Bachelor Thesis

Learning Piano Through an Augmented Piano System

by

Linsey Raymaekers

Promotor: Prof. Dr. Kris Luyten
Supervisor: Jo Vermeulen

2012-2013

Submitted to achieve the bachelor's degree in
CS/ICT/Knowledge Technology at Hasselt University

universiteit
►►hasselt

Abstract

Individuals interested in learning to play the piano must generally learn sheet music notation before they can begin playing the instrument. This contrasts with certain other instruments, such as the guitar, which have other forms of music notation available that are much easier to learn. The concept of a piano roll is as an alternative music notation for the piano which circumvents the need for the individual to learn sheet music notation before he can begin playing the piano. The effectiveness of this concept has been proven by the piano learning game Synthesia. However, this software is limited to a computer monitor which makes it less than optimal for piano learning due to scale differences and lack of correlation between the virtual and the physical piano. It is proposed in this thesis that by augmenting a physical piano with a piano roll that is in the same scale and locality of the physical piano, the effectiveness of the piano roll as an alternative music notation can be increased further. A projection-based augmented piano system is built to demonstrate this. A small-scale user test then shows that it can successfully aid beginners with no prior musical knowledge in rapidly being able to play simple one-handed melodies on the piano. The concept of an augmented piano system is then extended further by presenting features that can improve the educational value of such a system and by discussing its potential future usage in the areas of music education and entertainment. Main benefits include its to-scale visualization on the physical piano, immediate visual feedback of the user's keystrokes on the piano keys, and its ability to aid users in learning to play melodies quickly, even when they have no prior experience or music knowledge. Major limitations of the current system include its sensitivity to room lighting, lack of visual feedback on black piano keys and a limited resolution of the projection image. These limitations are attributed to the usage of projection-based methods.

Preface

As a self-taught guitarist and pianist pursuing a major in computer science, it has always been in the back of my mind to do something interesting that combines these fields. Nearly a year ago, the idea to augment a piano sprang from a brainstorming session at home for an assignment on augmented reality applications. Walking around the house, I asked myself one question for each object I saw: *How can I augment this object to make it more useful?* The moment I set eyes on my digital piano and the question started forming in my thoughts, I had to think of the Synthesia game I knew vaguely and how amazing it would be to bring that concept to a real piano. This idea stuck with me, and when the time came to choose my bachelor thesis subject, my gut feeling told me to pursue it. Yet, I was filled with doubt and feared that the idea might not work out and that I would fail in its execution. Despite these fears, I submitted it as a proposal to prof. Kris Luyten, who eagerly agreed to be my promotor, and soon enough, I began to work on it. Since then, many who share this enthusiasm have crossed my path, and the project has sparked the interest of more people than I had even hoped for.

Before proceeding to the main substance of the text, I want to thank everyone that has been involved in the creation, testing and supporting of this work, even those who have merely expressed their enthusiasm or interest. Knowing that that enthusiasm is present in others has given me the drive to continue work on the project beyond the scope of the thesis. In particular, I want to thank Karel Robert for helping out with the designs, his infectuous enthusiasm and his creative input to the work, Luc Adriaens for helping us capture a demo movie, and Jo Vermeulen for editing of it, the beloved family members who helped test the system, and for their enthusiasm in doing so, my promotor Kris Luyten and supervisor Jo Vermeulen for their continuous support and immediate feedback, their creative input and the opportunities they have helped create, my family and friends, in particular, L.S., M.T., and my boyfriend T.S., who supported me during a very busy and overwhelming year, helped me stay focused when I most needed it, and made sure I took enough time outs to still enjoy the ride.

Dutch Summary

Introductie

Bij het leren bespelen van een muziekinstrument is het vaak nodig enige kennis te hebben van muziektheorie, in het bijzonder moet men in staat zijn om noten te lezen. Pas wanneer notenleer gekend is kan men het instrument in kwestie bespelen. Voor vele instrumenten, zoals de gitaar, zijn alternatieve muzieknotatievormen beschikbaar waardoor men ook zonder notenleer het instrument kan leren bespelen. Voor de piano in het bijzonder zijn er weinig zulk alternatieve notatievormen. Het reeds bestaande muziekspel *Synthesia* past het concept van een *piano rol* toe om op een interactieve manier de gebruiker te helpen liedjes te leren spelen op de piano, zonder dat enige voorkennis van muziektheorie of notenleer nodig is.

