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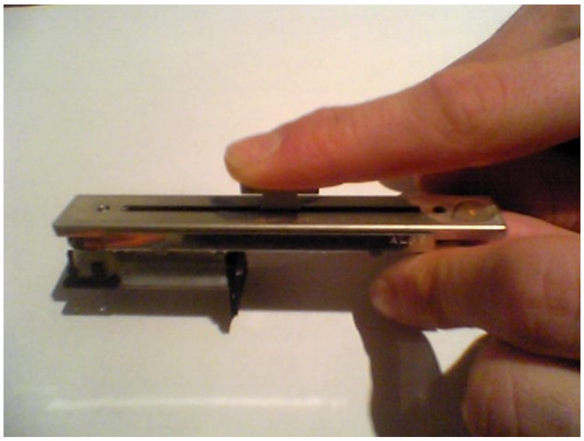

Digital Force Feedback Slider: Software Design and Implementation

Master of Science Thesis

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Digital Force-Feedback Slider: Software Design and Implementation

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Abstract

This report presents and discusses software realization for a user interface device called force-feedback slider. Our force-feedback slider is a one-dimensional actuated device connected to a host computer via USB. The main feature of this device is its ability to display force to its user and estimate the force employed by the user's hand. The work started as a project to improve the functionality of an existing analogue device. Since the analogue device was difficult to control, a new digital device was designed and realized. In this report the modelling and implementation of the new device is discussed and the results and potential future works are represented.

Acknowledgement

My master thesis work was conducted at T2i lab at Chalmers University of Technology in Gothenburg Sweden. The project included 20 academic credits and is conducted as an end phase to my master program in computer engineering.

This project was defined and supervised by Morten Fjeld. Here I want to thank him for all his help, effort and support which made the conduction of this interesting project possible for me. I thank Julio Jenaro for his work on the hardware of the system and his helpfulness. I also want to thank the other members of the T2i lab for their constant support and help and for providing a nice, calm and friendly atmosphere to work in.

Contents

Definitions

Lookup table is a data structure and in our case an array with different values for different parameters that can be looked up from the memory by the program. This reduces the delay and computations done by the processor.

Application or application software is a part of the computer software which uses the basic functionality given by the different devices and drivers and services to provide functionality to the user or perform a specific task on the computer.

Java is an object-oriented programming Language. Java was developed by Sun Microsystems during 1990s.

Embedded system is a computer designed for a specific purpose and only performs the tasks that are predefined for it.

Host computer When an external device is connected to a computer, the computer is called host to that device.

Acronyms

OS	Operating System
I2C	Inter-Integrated Circuit
TWI	Two-Wire Interface
USB	Universal Serial Bus
ASIO	Audio Stream Input Output
ADC	Analogue-Digital converter
DAC	Digital-Analogue converter
PWM	Pulse width modulation
LUT	LookUp table
FF	Force Feedback
FFS	Force Feedback Slider
API	Application Programming Interface
RISC	Reduced Instruction Set Computer
USART	Universal Asynchronous Receiver/Transmitter
UART	Universal Asynchronous Receiver/Transmitter

1 Introduction

This report discusses the process and results of digitalizing the platform of a force feedback slider. This project has been done as a master thesis at the Computer Science and Engineering department at Chalmers University of technology in Gothenburg, Sweden. The project started in summer 2006 and ended in February 2007.

In the physical world much information is received with the help of the tactile sense. Most often this information is unique for this sense and can not be received from any other perceptual channel. Human beings have a fast sense of touch [1] and we are used to receive tactile feedback to build a better comprehension of things. In the computer world most of the information is received via the visual and hearing senses. In some cases this might overload the visual channel. Furthermore much information normally received in the everyday situations is not attended. To overcome this gap between the digital and physical world some efforts from research and industry has been made. Most of the existing force feedback systems that were available before the start of the project like Phidgets [2], iStuff [3] and commercial force-feedback joysticks have had force as output and not input, therefore not being able to interpret the user force fully. Most of the systems even lack the capability to dynamically steer and control the output force in a quick and natural way and the feedback is widely by vibrations of different frequency and intensity.

1.1 Purpose of the Project

Research about user interface devices with force feedback is relatively new. Hoping to make progress in the field, the force-feedback slider (FFS) project was started. The project was designed to build a system to operate with force in addition to position as input and output. To prove this concept the analogue slider was built in the scope of another master thesis performed at Chalmers University of Technology. The system presented large delay and instability trying to create some force feedback. The system also had some integration issues with different computers and platforms.

These facts required us to make a new digital platform, a more stable system with less delay to give the user a better feeling of a continuous force feedback.

1.2 Potential Applications

The physical sliders are used to easily control one-dimensional parameters of systems. Today the sliders are more advanced and can dynamically be controlled by digital systems. Adding a force feedback feature to a slider can be interesting for many applications. Some of those applications are:

- **For education purpose:** The FFS can be used to simulate physics laws and even for learning of multi-dimensional mathematical models in other fields.

- **In industrial machines:** An example can be steering a robot or machine from distance. This is of course possible now but the extra force feedback feature makes the control much more accurate and natural. This has of course been already used in some industries, but the cost of the devices there are much higher than the one we provide.

- **Medicine:** This device can be used for remote controlling a surgery robot or it can even be used for optimization purposes in medical treatments.

1.3 Problem Definition

According to the purpose of the project a system with the following properties is required:

- The system should consist of up to 16 one-dimensional actuated sliders.
- The device should be able to connect to the computer via USB.
- The system should be OS-independent.
- It should be able to operate with different forces and dynamically change the forces during operation.
- The force and position should be available as input and output for each and every slider in the system.
- The sliders should respond to the orders sent by the computer in less than half a second.
- The user should feel the feedback as a smooth and continuous force. The human tactile sense detects forces with frequency less than one KHz as inconsistent. Therefore to generate a smooth and continuous feeling the sliders should operate with a frequency more than this amount.
- The system should be stable and perform its functionality as long as the user wants it to. It should even be independent of any computer settings that are not directly related to the device.
- The system should provide a standard and easy to use API for developing applications easily.
- The sliders should be able to cooperate and work synchronously if the application requires that.
- The following force functions should be accessible to application programmers:
    - User mode: Allowing the application to control the slider directly during run-time
    - Function mode: Creates forces according to polynomial functions.
    - Lookup table mode: slider behaves according to the specifications in the lookup table sent to it.
- Each slider should have a button implemented which can have different functionalities depending on the application. This functionality can be chosen by the application via the API.

- Each slider should have a diode onboard that can be turned off an on by the application via the API.

1.4 Previous work

This part introduces the background of the project as it was before the start of this master thesis.

1.4.1 Analogue Slider

The analogue FFS [4][5]is a motorized potentiometer, previously part of a sound mixer. The digitalization of the signals from the slider is done by an external sound card connected to the PC via USB. A special circuit is designed and put on top of the sound card that takes care of the conversions and other necessary tasks. When the converted digital values come to the PC from the sound card they are processed. When they are ready they will be sent as digital signals to the sound card and there they are converted to analogue voltage understandable for the slider motor.

Analogue FFS features five predefined modes. In position, the slider is used only as input device, the motor is switched off, and the user can move the slider without FF. In elasticity, default position and maximal force are set and the user’s fingers have to overcome this force. When the handle is released, it returns to the default position. Gradual offers a number of discrete steps into which the handle can snap. In texture, high-frequency low-intensity vibrations are applied to the handle, thus giving users an impression of a rough surface. In oscillation, the handle comes to rest after a damped sine movement. These five haptic profiles are abstract descriptions of FF capacities; other applications can be composed from these modes.

1.5 Report Structure

The report is offered in eight parts. The **Introduction** gives an overview of the background and goals of the project. The **Employed Technologies** are summarized and presented in the next part. In the **Analysis** section, the approaches are discussed. The final **Software Design** is given after the analysis section. **Software Implementation** and **Testing** show how the design was followed and realized to achieve the project goals. Finally, the **Conclusion** and **future works** will end this report.

2 Employed Technologies

The technologies used during the project are briefly presented in this chapter. This is just a short reference and description and more information can be found following the references.

2.1 Analogue-Digital Converter (ADC)

An AD-converter is a circuit that converts continuous signals to discrete digital values. A DA-converter performs the opposite task. In the case of this project the AD/DA converters convert the continuous voltage to digital values understandable by the computer or the other way around.

The resolution of the conversion is the different number of digital values that the analogue signals can be converted to. The resolution is usually expressed in bits. Meaning if the ADC produces 1024 different values it is said to operate with 10-bit resolution ($2^{10} = 1024$).

2.2 ASIO (Audio Stream Input/Output)

ASIO [6][7] is a protocol for low latency digital audio designed by Steinberg. ASIO is an application program interface toward the sound card. Unlike Microsoft’s DirectSound which usually is for stereo input and output, ASIO can handle several input and outputs. This technique is used by recording studios and professional musicians due to its low delay and the possibility of several input and output channels. The low delay provided by this method is due to the bypassing of the operating system audio mixing kernels. Hence, ASIO can communicate directly with the audio hardware.

2.3 Atmel ATmega8

According to Atmel Atmega8’s datasheet [8]:

> “The ATmega8 is a low-power CMOS 8-bit microcontroller based on the AVR RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega8 achieves throughputs approaching 1 MIPS per MHz, allowing the system designer to optimize power consumption versus processing speed.”

2.4 I2C

According to wikipedia.org [9]:

> “I²C is a multi-master serial computer bus invented by Philips that is used to attach low-speed peripherals to a motherboard, embedded system, or cell phone. The name stands for Inter-Integrated Circuit and is pronounced I-squared-C and also, incorrectly, I-two-C. As of October 1, 2006, no licensing fees are required to

implement the I²C protocol. However, fees are still required in order to obtain I²C slave addresses.

I²C uses only two bidirectional open-drain lines, serial data (SDA) and serial clock (SCL), pulled up with resistors. Typical voltages used are +5 V or +3.3 V although systems with other, higher or lower, voltages are permitted.

