```

Finally, to update the display in regular intervals, we add the following at the end of `Process`:

```
  if( Parameter( "VisualizeLowPass" ) == 1 )
    mSignalVis.Send( output );
```

We might also send data to the already existing task log memo window, adding another member

```
  GenericVisualization  mTaskLogVis;
```

initializing it with

```
LPFilter::LPFilter()
: ...
  mTaskLogVis( SOURCEID::TASKLOG )
{
 ...
}
```

and, from inside `Process`, writing some text to it as in

```
if( ( *output )( 0, 0 ) > 10 )
{
  ostringstream oss;
  oss << "LPFilter: (0,0) entry of output exceeds 10 and is "
      << ( *output )( 0, 0 );
  mTaskLogVis.Send( oss.str() );
}
```

Multiple filter instances

When instantiating a filter more than once, one needs to maintain multiple "instances" of the filter's parameters as well. In the following example, we will number filter instances from 1 to N, and append instance numbers to parameter names in order to obtain a separate copy of the parameters for each instance. To keep things simple, we use the initial version of `LPFilter` – without visualization – in the example.

To obtain 1-based instance numbers for the instances of `LPFilter`, we introduce a static class member that acts as an instance counter – static data members of a class exist once per class, so we will increment the counter in the constructor, and decrement it in the destructor, to obtain a number that will always represent the current number of class instances.

Practically, this implies

- adding the lines

  ```
  std::string mParamName_LPTimeConstant;
  static int sNumInstances;
  ```

  to the end of the `private` section of the class declaration;

- adding the definition and initialization

  ```
  int LPFilter::sNumInstances = 0;
  ```

  to `LPFilter.cpp`;

- adding an initializer for `mParamName_LPTimeConstant` to the constructor, appending the instance number to it, and replacing all occurrences of the parameter name with `mParamName_LPTimeConstant`:

```
LPFilter::LPFilter()
: ...
  mParamName_LPTimeConstant( "LPTimeConstant" )
{
  ostringstream oss;
  oss << ++sNumInstances;
  mParamName_LPTimeConstant += oss.str();

  // Instead of using the BEGIN_... and END_... macros, we need
  // to construct our parameter by hand:
  string paramLine = "Filtering float ";
  paramLine += mParamName_LPTimeConstant
            + "= 16s 16s 0 0 // time constant for the low pass filter"
            + " in blocks or seconds";
  ( *Parameters )[ mParamName_LPTimeConstant ] = PARAM( paramLine.c_str() );
}
```

- changing the destructor to read

```
LPFilter::~LPFilter()
{
  --sNumInstances;
}
```

- replacing the literal occurrences of `"LPTimeConstant"` in the `Preflight`, `Initialize`, and `Process` functions with `mParamName_LPTimeConstant`.

Now, when adding multiple `Filter` statements to `UFilterHandling.cpp`, as in