De piano rol, te zien in figuur 1, bestaat uit naar beneden bewegende balkjes die zich elk naar een bepaalde toets op de piano bewegen. Wanneer een balkje de toets raakt hoort deze ingedrukt te worden totdat het bovenstuk van het balkje te toets bereikt. Op deze manier wordt nootduratie aangegeven. De groene balken geven noten aan die met de rechterhand gespeeld moeten worden, terwijl blauwe balken de noten voor de linkerhand aanduiden.
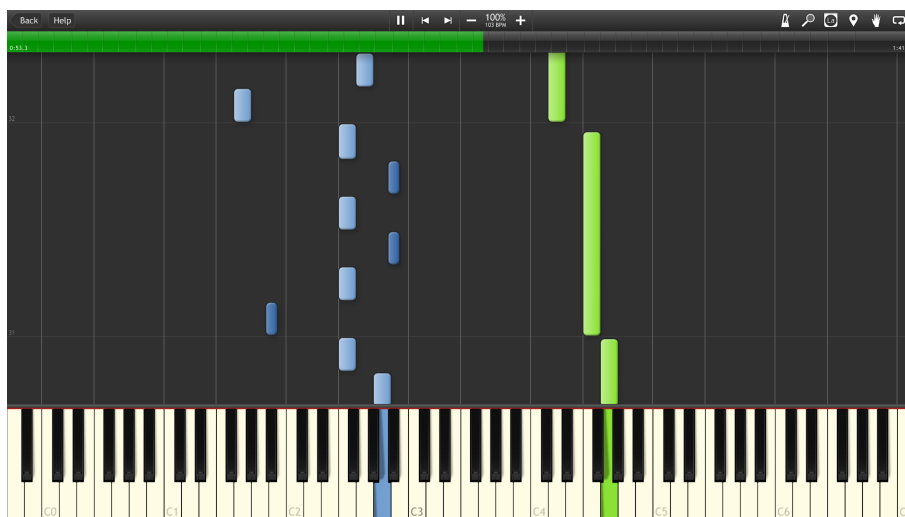

Figure 1: De piano rol in het muziekspel Synthesia.

Omdat Synthesia gelimiteerd is tot het computerscherm heeft dit als gevolg dat de virtuele en fysieke piano zich op verschillende schalen en lokaliteit bevinden, waardoor het voor een gebruiker verwarrend kan zijn om snel de juiste toetsen op de fysieke piano te vinden. Hierdoor wordt het volle potentiëel van de piano rol als alternatieve notatie tegengewerkt.

De Augmented Piano

In deze thesis wordt het concept van de piano rol naar de fysieke piano gebracht door een projectieopstelling te bouwen waarbij de piano rol geprojecteerd wordt op de pianotoetsen en op een projectieoppervlak dat zich aansluit aan deze toetsen (zie figuur 2). Op deze manier kan men muziek leren spelen aan de piano en zonder gebruik van een computerscherm.

Figure 2: De opstelling waarbij projectie gedaan wordt op een piano met 61 toetsen.

Een kleinschalige test met drie personen, waaronder twee kinderen van 4 en 8 jaar en één adolescent van 29 jaar, laat zien dat het mogelijk is om zeer snel melodiën te leren spelen zonder over enige muziekkenis te beschikken of ervaring te hebben met pianospelen.

Er worden ook aanvullingen besproken die kunnen bijdragen tot de didactische waarde van het systeem, zoals het interactief aanleren van akkoorden en toonaarden, alsook het bijbrengen van de basis van notenleer. Verder worden er mogelijke toepassingen van het systeem aangehaald op gebied van muziekeducatie en entertainment, zoals het gebruik van een meer uitgewerkte versie van het systeem tijdens muzieklessen voor beginners en kinderen in het bijzonder.