The I²C reference design has a 7-bit address space with 16 reserved addresses, so a maximum of 112 nodes can communicate on the same bus. The most common I²C bus modes are the 100 Kbit/s standard mode and the 10 Kbit/s low-speed mode, but clock frequencies down to zero are also allowed. Recent revisions of I²C can host more nodes and run faster (400 Kbit/s Fast mode and 3.4 Mbit/s High Speed mode), and also support other extended features, such as 10-bit addressing.

The maximum number of nodes is obviously limited by the address space, but also by total bus capacitance to 400 pF."

2.5 Pulse-Width Modulation (PWM)

According to wikipedia.org [10]:

> "Pulse-width modulation (PWM) of a signal or power source involves the modulation of its duty cycle, to either convey information over a communications channel or control the amount of power sent to a load.
>
> Pulse-width modulation uses a square wave whose duty cycle is modulated resulting in the variation of the average value of the waveform. If we consider a square waveform f(t) with a low value y_{min}, a high value y_{max} and a duty cycle D (see figure 1), the average value of the waveform is given by:
>
> $$\bar{y} = \frac{1}{T}\int_0^T f(t)\,dt$$
>
> As f(t) is a square wave, its value is y_{max} for $0 < t < D \cdot T$ and ymin for $D \cdot T < t < T$. The above expression then becomes:
>
> $$\begin{aligned} \bar{y} &= \frac{1}{T}\left(\int_0^{DT} y_{max}\,dt + \int_{DT}^{T} y_{min}\,dt\right) \\ &= \frac{D \cdot T \cdot y_{max} + T(1-D)y_{min}}{T} \\ &= D \cdot y_{max} + (1-D)\,y_{min} \end{aligned}$$
>
> This latter expression can be fairly simplified in many cases where $y_{min} = 0$ as $\bar{y} = D \cdot y_{max}$. From this, it is obvious that the average value of the signal ($\bar{y}$) is directly dependent on the duty cycle D."

2.6 USART (Universal Asynchronous Receiver/Transmitter)

According to wikipedia.org [11]:

> “A universal asynchronous receiver/transmitter (usually abbreviated to USART or UART) is a type of "asynchronous receiver/transmitter", a piece of computer hardware that translates data between parallel and serial interfaces. Used for serial data telecommunication, a UART converts bytes of data to and from asynchronous start-stop bit streams represented as binary electrical impulses.
>
> A UART is usually an individual (or part of an) integrated circuit used for serial communications over a computer or peripheral device serial port. UARTs are now commonly included in microcontrollers (for example, ATMEGA8). Many modern ICs now come with a UART that can also communicate synchronously; these devices incorporate the word synchronous into the acronym to become USARTs.”

3 Analysis

With the analogue system as a proof of concept, the project had come to its next step. In this step we wanted to build a stable prototype with more functionality than the existing device. In order to fulfil the requirements listed in 1.3 several solutions were suggested.

In the beginning we were looking for another analogue solution which could improve the existing system without the need to change the whole system. In order to do this we searched for better technologies than DirectSound to work with the signals in the sound card. Some different possible technologies were explored and the best one suited for this project was the ASIO technology. ASIO is a low delay, fast technology with ability to operate with several simultaneous inputs and outputs. The problem we encountered was that the sound card we were using was not fully compatible with ASIO. It was also hard to manage several sliders connected to the same card even with this technology. After some studies on this technology, we decided not to use the analogue platform any more and start building a new slider from scratch.

After exploring the different options and brainstorming with different experts in the area we decided to create a fully digital solution. In this solution microcontrollers with integrated AD/DA converters would be installed on the sliders in order to control their performance characteristics. The desired performance characteristics would be coded as lookup tables by the application running on the computer and sent to the memory of the microcontrollers. The microcontrollers would be able to decode the tables and move accordingly.

3.1 Hardware Design

The hardware of the sliders was designed by Julio Jenaro and the following is a quote from his report on the design of the hardware [12]:

> “The hardware design is manifold. Initially the system has to be able to control up to sixteen sliders. This can be achieved having one microcontroller in charge of the control of the sixteen motors and also of the communication with the PC using the USB protocol. In this case the motors could also be connected in a modular manner.

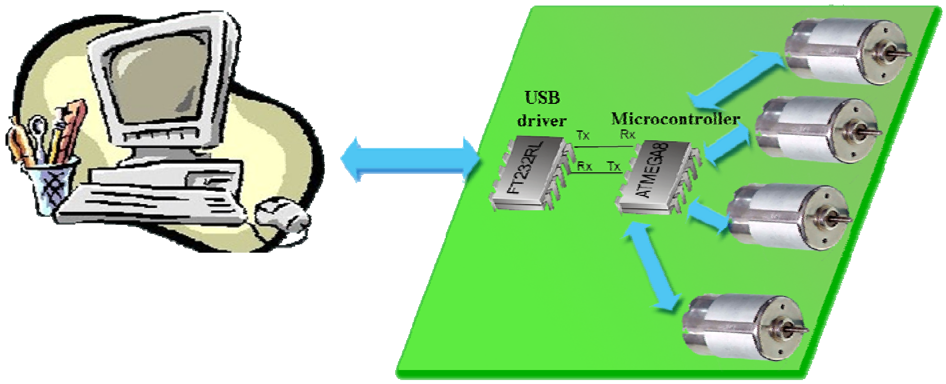

Figure 1: Diagram for only one microcontroller

After several simulations and studies, this first approach was discarded because despite it could accomplish the requirements of the controllability, it would require a very complex programming to optimize the timings in the motor control. Furthermore, this configuration would not be useful for future applications where more sliders were required, because only one microcontroller to control all the motors will take a lot of resources. A general description of this schematic is presented in Figure 1.

This option was discharged in favour of the final option of using one microcontroller to manage the communication with the PC and the different slider boards. This option may be not cheaper but introduce high range of modularity in the system, not only making it easier to redesign the system but also to fix the slider in case they break. In addition, this option was chosen in order to reduce the latency in the control of the motor, which was one of the priorities in the project.

The microcontroller Atmega8 was proposed for the project in due to its reduced price and its RISC architecture, contributing to a relatively easy programming of the firmware. This determined the hardware design in the main board and also in the slider board. The same microcontroller was chosen for both boards in order to facilitate the firmware programming, because in both cases no more flash memory was required and the number of resources was enough to fulfil the requirements in both kinds of boards.

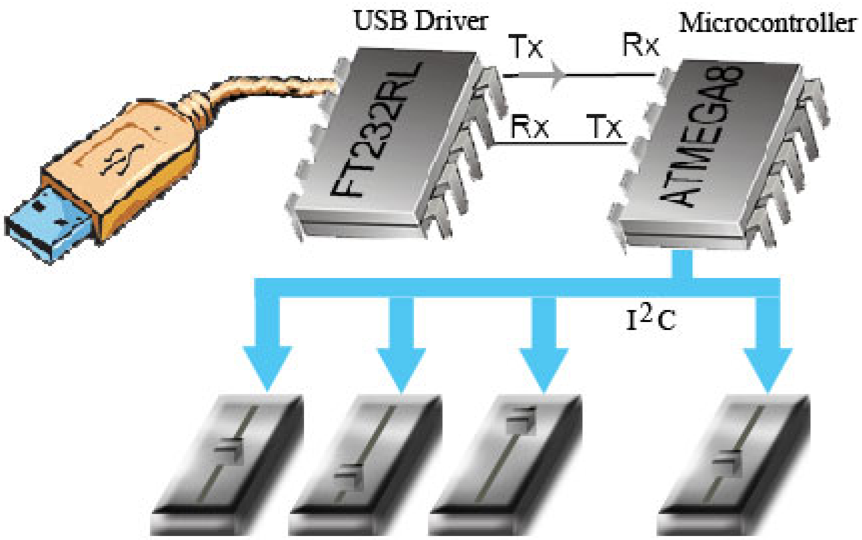

Figure 2: Diagram for the final hardware design

In order to communicate the slider boards and the main board it is necessary to design a communication bus. The I2C bus was chosen because it is easy to program and it allows connecting high number of devices and high communication speed. Meanwhile it also has a simple design Thanks to this protocol it could be possible in a future work to add EEPROM memories in a modular manner if more memory is required and also LCD screens.

Another requirement was to communicate the system with a PC. This can be achieved in different ways: serial port, parallel port, Bluetooth, infrared … At the end the USB connection was chosen because it tolerates high communication speed, it can be easily recognized by the operative system in the PC. Other important reason was its reduced cost and easiness to use and program the communication parameters. "

To generate different forces some options were available. The principle is to put different voltages over the slider motor to get different forces. Since the power supply generates a constant voltage, a technique should be used to regulate the voltage to different values. The technique that was chosen was PWM. In PWM the voltage is supplied to the motor for a quote of the time and for the rest of the time the voltage is zero. Using this technique the force experienced by the user is the mean of all the forces generated by the motor. This force will be experienced as continuous if the voltage over the motor is changed with high frequency. The final hardware design is shown in Figure 2.

Some other requirements of the device were that each slider should have a dedicated button and diode. These parts should be controllable by the application running the slider.

3.2 Requirements

According to the hardware design presented in the previous section, the system is divided in three parts: the slider board, the main board and the host computer. Each of these parts has its own software design and requirements.

Requirements for the slider board are:

- The frequency of PWM generated by the microcontroller on the board should be more than 10 KHz.

- The slider board should be connected to the main board via its TWI module running the I2C protocol.

- The slider board should take the commands from the main board and return the requested values to the main board.

- The slider should operate in the following modes
    - User mode: Allowing the application to control the slider directly during run-time
    - Function mode: Creates forces according to polynomial functions.
    - Lookup table mode: slider behaves according to the specifications in the lookup table sent to it.

- The slider should be able to read the force applied by the user to the slider handle and position of the slider handle.

- The slider should be able to dynamically change its force during run-time.