```
Filter( CalibrationFilter, 2.A );
Filter( LPFilter, 2.A1 ); // this instance owns LPTimeConstant1
Filter( SpatialFilter, 2.B );
Filter( LPFilter, 2.B1 ); // this instance owns LPTimeConstant2
Filter( ARTemporalFilter, 2.C );
Filter( ClassFilter, 2.D );
Filter( StatFilter, 2.E1 );
Filter( NormalFilter, 2.E2 );
```

each instance of `LPFilter` has its own parameter `LPTimeConstant1`, `LPTimeConstant2`, and so on, and the numbers are in the order in which the instances appear in the filter chain.

6.7 Entity–Relationship Model for Shared Classes

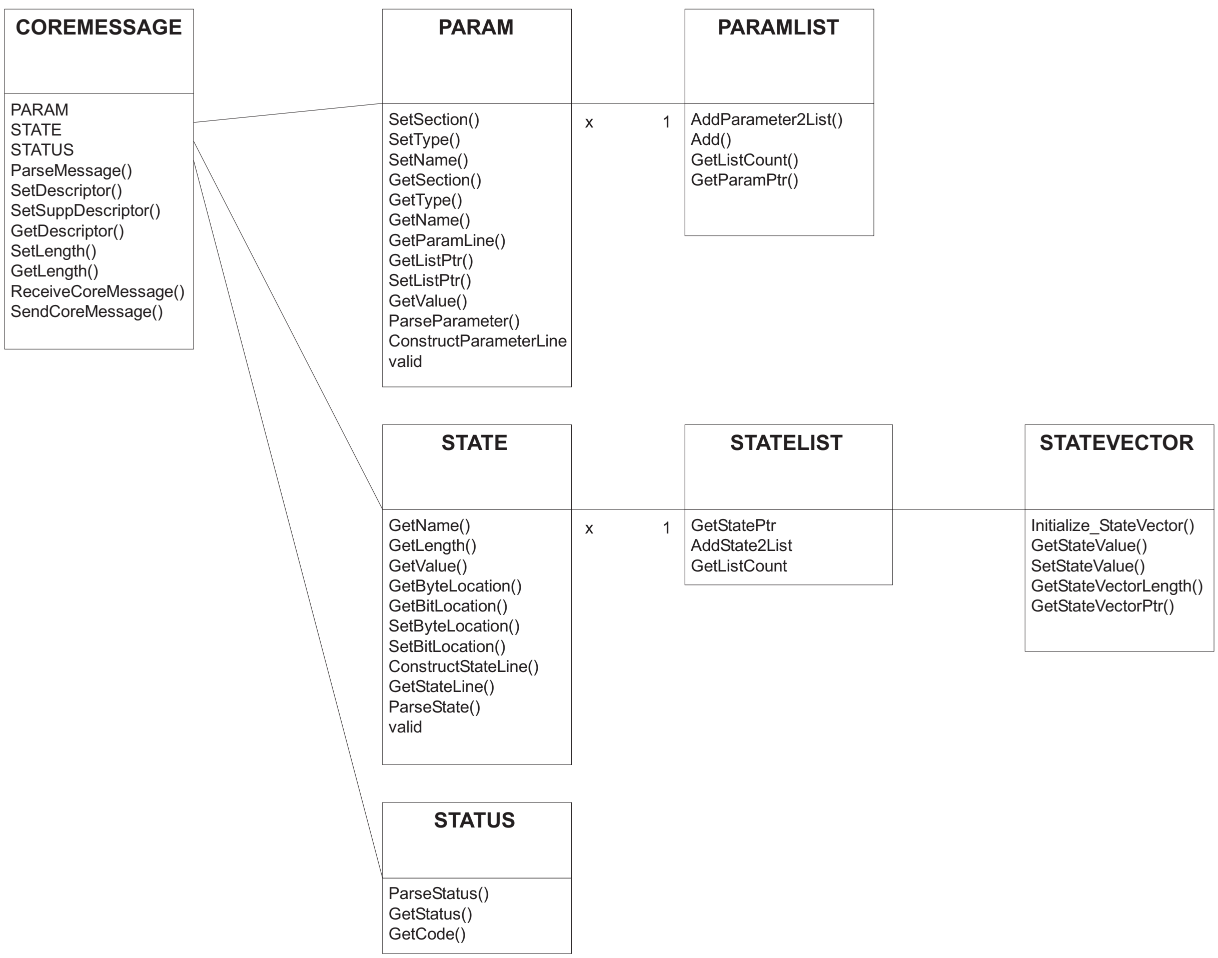


Figure 6.2: Class model for all shared classes

Chapter 7

Available Filters and their Parameters

7.1 EEG Source

7.2 Signal Processing

7.2.1 Calibration

The calibration filter (class *CalibrationFilter*) calibrates the incoming EEG signal. It performs a linear scaling, such that each channel is expressed in μV and has a mean of zero (i.e., $newvalue = (ADvalue - SourceChOffset) * SourceChGain$).

The calibration filter acts only on the subset of channels defined by *TransmitCh* and *TransmitChList;* regardless of this, the *SourceChOffset* and *SourceChGain* parameters refer to the full set of software channels as stored in the data file, in the order in which they are digitized.

Requested Parameters

Section	**Parameter**	**Data Type**
Source	SourceChOffset	floatlist
Source	SourceChGain	floatlist
Source	AlignChannels	int

Table 7.1: Parameters requested by the class CalibrationFilter

SourceChOffset specifies a list of offsets in AD units – one value for each channel. *SourceChGain* specifies a list of gains as used in described formula – one value for each channel.

AlignChannels specifies whether samples should be aligned in time – most data acquisition boards multiplex one A/D converter and thus samples for *SoftwareCh* channels are linearly distributed in time over $\frac{1000}{SamplingRate}$ milliseconds (0=no alignment, 1=perform alignment).

Input/Output