Conclusie

De belangrijkste voordelen van het systeem zijn de interactieve en op schaal gebrachte visualizatie, onmiddelijke feedback en de mogelijkheid voor gebruikers om meteen de piano te bespelen zonder enige voorkennis te hebben.

Limitaties van het systeem vanwege projectie zijn gevoeligheid voor kamerbelichting, gelimiteerde resolutie van het geprojecteerd beeld en het gebrek aan projectie op zwarte toetsen van de piano, wat geabsorbeerd wordt.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

1.1.1 Learning Piano

Ever since its invention many centuries ago, humans have been mesmerized by the beautiful sounds that can be produced by one of the most popular instruments: the piano. It is difficult not to appreciate the delicate tones that can be created by the swift and subtle movements of a skillful pianist. Some dream of having the same sense of skill as the great pianists of the past: Mozart, Beethoven, Chopin, Horowitz,... Others simply want to play their favourite songs on a piano. Those who then decide to start learning piano can do this by taking classes or by teaching themselves. Traditionally, the student or autodidact then moves on to learning to read sheet music[1] (see Figure 1.1), or learning to play by ear[2].

Figure 1.1: An example of sheet music.

Both of these approaches take substantial amounts of time, patience and practice, before one can even begin learning songs. However, in the beginning stages, such as playing a simple one-hand melody, the physical act of playing the piano is not all that difficult. At this point, reading sheet music is far more difficult than the physical act of playing what is written, which is, in its bare essentials, pressing piano keys in a particular order[3]. Thus, learning a

---

[2]Musical pieces all over the world are written down in the form of sheet music. It is universally understood, although certain elements of sheet music notation can differ between countries.

[2]Which means listening to a song or a melody and replicating it on a piano.

[3]Note that playing music requires more than just playing the correct notes on an instrument. Artistic expression also plays an important role and not everyone is equally gifted in this respect.

very simple piece of music, through reading sheet music, requires a great amount of patience and diligence for the beginning pianist, because he is still struggling to map the notes written on sheet music to what key he needs to press next. Some may be discouraged by this process and may give up the pursuit of music prematurely, which is a great loss. This especially holds true for those with no intention of becoming an advanced pianist and simply want to play casually.

Guitar players have alternatives in this regard, as they have wide access to *tablature* (see Figure 1.2). Tablature is similar to sheet music, in that it is used to write down a succession of notes to be played, but it does so in a much simpler form. A standard guitar has 6 strings and about 20 frets (frets are like keys on a piano, they represent a note), and tablature consists of 6 lines, each representing a string of the guitar, with numbers on these lines to represent the fret number that must be pressed at that time.

Figure 1.2: A tablature example[4].

Learning to read tablature is a substantially easier and faster process than learning to read sheet music. This may be why the guitar seems to be the most popular instrument of our time: it has a much lower threshold. Out of the people who try it, a substantially higher amount cross the initial hurdle of learning how to read tablature. This is in stark contrast to beginning pianists who may give up because difficulty with reading sheet music may discourage them to continue playing.

Part of the goal of this thesis is to offer a solution that lowers the threshold for those who have no knowledge of sheet music and are reluctant to learn it, but who still wish to learn how to play the piano.

---

[4]This example includes a clef which tells the duration of the notes, but many kinds of tablature omit this and use bars for note duration in stead.

1.1.2 An Alternative Note Representation

When *someone* or *something* shows the beginning pianist which keys to press in what order, it is not difficult to learn simple melodies or songs. The individual will then only need to memorize the order in which keys are pressed. With help of digital technology, this concept can be applied to bypass the need to read sheet music, and thus lower the threshold for beginning pianists.