- The microcontroller should be able to recognize if the button on the board is pressed or not.

- The microcontroller should be able to turn the diode on and off.

Requirements for the main board are:

- The main board should be connected to all the active sliders via an I2C connection.

- The main board should be connected via its USART interface to the USB chip onboard. This USB chip should connect to the computer and speak to the active program using the defined protocol for this communication.

- The main board should operate as a gateway between the sliders and the computer. It should forward the commands of the application running on the computer to any specified slider and it should answer the requests made by the application. These requests are the parameters of the sliders or the main board.

Requirements for the driver and API installed on the host computer are:

- The API should work for all operating systems.
- The slider functionality should be independent of any settings on the computer.

- The driver should be able to connect to the main board(s) connected to the computer. It should send and receive necessary information following a specific protocol also known by the main board.

- The API should provide standard and easy-to-use functions for the programmers developing software using the sliders.

4 Software Design

Given the hardware design the software is divided in several layers. Some layers are directly related to the physical boards and some are communication layers. In this chapter all the parts of the software design are discussed.

4.1 Slider Functionality

The microcontroller onboard the slider board is responsible for controlling the slider and handling the communication with the main board. In this section the functionality of the slider is discussed.

The functionality of the slider is mainly controlled by setting and reading the values of the different ports of the microcontroller. To be able to manage when to set the ports and what to set them to some technologies were used.

4.1.1 PWM

Due to the design of the hardware of the force feedback slider, the voltage sent to the slider motor is always either zero or the maximum voltage of the system. Using these two voltages we can only produce one force which is the maximum force. This is done by sending the maximum voltage to the slider motor all time.

To overcome this problem we should let the motor work with full speed for a part of the time and rest for the remaining part. If the motor is running with high frequency, these interruptions will not be noticeable by the human sense of touch. Since the maximum operating frequency of the PWM applied to the slider motor is around 20 KHz and the minimum frequency detected by human to be inconsistent is 1 KHz if we chose any PWM frequency between these values the slider will function according the requirements. Doing this we produce different forces, because the force felt by the user will be the average of the force created by the slider. For example if the slider works during 30% of the PWM length and rests the remaining time, the force experienced by the user will be 30% of the maximum force.

Since the produced torque is proportional to the current through the winding in the motor and the torque is the resultant force multiplied by the "radius of the motor", we can always perform a force control over the slider.

4.1.2 Functioning Modes

The slider functions in different modes. These modes are listed and explained bellow:

- **User mode:** In this mode the slider tries to get to a specific reference position applying a specific force. The force and the reference position are received from the application. Using this mode the application can completely control the movements of the slider during run-time and depending on any new event a new action can be taken.

- **Lookup table mode**: In this mode the instructions of how the slider should behave are sent from the beginning to the slider. The slider reads the lookup table and depending on the position of the slider and the direction of movement it performs different actions. The lookup table can of course be changed during run-time.
  The values in the table are intervals of position and what force should be applied in those intervals.
  The difference between this mode and the user mode is that in this case you know from the beginning how you want the slider to behave, but in the user mode you figure out the next action taken just when something happens.
  The lookup table mode is a very general mode and specializations can be made. One useful specialization is the Tick-mode. The Tick-mode is a standard for the software sliders. In this mode we receive some tick positions. When the position of the handle is close to one of those ticks, the slider moves toward the tick as if the tick absorbs the slider handle. To get away from the tick more force than the usual force should be applied.

- **Function mode:** The function mode simulates a polynomial function as the force of the slider. In the currently realized version the function is a second degree function.
  $F = a_1 * x^2 + a_2 * x + a_3$
  Where a_1, a_2, a_3 are constants provided by the current application and x is the deviation between the reference position and the current position of the slider.
  This mode can simulate very useful and common functions like the movement of a spring, which is $F = k*x$.

- **Program mode:** Using the program mode you can make the slider follow a certain path with certain forces. This is done sending a LUT to the microcontroller. This lookup table specifies the next goal position and with what force you want to get to that position. The difference between this mode and LUT mode is that this mode operates actively while the LUT mode is a more resistive mode which operates according to the current position of the slider.

- **Rest mode:** In the rest mode the slider motor is not working and it dose not apply any force. The slider just passively reads the value of the position and other parameters.

4.1.3 AD/DA Converters

Atmgega8 has four pins that can be dedicated to digital-analogue conversion. In the slider these four pins are dedicated to reading the *current* running through the motor, *voltage* over the motor, the *button* and finally the *position* of the slider handle. All the AD conversions are set to convert the analogue signals to digital values of 8-bit resolution, besides the current which is measured by 10-bit resolution.

The voltage pin is used to detect the voltage over the motor. This can be used for calibrating the different systems. By using different PWM pulses depending on the voltage two different sliders can produce the exact same force.

The value of the current is used to detect the user force. The current is measured with 10-bit resolution for getting a more accurate result of the user force. More about this is discussed in the next section.

4.1.4 Interpreting the User Force

When the user moves the slider handle a torque in the motor is produced. This torque changes the motor current from the standard value that it should have. By comparing this current with the current received when no user force is applied, as estimation of the user force can be calculated. This deviation is very small and this makes it very hard to calculate a precise user force. On the other hand the amount of the deviation is different depending on the average voltage over the motor. The higher slider force applied, the higher deviation is received. Unfortunately this deviation is not linearly proportioned to the slider force and is therefore very hard to calculate. This fact is illustrated in Figure 3.

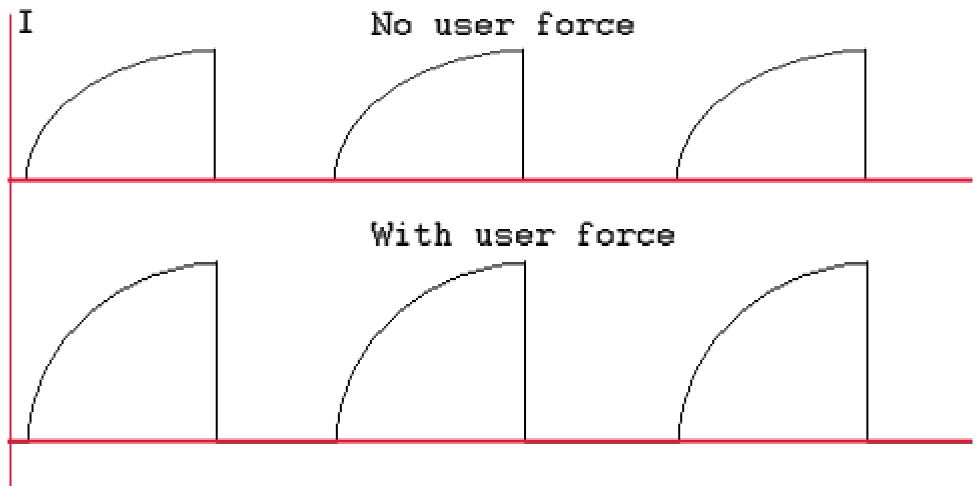

Figure 3: Interpreting the force that the user applies to the slider by measuring the current going through the slider motor.

Another problem with the current is that it takes time for the current to reach the final value. This time is called the rise time. Because of this, unlike the other parameters that can be measured any time, the current should be measured in the very last moment of the period of PWM that the motor is on. Although anti-noise precautions are used, all the other activities in the microcontroller make the process of calculating the current very noisy. All this together makes calculating the actual user force to a very hard process.

In the end of the project some of the problems could be solved and an approximate calculation of the user force could be performed. This was tested in a remote collaboration application that was done in the scope of another master thesis [13].

4.2 Communication between Board and Sliders (I2C)

The communication between the main board and the sliders is done via the TWI module of the microcontrollers. The communication protocol used is I2C. In the hardware the I2C bus starts from the main board and connects all the sliders together in a series connection.

In the software layer the main board is operating as the I2C master. Each slider has a unique slave address. When a packet is sent to the slider's slave address, a connection is started.

In the initialization process, the master (main board) addresses all the possible slave addresses. If any slider responds, the main board saves its address for future communication. After handshaking with all the connected sliders, the main board now wants to gather information from the sliders. Since the board is the master and only the master can initiate an I2C communication, the board starts to address each and every slider in order. The board can operate in the following two different ways. The first one is default.

- The board asks for all the parameters of the sliders. In return the slider answers with all the information and when done, the connection is terminated and the board addresses the next slider.
- The second solution is that the board asks the slider if anything has changes. The slider sends a byte representing what parameters have changed, following that the new values of the parameters.

4.3 Main Board Functionality

The main board does not have any operational duties. It just acts as a gateway for connecting the sliders to the computer. The reason why the sliders are not connected directly to the computer is to avoid having several USB modules and cables. This would also increase the amount of data processed by the computer which would be an undesired result. The main board functions as I2C master. It receives the data from the sliders and sends the interesting values on to the computer via the USB module.

4.4 Communication between Board and Computer (USART)

The microcontroller on the main board sends the data that should be sent to the computer to the USB chip via its USART module. It also receives the data sent by the application in the reversed way. The data sent by the main board can have the two following forms. This depends on the configuration decided by the application.

- In the first mode, the main board receives the data from the sliders. It keeps track of all the changes in the slider parameters. When something changes it sends the event on to the computer.
- In the second mode the main board does not send anything to the computer unless it has been asked to do so.

4.5 API

The API is done in Java. The reason for that is to have the maximum flexibility and platform independency. The sliders are also very closely related to the standard library *JSlider* which allows a very easy-to-use and standard API. The API design can be seen in Figure 4.