The input to an instance of this filter class is GenericIntSignal A (dimensions *TransmitCh* channels by *SampleBlockSize* elements). Its output is Signal B with the same dimensions.

7.2.2 Spatial Filter

The spatial filter class *SpatialFilter* performs for each sample vector (*TransmitCh* values – one for each channel) an operation as shown in Figure 7.1.

Requested Parameters

Section	**Parameter**	**Data Type**
Filtering	SpatialFilterKernel	matrix

Table 7.2: Parameters requested by the class SpatialFilter

The dimensions of *SpatialFilterKernel* are *m'* by *TransmitCh*.

Input/Output

The input to an instance of this filter class is Signal B (dimensions *TransmitCh* channels by *SampleBlockSize* elements). Its output is Signal C with the following dimensions: *m'* channels and *SampleBlockSize* elements.

7.2.3 Temporal Filter Using an AR Model

Each instance of the temporal filter class *ARFilter* requests the following parameters:

Requested Parameters

Section	**Parameter**	**Data Type**
Filtering	TempFiltCfg	matrix

Table 7.3: Parameters requested by the class ARFilter

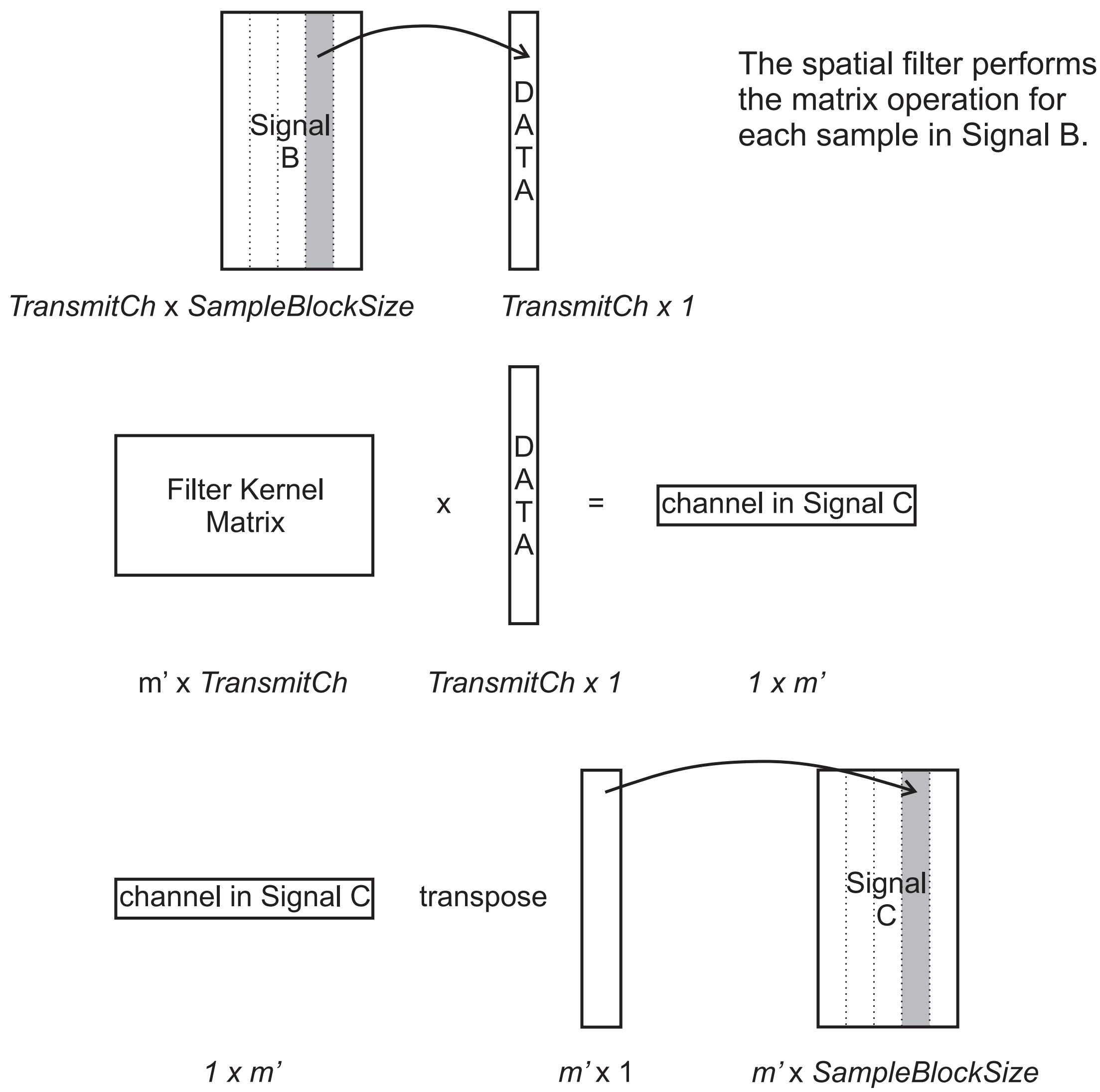


Figure 7.1: Matrix operation on the input signal

TempFiltCfg is a matrix of dimensionality m' x (max nr. of columns). It serves to configure the nature of temporal filtering.

Input/Output

The input to an instance of this filter class is Signal C (dimensions number of spatially filtered channels by *SampleBlockSize* elements). Its output is Signal D with the following dimensions: m' x n'.

7.2.4 Classifier / Translation Algorithm

An instance of *ClassifierFilter* transforms pre–processed signal components into signals that can – after normalization – be used for device control.

Requested Parameters

Section	Parameter	Data Type
Filtering	MUD	matrix
Filtering	MLR	matrix

Table 7.4: Parameters requested by the class ClassifierFilter