Synthesia is a piano learning program that accomplishes this (see Figure 1.3). It is labeled as a 'music video game', and is visually similar to other music games such as *Guitar Hero*[5]. When a digital piano is connected to the computer, the software can use the pianist's keystrokes to provide feedback. This immediately informs the pianist of any mistakes that are made.
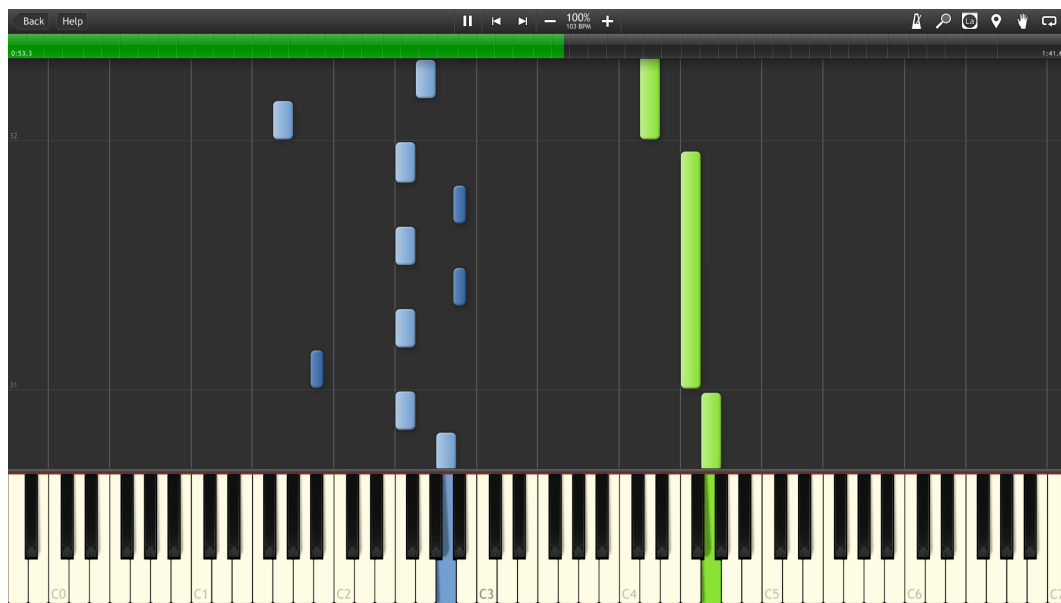
Figure 1.3: Synthesia during playback of a song. Blue and green bars represent notes played by the left hand and right hand, respectively.

The advantage of Synthesia over most popular music games is that it can be used to learn songs on the instrument in question, while the other games teach you very little about the instrument and are more focused on entertainment. In this sense, Synthesia bears more similarity to the guitar learning software *Rocksmith*, also labeled as a music video game, where you can plug in an actual guitar to play. It then teaches you certain fundamentals about playing the guitar.

Synthesia uses the concept of a *piano roll*[6] in which vertical bars move down toward a virtual keyboard. These vertical bars will be called *note bars* throughout the text, as each bar corresponds to a certain key, and therefore to a certain note. When such a falling note bar reaches a key, it needs to be pressed and held until the top of that note bar reaches the key. The piano roll can also be sped up and slowed down.

---

[5]http://guitarhero.com/

[6]Which comes the from physical piano rolls which are used as a music storage medium to drive player pianos.

Learning a song with Synthesia

When learning a song with Synthesia, what one does is look at which key, or keys, must be pressed next, find this key on the physical piano, and then press it when the corresponding note bar hits the key. Having an overview of upcoming note bars helps in preparing for the next key press. When doing this, a *mapping* is being formed in the brain: one sees a note bar falling toward a certain key, and then one presses the physical key that corresponds to it. This is what replaces the need for sheet music: in stead of mapping notes on a grand staff to keys on the piano, falling note bars are mapped to keys. For a beginner, the latter is much easier and straightforward, since the note bars are actually moving towards the corresponding keys.

It may seem like a daunting task at first to quickly make this mapping between note bars and keys, as there are 88 keys on a full-size piano. Knowing that the same pattern of keys repeats over the entire keyboard (see figure Figure 1.4), it suddenly becomes a much simpler task. The vertical lines on the piano roll make use of this fact, they indicate groups of four or three white keys (as can be seen in Figure 1.3).
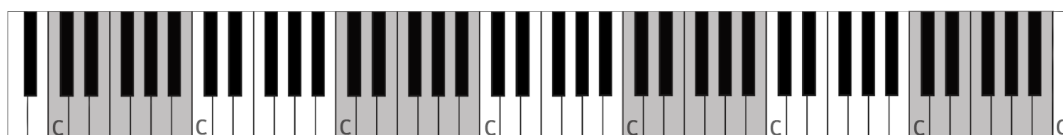
Figure 1.4: The pattern in piano keys: three white keys and two black keys followed by four white keys and three black keys make up an octave. Each white key left of a group of two black keys represents the note *C*, an octave apart.