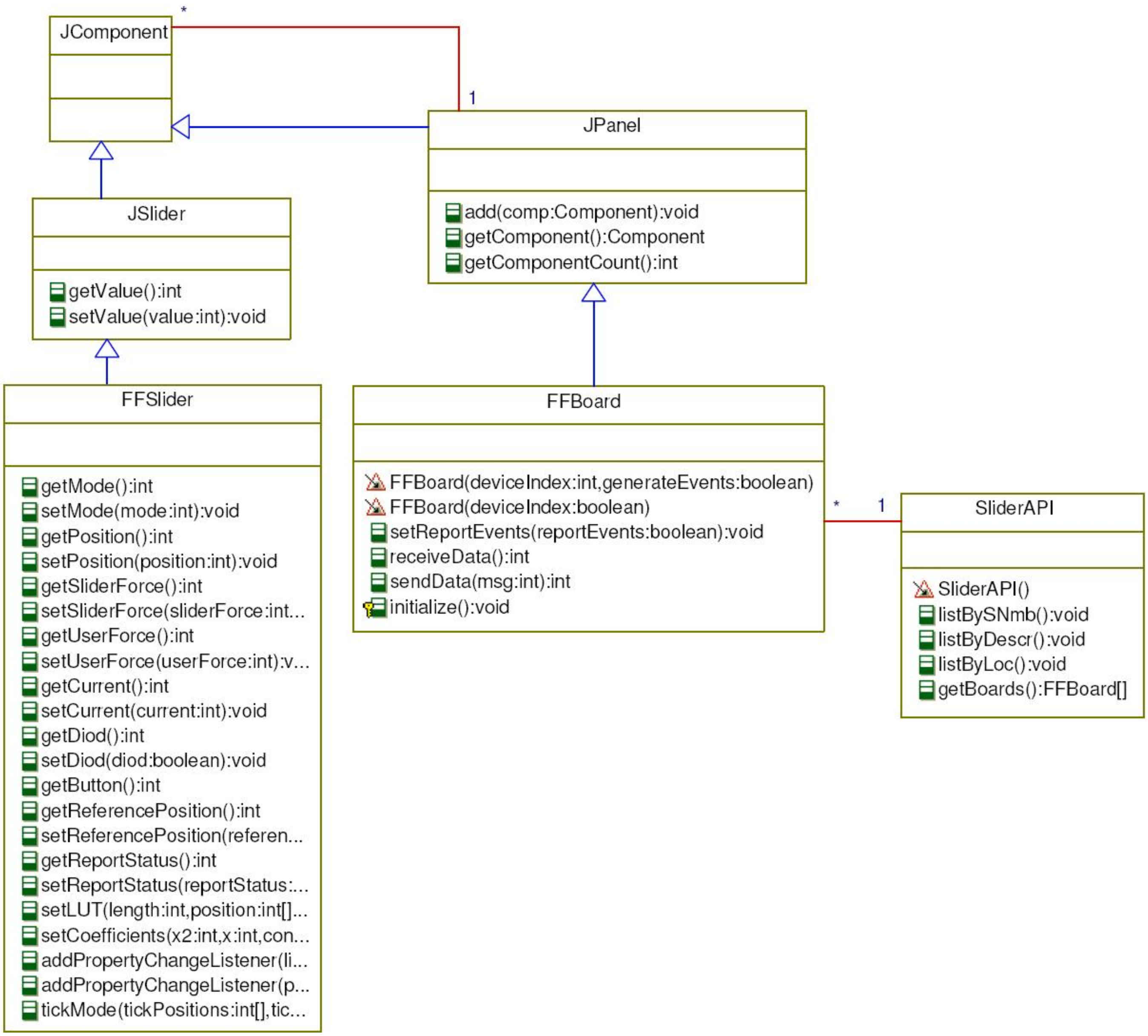

Figure 4: The software architecture of the API designed to communicate with the main board and the sliders connected to the board.

The API is designed in such a way that each board connected to the computer is seen as a JPanel container including several FFSliders which are Java classes extending JSlider. Each JSlider is directly corresponding to the physical force feedback slider. If the program is run in event based mode, which is the default mode, all the properties of the

FFSlider objects are automatically updated to correspond to the properties of the physical slider. This feature allows the user of the API to have access to all the values of the slider and have a graphical JSlider corresponding to each slider without having to write more than two rows of code.

Sending commands to the sliders is just as easy as reading their values. By calling a simple function the application is able to set any parameter of the slider. The user can even add a PropertyChangeListener to watch the changes in the sliders and act according to them.

5 Software Implementation

The implementation phase started by testing some very simple programs to test the functionality of the hardware and make sure all the parts were functioning as they were supposed to, for example the movement of motor and reading of the position. Since the design and realization of the hardware was going on in the same time as the software much of the hardware bugs were found and fixed before the implementation started.

After making sure of the functionality of the essential parts of the slider the implementation was divided into several phases. These phases are listed below:

- Movement of one slider with different operation modes. The lookup tables and the coefficients of the polynomial equations are hard coded into the code in this phase. Make sure the right value is read from the AD/DA converters.
- Fixing the I2C protocol for one slider. Make sure the right data is sent over the channel.
- Completing the I2C protocol for several sliders and make sure commands sent from the main board are executed at each slider.
- Sending data from main board and receiving them in the computer.
- Creating the API and receiving data and sending commands from the computer to the sliders.
- Fixing events in the main board and the slider board

After each phase a test and integration phase is performed to make sure that all the new functionality is working and the previous functioning parts are still running properly.

5.1 Implementation Languages and Environment

Implementation of the code for the microcontrollers was done in the programming language C. The programming environment was AVR studio 4.0 [14] which is a special made editor and C compiler for AVR embedded systems. This program could compile the C files and converted them to HEX-files which could be programmed directly to the microcontrollers.

Since the choice of Java for the API, Eclipse [**Error! Reference source not found.**] which is a powerful Java development environment was used. The classes used were mostly the standard classes of Java 1.5. An extra library called FTD2xx was added for handling some parts of the USB communication. [16]

All the coding was done under the operative system Windows XP with service pack 2. D2XX driver and dll-file [17] were installed on the PC. This made the computer able to recognize the main boards connected. The drivers were for the communication between the PC and the USB chip installed on the main board. After installing the driver with the help of a test program called D2XXAPP [**Error! Reference source not found.**], we were able to monitor and track the communication over the USB channel.

In order to program the microcontrollers a programmer was required. For this matter we chose AVRISP mkII [**Error! Reference source not found.**], which is a standard AVR programmer connected to the PC via USB. The programmer is even compatible with AVR studio.

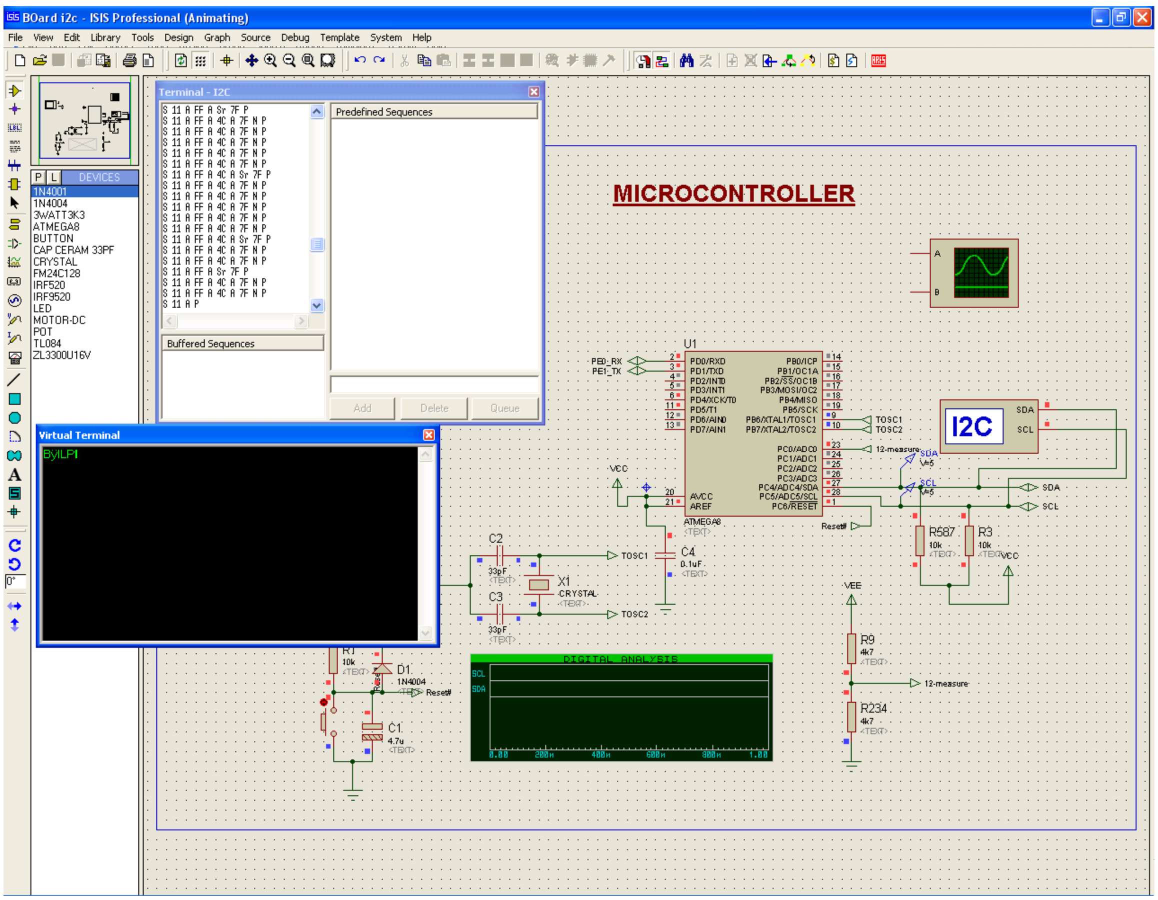

Figure 5: Proteus 6.0 simulator was used to simulate and debug the FFS.

For testing the I2C connection and some other functionalities of the slider, a simulator called ISIS, which comes with the developing environment software Proteus 6.0 [**Error! Reference source not found.**] was used. By defining the schematics of the circuit Proteus simulates it. This was used mostly for testing the I2C communication. A picture of the interface of this program can be seen in Figure 5.