MUD and *MLR* are matrices of the same dimensionality as Signal D (m' x n'). The two scalars in the resulting control signal (Signal E) – one for up/down and one for left/right movement – each are linear combinations of Signal D and their respective weight matrix (*MUD* or *MLR*) as follows: $updown = \sum_{i=0,j=0}^{i<m',j<n'} MUD_{ij} * SignalD_{ij}$

Input/Output

The input to this filter class is Signal D with the following dimensions: m' x n'. The output is Signal E with *NumControlSignals* channels and 1 element per channel.

7.2.5 Normalizer

An instance of *NormalizeFilter* makes each scalar in the vector of control signals (Signal E) zero mean and thereafter normalizes it to a desired range (not exceeding -32767 to +32767).

Requested Parameters

Section	Parameter	Data Type
Filtering	Gain	floatlist
Filtering	Intercept	floatlist

Table 7.5: Parameters requested by the class NormalizeFilter

Each of the *NumControlSignals* scalars in *Gain* and *Intercept* are used as follows: $SignalF_i = Gain_i * (SignalE_i + Intercept_i)$

Input/Output

The input to this filter class is Signal E with the following dimensions: *NumControlSignals* channels and 1 element per channel. Its output, Signal F, is of the same dimensionality.

7.2.6 Slow-Wave-Feedback

Author and Introduction

Description of Signal Processing Module for the Slow-Wave-Feedback written by Dr. Thilo Hinterberger, University of Tübingen, Germany.

The calculation of the Slow-Wave feedback signal is subdivided into three modules: The SW-Filter, which is realized as an efficient boxcar-filter, the SetBaseline module, which subtracts a defined baseline from the signal and an artifact correction module, which contains two different artifact correction modes.

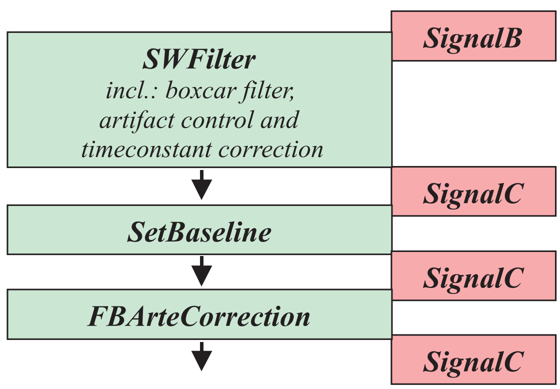


Figure 7.2: Data flow in the slow wave filter

Temporal SW-Filter

Following states are used: Artifact (bool) is set to 1 when the signal changes exceed the threshold values defined in ThresholdAmp (see below). BeginOfTrial is checked to trigger the start of the trial and reset the internal counter.

Requested Parameters

The SW-Filter uses the following parameters:

```
SWFilter int SWAvgSpan= 0.5 0.5 0 10
         // Averaging window in s
SWFilter intlist SWInChList= 3 0 1 2 0 0 63
```

```
         // Channel index of input signal (include artifact channel!)
SWFilter intlist SWOutChList= 3 0 1 2 0 0 63
         // Channel index of output signal (include artifact channel!)
SWFilter floatlist ThresholdAmp= 3 100 100 400 200 -2000 2000
         // Threshold for invalid Trial in uV
SWFilter float Tc= 0 16 0 1024
         // Time constant filter settings in s
Visualize int VisualizeSWFiltering= 1 0 0 1
          // visualize SW filtered signals (0=no 1=yes)
```

SWAvgSpan defines the time window of the boxcar-filter. SWInChList defines, which channels from Signal B are filtered. They are sorted to the channels in Signal C which are selected in SWOutChList. In the Standard setting, three channels are filtered. The ThresholdAmp is an artifact control parameter. In between one trial (from one BeginOfTrial to the next), the amplitude is not allowed to vary more than the in ThresholdAmp defined size in V. Otherwise the trial should be neglected and set as invalid in the application module (state Artifact is set to one). A time constant (Tc) correction function simulates a real DC-behaviour, even if the amplifier has no DC-option. This can be done by the knowledge of the amplifiers' time constant, which is set as the parameter Tc. To avoid that the signal will drift towards very high positive or negative values, the correction signal is set to zero each time, when BeginOfTrial is one. Tc=0 will switch off the Tc-correction. Note: The Tc-correction will only work properly, when the A/D-converter and the amplifier puts out 0 when the input is 0 V and there is no electrode polarization! If you are not sure, switch off this correction.

Baseline Setting

Following states are used: Baseline (bool) is set to 1 during the baseline period between BaseBegin and BaseEnd. Otherwise it is zero. BeginOfTrial is checked to trigger the start of the trial and reset the internal counter.

Requested Parameters

The SW-Filter uses the following parameters:

```
BLFilter float BaseBegin= 0.9 1.9 0 60
         // Begin of Baseline in s
BLFilter float BaseEnd= 1.0 2.0 0 60
         // End of Baseline in s
BLFilter intlist BaseChList= 3 1 1 1 1 0 1
         // 1 to mark that BL is subtracted
```

```
Visualize int VisualizeBaselineFiltering= 1 0 0 1
          // visualize baseline filtered signals (0=no 1=yes)
```

The baseline is set each trial at the time point BaseEnd seconds after BeginOfTrial was set to one. The baseline amplitude is the average amplitude in the time interval between BaseBegin and BaseEnd. The baseline is subtracted of all channels marked with 1 in the BaseChList. As default, baseline subtraction is applied on all three channels.

This version still uses the parameters BIPts and FIPts, which define the duration of the baseline-interval and the feedback-interval in seconds. These parameters are used for the buffer, which needs the duration of a trial. They will be no longer used in the next version.

Artifact Correction

Following states are used:

Artifact (bool) is set to 1 only in ArteMode=3 when the feedback signal is set to zero due to the EOG artifact BeginOfTrial is checked to trigger the start of the trial and reset the internal counter.

Requested Parameters

The SW-Filter uses the following parameters:

```
ArteFilter intlist ArteChList= 3 2 2 -1 2 -1 63
  // Assignment of artefact channels, -1: no artifact channel
ArteFilter floatlist ArteFactorList= 7 0.15 0.15 0 0 0 0 0 0 -1 1
  // Influence of artefact channel on input channel,
     -1: no artifact channel
ArteFilter int ArteMode= 0 1 0 3
  // Artefact correction mode, 0 off, 1 continuous, 2 conditioned
Visualize int VisualizeFBArteCorFiltering= 1 0 0 1
  // visualize FBArte corrected signals (0=no 1=yes)
```

Artifacts are corrected on all channels which are not marked with -1 in the ArteChList. For the correction, the channel number at the position of the channel in the ArteChList is used as artifact channel. For example, the standard setting corrects the channels 0 and 1 by using channel 2 for the correction. The correction factor is the factor set in ArteFactorList, 0.15 in the standard setting.

For the ArteMode parameter, the following values are possible:

- `ArteMode 0` switches this filter off.

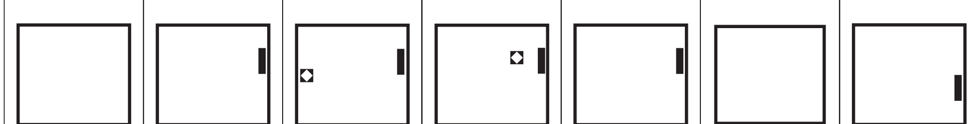
- `ArteMode 1` will subtract the artifact channel multiplied with a constant factor.
- `ArteMode 2` will correct the signal according to Koutchoubey, 1997: If the artifact signal has the same sign as the control signal, a correction is applied by subtracting the artifact signal; otherwise, no correction is performed. If the artifact crosses a threshold value, feedback is suppressed.
- `ArteMode 3` is working identically to `ArteMode 2` but sets the Artifact state to 1 when the feedback is set to zero.

7.3 Application

7.3.1 Right Justified Boxes Task

The right justified box task is a cursor task, in which the subject tries to hit one out of n targets on a screen in trials of equal length. As listed in figure 7.3, the task requests and controls specific states.

Whatever signal processing algorithm is used, it can passively monitor these states and modify its operation accordingly, e.g., one algorithm might derive its baseline from the inter-trial interval (i.e., ITI), whereas another might calculate it differently. In this fashion, signal processing algorithms can be interchanged without affecting the user application.



State	1	2	3	4	5	6	7
TargetCode	0	2	2	2	2	0	3
Baseline	1	0	0	0	0	1	0
Feedback	0	0	1	1	0	0	0
IntertrialInterval	1	0	0	0	0	1	0
ResultCode	0	0	0	0	1	0	0

Figure 7.3: Time Line for Right Justified Box task. The top-most target position corresponds to TargetCode=1. TargetCode increases towards the bottom. ResultCode corresponds to the target actually selected. Thus, if TargetCode equals ResultCode, the trial was a hit, otherwise a miss.

Figure 7.3 illustrates the time line for the right justified box task and, for each time interval, its respective content for each state.

1 is the intertrial interval, were the screen is blank and baseline data can be collected (optional). In 2 the target is presented, but the cursor is absent (no feedback). In 3 the cursor is present and it's vertical movement is controlled by the user's EEG. Horizontal cursor movement is under computer control and is at a constant rate. In 4 the cursor approaches the target and in 5 the target has been hit and trial-outcome feedback is presented. In 6 the screen is blank (intertrial interval again) and in 7 another target is presented.

Chapter 8

Glossary

Real Time

There are many definitions of the term *real time*. One example (as presented on http://www.zdwebopedia.com/TERM/r/real_time.html) is:

Occurring immediately. The term is used to describe a number of different computer features. For example, real–time operating systems are systems that respond to input immediately. They are used for such tasks as navigation, in which the computer must react to a steady flow of new information without interruption. Most general–purpose operating systems are not real–time because they can take a few seconds, or even minutes, to react.