At this moment, Synthesia is one of the most popular ways to create piano tutorials on YouTube, and many videos are available there showing songs played in Synthesia. The software has more advanced features than those discussed here, such as a paid *Learning Pack*[7] that users can buy, which offers features such as displaying sheet music in real time. For a complete list of its features, see the Synthesia website[8].

Bringing the Piano Roll to the Physical Piano

Even though Synthesia offers an effective way to learn songs on the piano without needing to read sheet music, there is one limitation which is discussed here. The typical setup when using Synthesia in conjunction with a physical piano is to have a computer screen stand somewhere near the piano, preferably right behind it, or on it, for easy viewing. No matter where the computer screen is placed, the setup results in having a small, virtual piano keyboard on the screen, while the physical piano is substantially wider. In [1], it was found that this scale difference resulted high error rates when playing melodies on a piano using on-screen visual aids. This scale difference is shown in Figure 1.5. It can be especially challenging for beginners who have no feel for where specific keys are located yet.

As shown [1], providing visual aid in the same scale as the instrument can overcome this difficulty, demonstrated in Figure 1.6. Now there is no confusion as to where the note bars are moving, and keys can be found very quickly. A standard computer monitor cannot be used to achieve this, so another method must be used to visualize the piano roll in this manner.

---

[7]http://www.synthesiagame.com/learningPack.aspx
[8]http://www.synthesiagame.com/
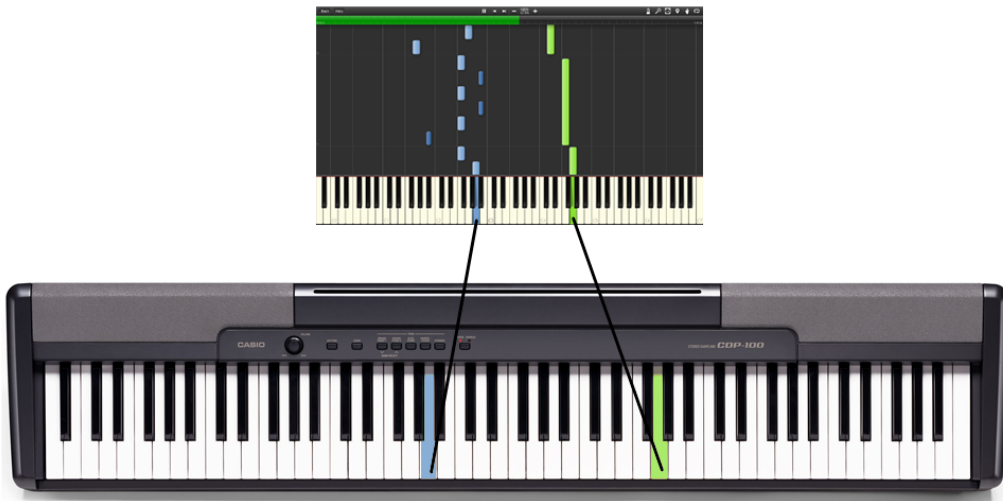
Figure 1.5: Difference in size between a physical, and an on-screen piano.
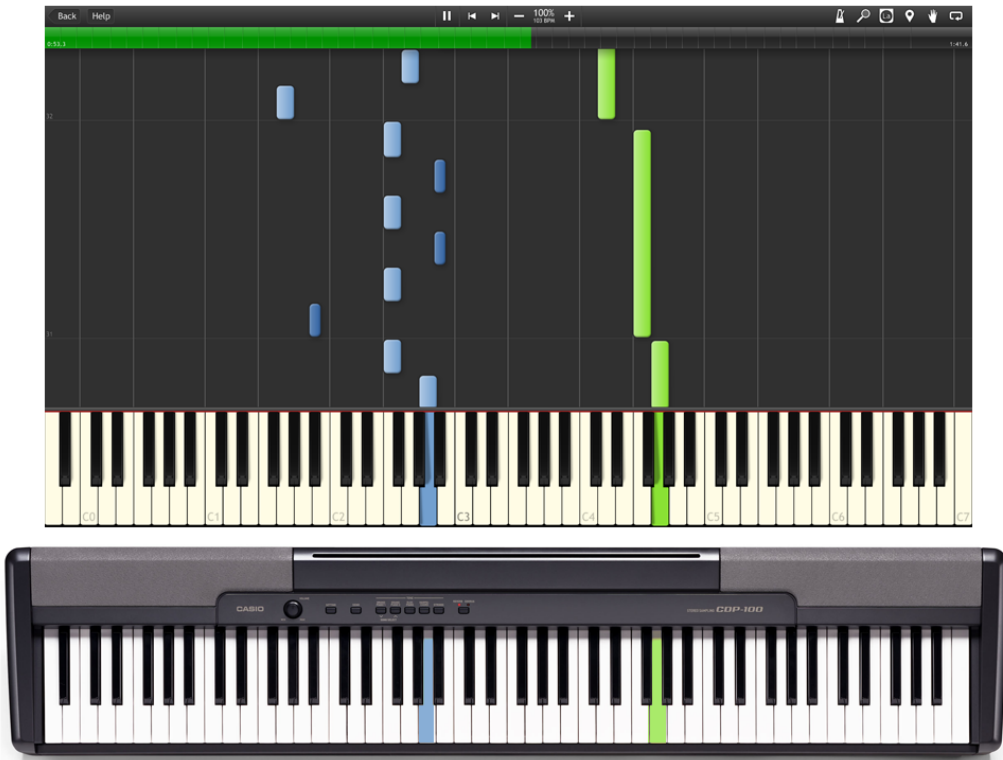
Figure 1.6: The piano roll in the same scale as the piano.