5.2 Integration and Test

After each cycle of implementation the integration was tested, because much of the codes from different parts were directly connected to each other. This was due to the fact that the design consisted of several layers several layers with communication protocols between each two layers. Therefore it was essential to find out partly whether the hardware was working as it should and partly make sure that the communication protocols were free of bugs as soon as possible.

To test the functionality different methods and programs were used.

- To check the functionality of the slider different test codes were tested for checking the movement of the slider. Some hard coded tricks were also used to make sure that the AD conversion was working correctly. When an error was detected, with help of multimeter and oscilloscope the bug was found and fixed.

- To test the I2C communication the Proteus program was used. Loading the HEX-codes in the program you can see all the elements of the I2C communication. The start, stop, acknowledgement and values sent over the I2C channel are presented in a structured way.
  Unfortunately because of some bugs in the Proteus program for handling the I2C communication, discovered late in the testing process, we had to do the testing using other methods. The final method used was to fix the USB communication and send the I2C data over the USB to be able to debug the I2C communication protocol.

- Testing the USB communication protocol was done with help of the program D2XXAPP. This program showed all the data received over the USB channel in a terminal window. This way the communication could easily be checked. This program also helped debugging the I2C protocol as stated in the previous bulletin.

- Testing the API was done by developing an application. The application was made in the scope of another master thesis running in parallel with this one. The main goal of the application was to create remote collaboration using the force feedback sliders. In this application two main boards with sliders connected to each were connected to two different computers. The movement and force of each slider was then transferred to another slider on the other computer. The results of that project are available on the report of that thesis [13].

5.3 Problems

During the implementation process we encountered several problems. Due to the complexity of the system and lack of debugging environments some of the problems took a long time be found. Some of the problems have already been mentioned. Most of them have already been solved but there were some problems that still exist and will be solved in the future. The problems are listed below:

- **Reading user force:** As mentioned before the calculation of the user force was if not impossible but very hard task with the current design. This is being worked on and will be fixed in the next version of the slider.

- **Instability in USB connection:** In the initialization of the main board there is some instability with the USB connection. This causes that the system should be restarted some times in order to function properly. This problem is because of the overflow of information in the USB channel. This can even occur under the run-time but it does not create any problems. This noise can be corrected but due to the lack of time it still exists in the current prototype.

5.4 Final product

The system existing today is shown in Figure 6 and has the following properties:

- The system consists of a main board and up to 16 sliders connected to it. This number can easily be many more and even up to 128 if the power supply supports that number of sliders.

- The main board is connected to the computer via USB.

- The system is OS-independent since the API is written in Java and can be run by Java virtual Machine. The drivers for the USB communication are available for most of the operative systems.

- The sliders can operate with different forces and dynamically change to other forces during run-time.

- The force and position are available as input and output for each and every slider in the system.

- The operation delay is not noticeable with the sense of touch. The movements and forces are smooth and continuous. The sliders operate with frequency 6.1 KHz.

- The system is stable, besides the problems mentioned in the *problems* sections, and independent of any external settings on the computer it is connected to.

- The API provided is standard and easy-to-use.

- The sliders can easily cooperate and affect each others performance characteristics without creating any noticeable delay.

- The following force functions should be available
    - User mode
    - Function mode with polynomial function of second degree.

- Lookup table mode
- Program mode

- Each slider has a button. The functionality of this button depends on the application currently running.

- Each slider has a diode onboard that can be turned off an on by the application.

Figure 6: Design of the final product

6 Conclusion

The project was started with the goal to create a tangible user interface with force feedback that was easily programmed to simulate different force functions. The final product fulfils all the primary goals although it sometimes has stability problems during start-up. The problems of the product have been discussed in a separate section.

The project started as an attempt to improve an existing proof of concept analogue system developed in T2I lab. After carefully analyzing the options and solution, a fully digital platform was decided to be built. The hardware consisted of a main board with an ATMEGA8 microcontroller onboard and several sliders that are connected to the board. The sliders have a slider board with a microcontroller onboard dedicated to take care of the movement and communications of the unit.

The slider boards are connected via an I2C communication channel to the main board. Via this channel the order are delivered to the slider and the current status of the slider is reported to the board. The board tracks the changes in the sliders and reports them to the computer via a USB cable. On the computer there is an application running that receives these changes and sends commands back via the same channels to the sliders accordingly.

On the computer an API is designed to make the development of applications easier. This API is made in Java for maximum platform independency. The API provides an easy to use interface for programmers.

The software system was designed in several steps. After the final design of the hardware was done a study was made on the structure of the system. The design of the system was made in several layers as described. To make the testing and integration easier the implementation was divided into several steps. After each step a complete test and integration phase was performed to make sure all the new and old functionality were operating. After completing all the steps some simple final test programs were made to test the whole system. A larger application was also made in the scope of another master thesis.

In conclusion the final product of the project is a set of stable force feedback sliders. These sliders can be used for developing different application in which the extra information using the tactile sense is desired. The wide range of use is stretched from simple education application to very complicated remote controlling machines in industrial factories.

6.1 Future work

The aim of this project has mostly been research in the area of force feedback in human computer interactions. Therefore most of the effort in the project was laid on testing the different possibilities and opportunities in the area rather than creating a commercial product. This has leaded us to a final product that is not necessarily optimized and stabilized as a product to be distributed widely. In order to improve the reliability factor of the prototype the following improvements are suggested:

- Improve reading of user force by changes in hardware and software.
- More stable USB connection during start-up and avoiding overflows and collisions in the USB data traffic.
- Program the microcontrollers via the existing USB connection instead of using a special programmer for better upgrade possibilities.
- Handle I2C slave addressing of the sliders in a dynamic way for better modularity.

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Appendices

A - User Manual

This part is not published in the public version of the document. To get this information please contact Ali Shahrokni or Morten Fjeld.

B - Communication protocols

This part is not published in the public version of the document. To get this information please contact Ali Shahrokni or Morten Fjeld.

C – Conference Paper 1, 2006:

A. Shahrokni, J. Jenaro, T. Gustafsson, A. Vinnberg, J. Sandsjö, M. Fjeld (2006): One-Dimensional Force Feedback Slider: Going from an Analogue to a Digital Platform. Proc. ACM NordiCHI 2006, pp. 453-456.

One-Dimensional Force Feedback Slider: Going from an Analogue to a Digital Platform

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ABSTRACT

This paper examines the use of motorized physical sliders with position and force as input and output parameters for tangible human computer interaction. Firstly, we present an analogue platform. It was used to realize two proof-of-concept applications: one for learning system dynamics as part of physics education and the second for interaction with music loops. Based on the insight gained with the analogue platform and the two applications, we took the first steps towards a digital platform, also presented here. More generally, the paper presents so-called haptic modes, which may be generated using force feedback control of motorized sliders. The paper also briefly presents parts of the underlying software and hardware which was designed and realized as part of this project.

Author Keywords

HCI, User interface design, physical prototyping, haptic interface, force feedback, slider, TUI

ACM Classification Keywords

H.5.2 User Interfaces: Tangible user interfaces (TUI), Haptic interface, prototyping

INTRODUCTION

It is known that human beings have a very fast operating sense of touch [1] and several research projects [2][3] have capitalized on this fact. Interactive systems with motorized sliders have been suggested in the iStuff [4] and Phidgets [5] projects, as well as in commercial joysticks with force feedback. Haptic display for so-called 3D haptic widgets has been examined [6]. Most of the existing approaches have proposed motorized sliders for output only, with no dynamic control of output force or registration of user input force. These devices with force feedback are not attuned to human tactile sensing and the feedback is mostly simulated by vibrations of different frequency and intensity.

To explore a wider use of force feedback with one-dimensional motorized sliders, we have started a project called Force Feedback Slider (FFS). Motorized physical sliders with position and force as input and output parameters lend themselves well to tangible interaction (Fig. 1). Their capacity to support direct [7] tangible interaction can be proved at several levels. While the directness of 3D interaction has been widely explored, there is a need for more direct interaction with multivariate models. For instance, the externalization of abstract mathematical models was studied by Tweedie et al. [8], as they examined a yield enhancement function of upper and lower bounds.

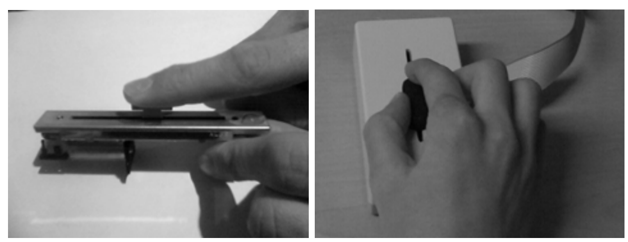


Figure 1. Motorized slider (left) and application (right).

From a human's perceptual point-of-view, the absence of tactile feedback in GUI interfaces may overload our visual senses and lead to increased physical strain. While GUI input is largely limited to discrete operations such as typing and selecting, a mouse affords some degree of continuous control. However, since mouse interaction occurs mainly without physical resistance and tactile response it is not very effective. End-users who draw, sculpt, or create continuous audio lines for long periods of time using a mouse often become frustrated and experience pain. There are negative health consequences to the fixed posture and small repetitive movements required by working with a GUI interface [3]. We admit that one-dimensional sliders will not solve this problem. However, the combination of alternative task-specific UIs, including actuated sliders, may be an improvement.

The next section presents an analogue FFS platform, including its software, followed by two proof-of-concept applications and some discussion. This is followed by a section on a digital FFS platform, including its hardware and software. The final section discusses the results, relates them to the other projects [4][5], and envisions the next steps in the FFS project.

ANALOGUE PLATFORM

The first version of the FFS is a layered analogue system which is connected to the computer through a USB interface. The software is written in Java which maximizes compatibility with different operating systems and Java Applets. Using this device as a proof of concept, two distinct applications were realized: the first for direct interaction with a projectile motion model, *Catapult* (Fig. 2) [2], and the second for direct manipulation of sound during playback in a program, *FeelTheBeat* (Fig. 3) [9].