Real time can also refer to events simulated by a computer at the same speed that they would occur in real life. In graphics animation, for example, a real–time program would display objects moving across the screen at the same speed that they would actually move.

Appendix A

List of Requested States

Project	**Unit**	**State**	**Description**
DTsource	DTADC.cpp	Running	Indicates when system is running
DTsource	DTADC.cpp	Active	What is the difference between running and active?
DTsource	DTADC.cpp	SourceTime	Time when data is acquired
Dtsource	DTADC.cpp	RunActive	What is the difference between this, active and running?
SignalProc	Statistics	Artifact	Identifies artifact in current data
Application	Application.cpp	StimulusTime	Time when stimulus is displayed
Application	Application.cpp	TargetCode	Identifies the active target
Application	Application.cpp	Baseline	Identifies when baseline data is collected
Application	Application.cpp	Feedback	Identifies when feedback is presented to user
Application	Application.cpp	IntertrialInterval	Identifies inactive period between trials
Application	Application.cpp	Outcome	Identifies trial outcome (0= pending, 1= hit, 2=miss)
	to	be	announced

Appendix B

List of Requested Parameters

Project	Unit	Section	Type	Parameter	Description
Dtsource	Storage.cpp	Storage	string	FileName	Name of Data File
Dtsource	Storage.cpp	Storage	string	SubjectName	Name of subject
Dtsource	Storage.cpp	Storage	string*	SubjectSession	Session Number
Dtsource	Storage.cpp	Storage	string*	SubjectRun	run number
Dtsource	Storage.cpp	Storage	string	StorageTime	time of beginning of data
Dtsource	dtadc.cpp	Source	int	SoftwareCh	number of digitized channels
Dtsource	dtadc.cpp	Source	int	TransmitCh	number of transmitted channels
Dtsource	dtadc.cpp	Source	int	SampleBlockSize	number of samples transmitted at a time
Dtsource	dtadc.cpp	Source	int	SamplingRate	sample rate
Dtsource	dtadc.cpp	Source	string	BoardName	AD board name from driver
Dtsource	dtadc.cpp	Storage	string	FileName	Data File Name
SignalProc	Calibration	Filtering	floatlist	SourceChOffset	offset in A/D units
SignalProc	Calibration	Filtering	floatlist	SourceChGain	gain for each channel (A/D units to μV)
SignalProc	Calibration	Filtering	int	AlignChannels	align channels in time (0= no, 1= yes)
SignalProc	Calibration	Visualization	int	VisualizeCalibration	visualize calibration channels
SignalProc	Spatial	Filtering	int	SpatialFilteredChannels	Number of spatially filtered channels
SignalProc	Spatial	Filtering	matrix	SpatialFilterKernal	Spatial Filter Kernal Weights
SignalProc	Spatial	Visualization	int	VisualizeSpatialFiltering	Visualize Spatial Filtering?
SignalProc	Temporal	Filtering	float	StartMem	Start of Spectrum in Hz
SignalProc	Temporal	Filtering	float	StopMem	End of Spectrum in Hz
SignalProc	Temporal	Filtering	float	deltaMem	Resolution (line density) in Hz
SignalProc	Temporal	Filtering	float	MemBandWidth	Spectral Bandwidth in Hz
SignalProc	Temporal	Filtering	int	MemModelOrder	AR model Order
SignalProc	Temporal	Filtering	int	MemDetrend	Detrend data? (0=no, 1= mean, 2=linear)
SignalProc	Temporal	Visualization	int	VisualizeTemporalFiltering	Visualize Temporal Filtering
SignalProc	Classifier	Filtering	matrix	MUD	Classifier Up/Down Control Weights
SignalProc	Classifier	Filtering	matrix	MLR	Classifier Left/Right Control Weights
SignalProc	Classifier	Filtering	int	VisualizeClassFiltering	Visualize Classifier Filtering (y/n)
		to	be	announced	

Appendix C

List of Source IDs

Module/Filter	Defined As	Source ID
EEG Source	SOURCEID_EEGDISP	53
Calibration Filter	SOURCEID_CALIBRATION	54
Spatial Filter	SOURCEID_SPATFILT	55
AR Temporal Filter	SOURCEID_TEMPORALFILT	56
Classifier	SOURCEID_CLASSIFIER	57
Normalizer	SOURCEID_NORMALIZER	58
Statistics Module	SOURCEID_STATISTICS	59
User Task Log	SOURCEID_TASKLOG	60
to	be	announced

Appendix D

Error and Status Messages

Code	Text
200	EEGsource module initialized successfully ...
201	SignalProcessing module initialized successfully ...
202	Application module initialized successfully ...
203	EEGsource started ...
204	EEGsource suspended ...
205	SignalProcessing started ...
206	SignalProcessing suspended ...
207	Application started ...
208	Application suspended ...
300	Parameters are inconsistent ...
301	State vector update timeout !
302	PostSetInterval shorter than time derived by NumERPSamples
303	One of the parameters needed by the task not found
400	Could not initialize socket connection to Signal Processing
401	Could not initialize socket connection to Application
402	Could not initialize socket connection to Source
403	Signal Processing dropped connection unexpectedly
404	Source dropped connection unexpectedly
405	Application dropped connection unexpectedly
406	Could not set SourceTime in the statevector
407	Error creating filters
408	Error initializing filters
409	Error while processing filters
410	Source: could not initialize connections
411	Error in Source: Exception thrown while initializing: !
412	Signal Processing: state vector is not defined !
413	Signal Processing: Exception thrown in Initialize()
414	Application: state vector is not defined !
415	P3 Temporal Filter: Inconsistency or ran out of buffers
416	P3 Speller: Could not open target definition file
417	Number of targets HAS TO BE 2 in Yes/No mode !!
499	Logic Error (error condition otherwise unhandled)