1.2 Goal of the Thesis

The limitation with any type of on-screen piano learning software is that its visualization is restricted to a small computer screen, giving rise to the problem of having to form a mapping between different scales of the piano keyboard. In order to circumvent this difference in scales, the virtual piano roll needs to be visualized *at* the physical piano and *in the same scale* as the piano. This would be similar to another person telling you exactly which key to press next while pointing at it, but in a more controllable, automatized way. The piano roll offers the advantage that the pianist can see upcoming notes in his peripheral view so he can prepare to move his hands to the exact area the note bars are falling towards, as opposed to first translating some position on a small screen to a position on a much wider piano.

The thesis aims to achieve the following:

- Prototype a setup which visualizes a simple piano roll at the physical piano and in the same scale as the piano, as in figure Figure 1.7. (Section 3: The Prototype)

- Identify how such an augmented piano concept could be expanded further, specifically to improve the piano learning experience for beginning pianists. (Section 5: Future Work)
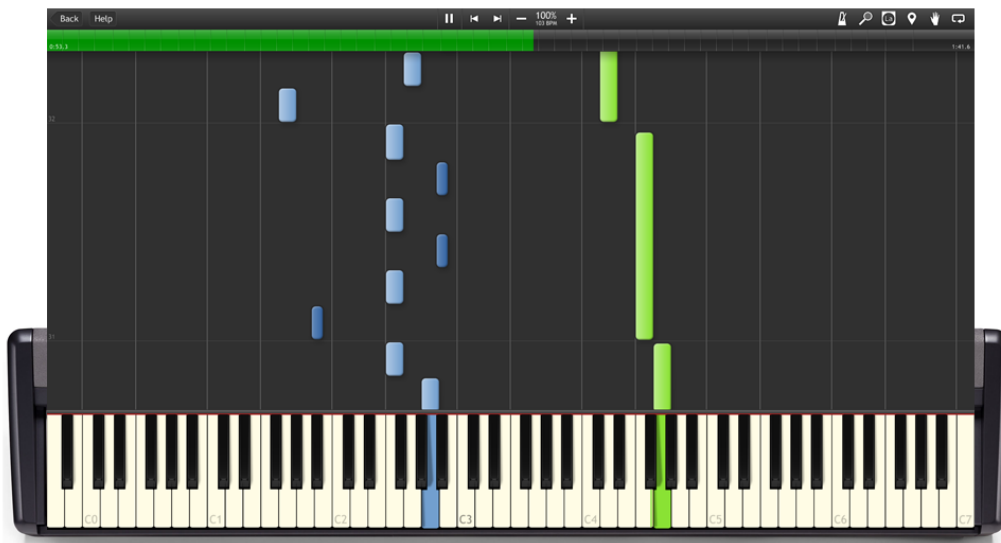
Figure 1.7: The piano roll brought onto a physical piano.