Software of the Analogue Platform

The slider is designed in several layers which have been previously described in a separate paper [10]. The physical layer consists of an external USB sound card and the slider board. The sound card is used to control the slider board and send commands to the slider. It also functions as an AD/DA converter. To stabilize the movement of the slider a P-regulator is attached to the slider board.

The driver layer is in direct contact with the sound card and sends and receives the commands directly from the analogue hardware. Depending on which haptic mode[1] the application requests a slider to run, the driver uses different lookup tables (LUT) to control the behavior of the slider. Each LUT contains the force to be applied by the slider depending on the user force and the position of the slider.

The slider should be compatible with major operating systems and be easy to develop new applications for. To achieve this goal an application program interface (API) layer is provided in Java. This API allows the writing of an application for the FFS without any knowledge of how the slider fundamentally works. Most operating systems support Audio-Class-USB and have available device drivers. Also, the API is executable in the Java Virtual Machine. Thus the portability between the different systems is successfully achieved.

Applications with the analogue platform

As mentioned in the previous sections, two applications were realized to prove the functionality of the analogue system.

Catapult [2]

This is a secondary education (K-12) application allowing for direct manipulation and testing of a catapult (Fig. 2). Physics education often relies on the visualization of theoretical laws to enhance the learning experience, and while Java animations are widespread, they generally lack user interaction. So, FFS could be advantageous to any application used to interact with the law of physics. Here, the users receive both tactile and visual feedback using the software. We conjecture that a UI calling upon two perceptual channels at the same time may help users to more easily construct a mental model of the subject-matter content. This application used the API.

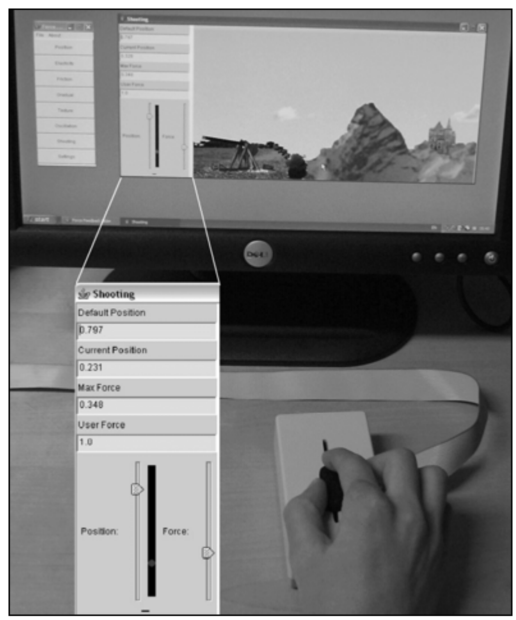


Figure 2: The FFS in operation with catapult.

FeelTheBeat [3]

This is an application allowing for direct manipulation of sound during playback (Fig. 3). Computers are widely used in music performance and production. DJs increasingly use computers rather than analogue turntables and mixers [11]. Musicians use sequencing software in composition and ubiquitously employ computers in their productions. Sequencing software

[1] FFS offers five haptic modes: In *position*, the slider is used only as input device, the motor is switched off, and the user can move the slider without FF. In *elasticity*, a default position and a variable resisting force are defined. The user's fingers have to overcome the resisting force. When the handle is released it returns to the default position. *Gradual* offers a number of discrete steps into which the handle can snap. In *texture*, high-frequency low-intensity vibrations are applied to the handle, thus giving users an impression of a rough surface. In *oscillation*, the handle comes to rest after a damped sine movement. These five haptic profiles are abstract descriptions of elementary capacities; other applications can be composed from these modes. Any finite function that can be written as a mathematical expression is allowed [2].

[2] http://www.t2i.se/pub/media/ShootingDemo.avi

[3] http://www.t2i.se/pub/media/FeelTheBeat.mpeg

offers the ability to arrange and transform music, primarily in an offline situation, but with notable exceptions such as Ableton Live, which is designed for live performance. The aim of this application is to develop a tangible user interface for common sequencing operations such as the looping of a sound. Samples of duration between 1 to 8 beats corresponding to 0.5 to 8 seconds are used in this case. The interface allows the display and modification of sound during playback and should operate in a direct way [7]. Furthermore, the slider moves with different accelerations depending on the amplitude of the sound that is played, generating different perceivable forces. The proposed interface employs a loudspeaker and a motorized slider [12] [9], thus offering continuous audio, visual, and haptic cues during playback. The slider handle moves according to a predefined temporal audio parameter and thus gives immediate and continuous feedback corresponding to the current playback state. When the user holds or moves the handle, the audio parameter changes and the audio playback is altered accordingly. As the sound software applied here was written in C++, this application communicated directly with the sound card, bypassing the Java API.

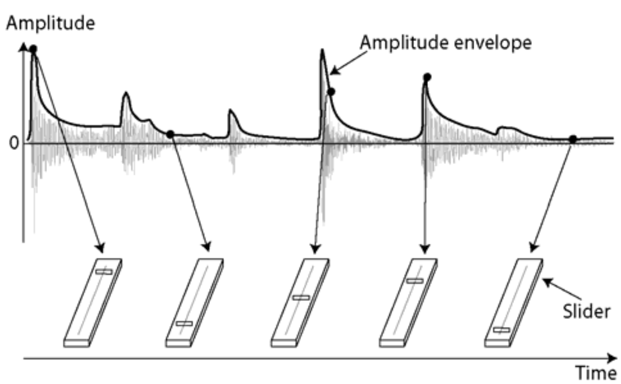


Figure 3. Amplitude envelope of sound and slider position.

Analogue platform: discussion

The analogue slider proved the validity of the idea. By implementing a prototype system and testing its operation, the way for improving the system opened up.

However, the analogue system exhibited a high latency due to the fact that the data was processed through the operating system, an external sound card, and the slider board. Conversion between analogue and digital data and the operating system's sound mixer were responsible for the largest parts of the delay. The design was not sufficiently stable and depended on low-level operative system settings. Nevertheless, the analogue platform served as proof-of-concept. The next step was digitalizing the system and combining several sliders to perform a task.

DIGITAL PLATFORM

Based on previous experience and project aims, we formulated a set of *use requirements* for the digital FFS platform: i) low latency, ii) high stability, iii) platform independency, iv) extendable to maximum of 16 sliders mounted into a compact box, v) programmable via a standardized API, vi) remote haptic collaboration enabled.

The goal of digitalizing the system was to preserve its advantage, solve the shortcomings presented above, and thereby meet the use requirements. The most critical problem is the high latency which causes the user to experience the force change as discrete and not continuous. Another major problem is system instability. An additional requirement is to make the system independent of operating system configurations and settings. The digital solution is still under construction but the tests conducted so far have shown promising performance and much shorter delays. In the following section we present and discuss hardware and software issues of the digital platform.

Hardware of the digital platform

The digital version of the slider is designed in a modular way and each slider can operate either individually or within a combination of several sliders. Each slider has a µcontroller operating at a clock frequency of 16 MHz. It has several ADC converters digitalizing the analogue data much faster than the sound card in the analogue version. This reduces the latency of the slider considerably as compared to the analogue system. The discreteness should be undetectable by the human sense of touch.

The platform should allow the simultaneous operation of several sliders side by side (Fig. 4). If each slider was directly connected to the computer it would complicate the system and increase the latency. Therefore, a mainboard was designed that can control up to 16 sliders simultaneously. It operates with the same kind of µcontroller as each slider and at the same frequency. The mainboard and the sliders are connected by an I2C bus [13] which operates at a frequency of 400 KHz. The sliders operate independently and therefore the bus is only used to read the force or position of each slider or to send LUTs to each slider. Thus, the amount of data transferred by the bus is relatively low and should not slow down the sliders.

Using in-house designed technology, the µcontroller which drives the slider motor is able to determine approximate forces applied by the user's hand and to generate different resisting or active/driving forces. A specific force is generated by sending the corresponding current to the slider motor.

Software of the digital platform

Similar to the analogue design, the digital design has two different layers of software: the µcontroller code and the API code, which is the interface for the application developer.

µcontroller programming

Each slider has a LUT stored in its memory according to which it operates. Depending on the position of the handle and some other factors, the slider generates a specified force by applying the suitable current required by the slider motor.

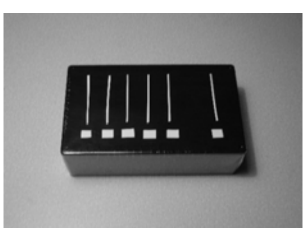
The mainboard µcontroller keeps track of the current position and force of each slider. It can also send a new LUT to the sliders using the I2C bus whenever a slider's operating mode changes.

Application Programming Interface (API)

As in the analogue version, the API simplifies the development of new applications. Due to the same reasons mentioned for the analogue system, the API is written in Java. To make its use easier, the API inherits the standard class (component) JSlider [14] which is the standard soft slider class in Java library. To program, the developer either chooses a standard operation mode or provides a force function to be simulated by the slider. The slider can either be resistive, active/driving, or both. This means that it may resist against the user force (up to a certain level given by the motor used), automatically move with different forces, or combine these two depending on the position of the slider handle.

Digital platform: discussion and outlook

We have achieved positive results in the design and realization of the digital platform. In the next steps, we foresee improvements in usability and robustness of the hardware, the protocol, and the API. We also intend to examine system performance related to human perceptual factors such as haptic profile resolution, system feedback, latency, and stability.



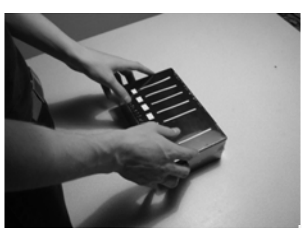


Figure 4. Mock-up of multi-slider interactive device (left) and the same mock-up device in use (right)

SUMMARY

We have presented an analogue and a digital realization of the Force Feedback Slider (FFS). Most of the features offered by iStuff [4] and Phidgets [5] such as USB interface, modularity, and use of physical sliders are or will be offered by the FFS. In contrast to commercial joysticks with force feedback, FFS is planned to offer accurate customized force feedback matching real world settings, such as mechanics and music, more realistically. In summary, we expect the FFS to be a versatile force feedback device for developers and end-users.

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One-Dimensional Force Feedback Slider: Digital Platform

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ABSTRACT

This paper examines the use of motorized physical sliders with position and force as input and output parameters for tangible computer interaction. We have designed a device with the purpose of controlling, in real time, a motor which is integrated into a slider system with accuracy and latency values sufficient for productive interaction. This was accomplished with a microcontroller that handles the I2C protocol for communication with a master device that centralizes the sliders' information. The system is modular, using the configuration of one mainboard and I2C protocol to communicate with the sliders. The mainboard interacts with the computer through a USB connection. The mainboard also controls the sliders, each sitting on a slider board. This paper also presents the designs and realizations of the mainboard and slider board hardware components. Finally, the paper envisions future applications of force feedback sliders such as mapping of GUI sliders onto physical sliders, polling of user impressions based on non-verbal selections cues, and remote controls with haptic feedback.

Author Keywords:
Force feedback slider, digital hardware, haptic display, PID, PWM, lookup table

Index Terms:
H.5.2 User Interfaces, Physical user interfaces, Haptic user interface, GUI

1 INTRODUCTION

Human beings base their relationship with their environment primarily on visual sensing. When interacting with computers we often overload this sense, it being the main channel for feedback. To reduce the task load on the visual sense, we seek to utilize alternative perceptual channels; here, the sense of touch. We only seldom use this sense when interacting with computers despite its capability of fast operation [1].

While direct 3D interaction/manipulation has been widely explored, the directness of haptic interfaces has not, even though it may be justified at several levels [14]. Indeed, several research projects [7][9] have examined and proved the benefit of touch sensing in human-computer interaction. The use of force feedback may give users an added feeling of interaction with a real system. This insight has been utilized in various fields such as tele-surgery [12][6], digital media, and space station maintenance. Aiming to explore a wider use of force feedback, we carried out a project called Force Feedback Slider (FFS)[1] in which motorized physical sliders are used to interact with users, utilizing position and force as the main factors to achieve dynamic control (Figure 1). At the same time, we read these values from the device to record the user's reaction.

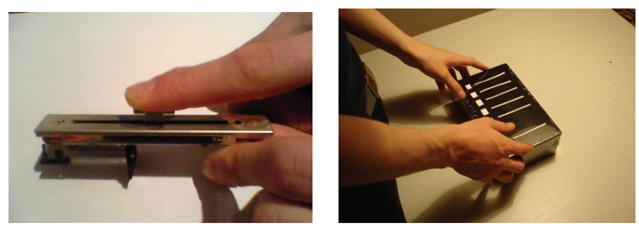

Figure 1. Motorized slider (left) and mock-up box of multi-slider interactive device (right).

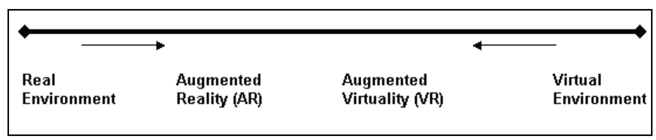

Figure 2. The FFS is intended to bring real and virtual environments closer, thereby bridging the left and right part of the Milgram continuum [10].

The first versions of the system were based on an analog control of the motor [1][7] and some applications were developed to test the device, such as an educational physics application simulating a catapult [7] and a real-time music-editing system called *FeelTheBeat* [1]. Our current goal is to digitalize the device and turn it into a more versatile and configurable platform. This may enable the design of a variety of single and multi-slider applications (Figure 1).

2 RELATED WORK

USB/MIDI state-of-the-art user interfaces for music editing like the Behringer B-Control Fader BCF2000 [17] and the Mackie Control [19] already offer touch-sensitive motorized sliders. However, the driving force in such sliders cannot be controlled

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[1] The project web site offers video documentation and previous papers from the FFS project: http://www.t2i.se/projects/ff.php

since they are based on speed control. This type of control employs a constant current, giving a constant torque. While such control is sufficient for audio editing, we aim for a more generic interface where force serves as feedback in user-system interaction. Hence, the novelty of the presented FFS lies in its capacity to control the driving force while at the same time measuring the force applied by the user. While the system we design offers most standard features of actuated sliders, we also plan to support applications where force serves as an input-output medium (Table 1). A goal of this project is to offer a versatile platform to map GUI slider onto a set of FFSs and thereby to achieve a higher degree of mixed reality interaction [10].

Table 1. Position-Force matrix plotting two state-of-the-art user interfaces for music editing in relation to the FFS according to their input and output capacities.

		FORCE	
		OUT	**IN**
POSITION	**OUT**	Behringer Mackie FFS	FFS
	IN	Behringer Mackie FFS	FFS

3 Digital Force Feedback Slider

The goal of digitalizing the system is to address a set of critical issues in the analogue version while preserving the system's advantages. The first issue was the high latency, which caused users to experience the force change as discrete and not continuous. The second issue was the system's instability in controlling the motor, which caused non-optimal movement patterns. These two issues were particularly difficult to address at the same time. The third issue was an over-dependency on operating system configurations and settings. Also, the motor control function in the analog system [7] was hardware based, and therefore difficult to modify.

Based on previous experience with the analog FFS [13] and on the project's goals, we formulated a set of *use requirements* for the digital FFS platform:

i) low latency

ii) high stability

iii) easy access to update motor control function

iv) platform independency

v) extendibility to a maximum of 16 sliders mounted into a compact box

vi) programmable via a standardized API

vii) remote haptic collaboration enabled

The digital solution is still under construction and the tests conducted so far have yielded promising functionality and reduced delay times. The following sections will discuss the design of digital hardware realization, as we aim to fulfill all seven use requirements.

3.1 Hardware of the digital platform

The purpose of the system is to control multiple motorized sliders and obtain feedback measurements of position and force. To create a modular system, we split the platform up into two types of boards: one to regulate the motor (called a slider board) and another one to coordinate the slider boards and communicate with the computer (called the mainboard). In this way, the sliders operate independently and the bus is used to read the force or position of each slider and to send Look-Up Tables (LUT) to the microcontroller in the slider board. One microcontroller commands the mainboard and each slider board is then commanded by its own microcontroller. For this project, we chose to use the Atmega-8 microcontroller with a 16 MHz crystal. The RISC architecture of this chip can reach up to 16 MIPS (million instructions per second). This is fast enough to adequately control the system since the motor runs at up to 20 KHz (according to the Nyquist–Shannon sampling theorem).

A clock cycle in the microcontroller takes approximately 6 ns and the operation usually takes less than 10 cycles to execute, resulting in approximately 60 ns for the operation's execution. This latency is considerably reduced compared to the analog design and makes the discreteness imperceptible by the human sense of touch. Additionally, the microcontroller has 8 integrated AD converters which are very useful in reading the parameters of the motor and thereby controlling it. Another important feature is the Atmega-8's ability to handle the I^2C protocol used for communication between the slider boards and the mainboard. A description of the different subsystems is provided in the following sections.

3.2 Mainboard

The device is connected through the USB to the computer for fast data transmission and easy recognition by the operating system. This design increases the communication speed and thus reduces the latency experienced with the old analog platform [1][3][7]. To accomplish this, the mainboard uses a USB driver chip (FT232RL) to control the frame communication between the microcontroller and the computer. One of the most advantageous features of this integrated circuit is that it requires few external components to work properly and has integrated the EEPROM memory used to customize the device properties. The board is supplied with the 9 volt power supply used for the TTL circuits and the motors, reducing possible interferences as much as possible. The main function of the board is depicted a block diagram (Figure 3) followed by the current realization of the mainboard (Figure 4).

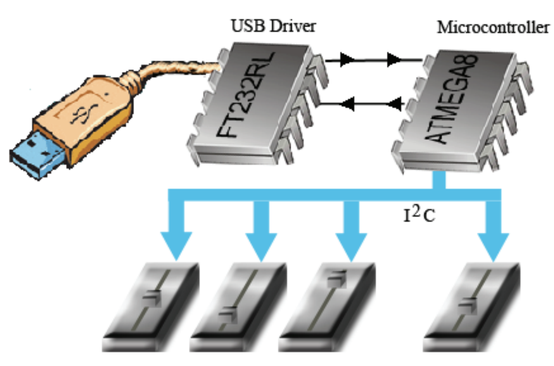

Figure 3: Mainboard block diagram with I^2C serial bus.

Thanks to the Atmega-8 features and some additional hardware, the mainboard is equipped to carry out I^2C communication with the sliders. This enables a running speed of 400 KHz, which amounts to very fast master-slave intercommunication. This bus also allows a large quantity of devices to be connected, enabling the control of devices that use many sliders such as DJ mixing boards. However, in our case, the system is designed and optimized to control up to 16 sliders in small applications.

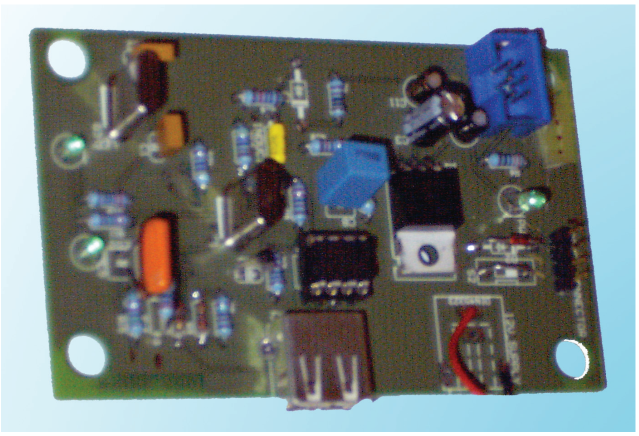

Figure 4. Current version of the mainboad.