2 Related Work

2.1 Visual Aids in Locality and Scale of the Piano

In [1], a hand-gesture based interface called *the Organ* was presented and evaluated in the context of remote piano collaboration[1]. This interface was designed to be in the locality and scale of the piano, as in Figure 2.1.

Figure 2.1: The Organ interface. Hand gestures of a remote piano player are shown above the piano keys. Image extracted from [1].
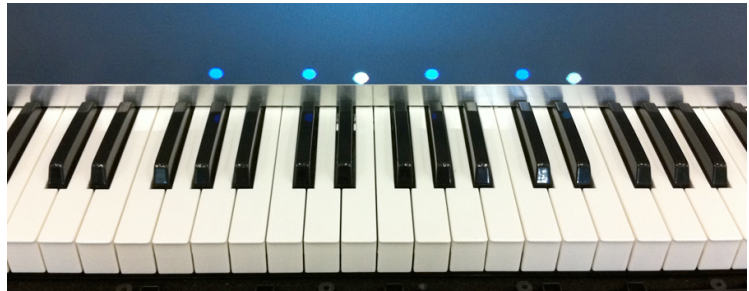
Figure 2.2: The dot-based interface used in evaluation of the Organ interface. Dots indicate what keys must be pressed next. Image extracted from [1].

They compared the Organ interface with two other methods: an on-screen representation of the hand-gestures in Figure 2.1, and a dot-based interface as in Figure 2.2. These three interfaces were then evaluated by measuring the time it took novices to learn a melody using each of the three interfaces. It was found that the Organ and dot method produced the best results, while the screen method was the least preferred and produced poor results:

> *5 out of 10 users ranked Screen as last place because of the "lack of reference frame between the image and physical keyboard" so that "it was difficult to tell where the teacher's hand was". "The difference of scale and the lack of correlation between the image and the physical" also contributed to the "increased visual processing load", making it the most difficult to learn from. [1]*

They also found that the Organ method encouraged correct finger usage, while in using the dot method, many testers used only one or two fingers to play the melodies. This shows that providing fingering hints is necessary to ensure correct fingering. These findings support the notion that displaying to-scale visual aids in the locality of the instrument are preferred over on-screen visual aids in piano learning for novices.

---

[1]Especially in the context of remote piano lessons for beginners.

2.2 Music Performance Games

In [2], the term *music performance game* is coined as a confluence between interactive learning applications and *serious games*[2], but with certain additional elements:

> *(1) As for all games, entertainment and immersion should be critical elements.*
> *(2) The game must directly involve the production of musical sound. In other words, the actions performed by the user during the game sequence should directly result in the production of musical sounds singing, playing a musical instrument, synthesizing sound, etc.*
> *(3) The game should attempt to achieve a specific goal within the performance aspects of music. Common examples are: playing a selected tune on the trumpet, playing major scales fluidly, singing different intervals in tune or learning to play specific chords on the guitar.*

As such, both Synthesia and the augmented piano system developed in the thesis can be labeled as music performance games.