3.3 Slider board

Each motorized slider is controlled by an electronic board attached to its base. We chose to have one microcontroller per motor rather than one central board controlling all the motors because this solution is more modular and the microcontrollers can better control each motor. Furthermore, this helps achieve the desired stability as described in use requirement ii.

In order to control the system, the microcontroller needs to measure the position and electric current. To measure the position, we use a potentiometer incorporated into the slider. A constant voltage is supplied to it, making it so that when the position changes the output resistance also changes, and with it the output voltage to be measured by one of the microcontroller's AD converters. A similar process measures the current by transforming the motor's output current. In order to drive a small motor in the forward and reverse directions we need an H-bridge configuration, which basically consists of four transistors that redirect the current in the desired direction. We used an integrated circuit for its following properties: greater stability, its minimizing of the differences between the transistors, reduced dimensions, a wide range of operating voltage (5-36 V), TTL/CMOS compatible inputs, faults status reporting, and current feedback output.

The control of the motor is achieved using PWM signals (Pulse Width Modulation) to control the voltage supplied and with it, the torque (which is proportional to the current). This PWM can be done in different ways. We used a fixed frequency of 10 kHz, generated with the microcontroller timer with a variable on/off cycle. With this configuration, the number of PWM duty cycles equals the average voltage over the motor, allowing us to achieve different speeds in the motor and control the current.

Each slider board will function as a slave device, working in a parallel process and waiting for petitions or orders from the mainboard. The communication through the I^2C bus is characterized by the reduced number of wires to transfer data (only two wires are needed) and data communication frequencies of 400 kHz, thanks to the Atmega-8. A block diagram of the system is shown in Figure 5.

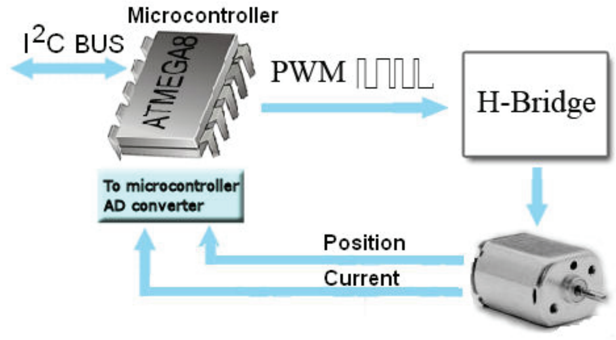

Figure 5. Slider board block diagram with I^2C serial bus. The microcontroller sends pulse width modulated signals to the H-Bridge.

For future applications, the slider platform also has a switch to enable/disable the slider or make the slider execute another function (it will be determined by software in the microcontroller firmware). This switch is connected to the microcontroller through an AD converter input. In the future, the switch may be replaced by a pressure-sensitive button, which can then be read by the AD converter.

In order to identify the devices, each slider board is defined by a unique memory address. This allows the mainboard to communicate directly with each of the sliders' microcontroller.

The slider platform is designed to memorize LUTs of 256 bytes for position and 256 bytes for force. With these LUTs, the slider is able to perform these different functions:

- *Position*: the slider is used only as an input device, the motor is switched off, and the user can move the slider without force feedback (FF).
- *Elasticity*: the user's fingers must overcome a force which increases with distance to default position. When the handle is released it returns to its default position.
- *Detents*: offers a number of discrete steps into which the handle can snap.
- *Texture*: high-frequency, low-intensity vibrations are applied to the handle, giving users the impression of a rough surface.
- *Oscillation*: the handle comes to a rest after a damped sine movement.

These five haptic profiles are abstract descriptions of elementary capacities; other applications can be composed from these modes. Any finite function that can be written as a mathematical expression is allowed [8]. The first design and the final slider are shown in Figure 6.

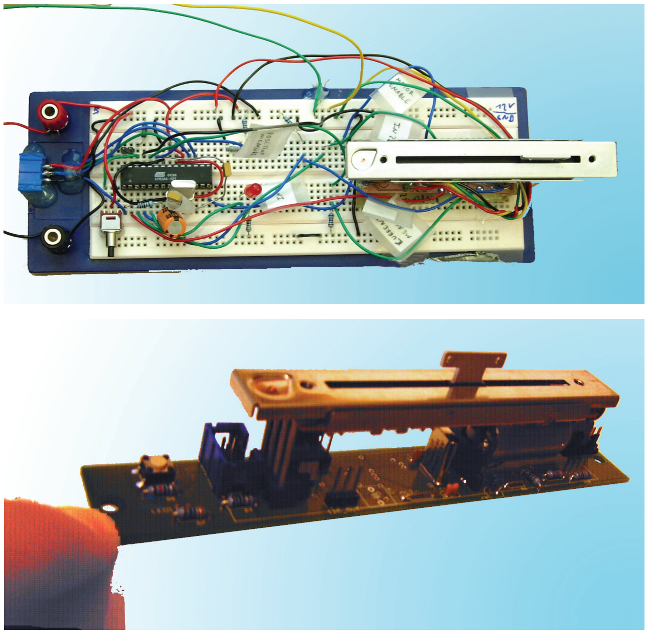

Figure 6. Testing board (top) and final slider board (bottom, here held by two fingers).

4 ONGOING IMPLEMENTATION

From several motor control alternatives, we are currently implementing a discrete PID control (Proportional-Integral-Derivative). This control was chosen because it is widely and successfully used in control applications. This control also prioritizes the precise output of the reference values below (Figure 7 shows a general case for PID control). The different parts of the PID control actuate the system in the following ways:

- Proportional term (P): gives the system a control proportional to the error.
- Integral term (I): stabilizes the system from the sum of the previous errors. It is useful to eliminate the stationary error.
- Derivative term (D): anticipates the future error so that the output is proportional to the error's rate of change over time. It improves the response if there is any sudden change in the system.

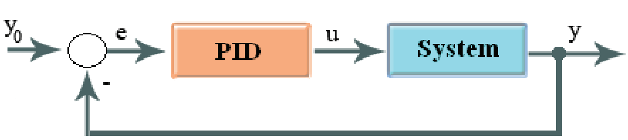

Figure 7. Close Loop System with PID where y_0 is reference input, e is error, u is controller output, and y is desired system output.

Each microcontroller has an automatic recalibrating system that calculates the parameters of the PID at startup. Thus, the slider is controlled with the same precision irregardless of changes in friction caused by slider deterioration over time or other factors.

5 SCENARIOS OF USE

We envision several applications, of which we present three. Firstly, we envision mapping Graphical User Interface (GUI) sliders onto a set of FFSs incorporated into a box (Figure 1, right). One use of such mapping could be in a financial modeling GUI (Figure 8). Here, FFS detents with varying number of levels may be programmed to provide haptic information about level of interest rate or amount invested. In this example, we hope to address typical ergonomic issues such as visual over-stimulation, strain symptoms in repeated mouse movements, and lack of direct and haptic input-output. Secondly, polling of physiological sensation in test subjects may benefit from haptic representation of non-verbal levels between upper and lower bounds such as warm/cold, long/short time, and long/short distance. Finally, remote controls involving multidimensional degrees of freedom may benefit from mapping on FFSs. For instance, haptic information of imminent collision risk or supportive cues in grabbing remote physical objects are applications we consider inviting for further investigation.

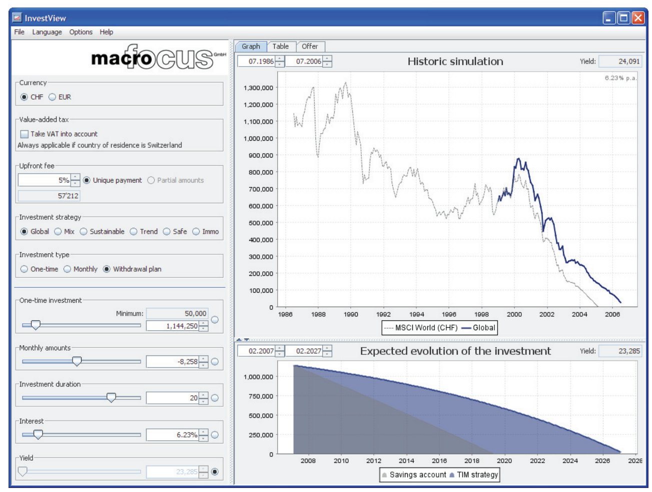

Figure 8. GUI for financial modeling, with soft sliders [20].

6 DISCUSSION AND OUTLOOK

We have presented a digital realization of the Force Feedback Slider (FFS). This new platform contains almost all of the features offered by the state-of-the-art user interfaces for music editing like the Behringer B-Control Fader BCF2000 [17] and the Mackie Control [19] such as a USB/MIDI interface, modularity, and the use of actuated physical sliders. Related research projects offering actuated physical sliders are iStuff [2] and Phidgets [5].

Our digital platform considerably reduces the latency as compared with our previous, analog version [1][7]. We now use an AD converter integrated into the microcontroller, which is faster than the soundcard used in the analog version. Only an API is needed to control the platform and the program to control the functions is in the motor's firmware. The delay has also been reduced, increasing the stability.

The five basic haptic functions suggested (position, elasticity, detents, texture, and oscillation) are implemented in the firmware of the microcontroller and not in the computer, making for reduced latency, improved stability, and thereby faster and easier control. We are currently implementing new functions based on combinations of the five basic functions that the slider is able to work with.

The haptic device has an enable/disable button and a LED which is able to indicate a predefined binary slider status, hence making the status visible to the user.

Finally, we have shown some future applications of the FFS such as the mapping of GUI sliders onto FFSs, polling of user impressions based on non-verbal selections, and a remote control with haptic warning cues. We even envision further uses, such as remote collaboration, educational uses, 3D graphics control, multi-factor optimization, music applications, collaborative editing [15], interpersonal communication [11], and haptic alphabets [4].

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