In their work, the game *Music2See* (Figure 2.3) was developed to demonstrate the concept of music performance games. The game allows users to practise songs on various instruments while being recorded through a microphone. During this practice, the game evaluates the user's musical performance in real-time and offers live feedback.
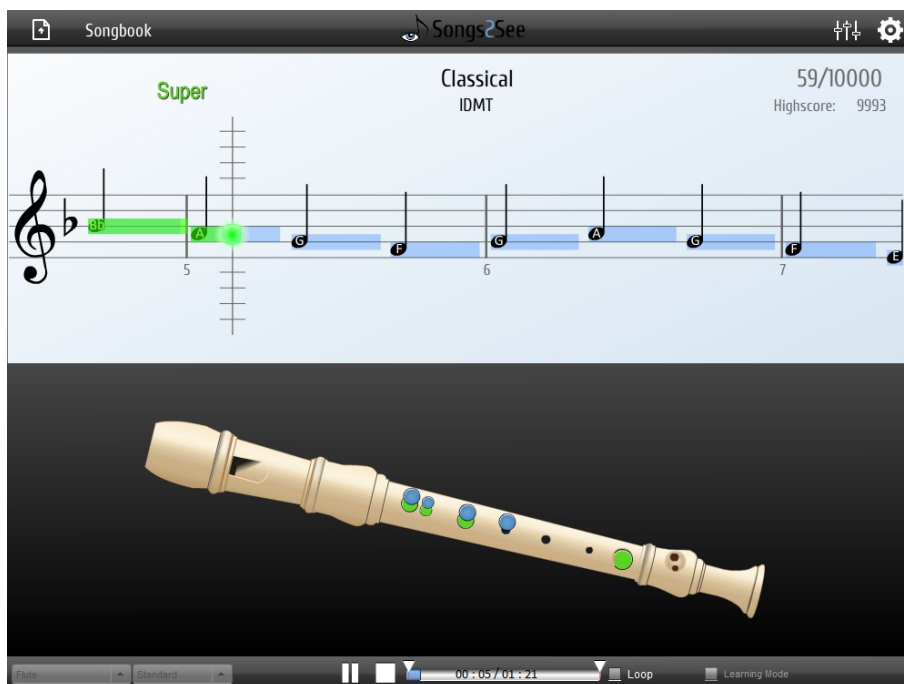
Figure 2.3: The music performance game Song2See [2].

Additionally, they evaluated their game in the context of *the conceptual framework for serious games*, defined in [3], with the goal to improve the final outcome and learning potential of the game. This framework is shown in Figure 2.4.

---

[2]Where the primary focus lies not in entertainment, but in educating the user, often directed at adults or adolescents.
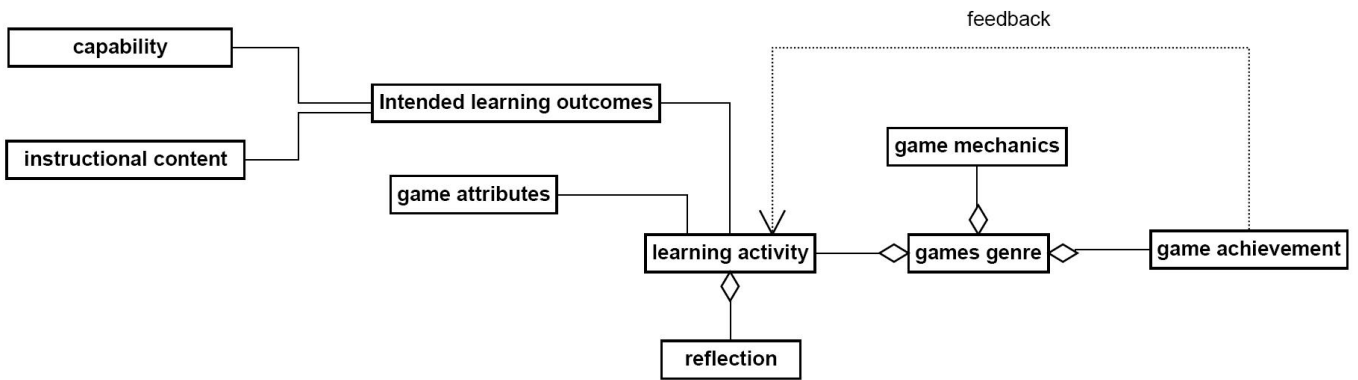
Figure 2.4: Structural diagram of the conceptual framework as defined by [3].

To optimally support music education[3]in the augmented piano system, more attention could be brought to the design of the system by evaluating it within the conceptual framework just mentioned. Such a detailed analysis is beyond the scope of the thesis, but could be performed in future work to enhance the learning value of the system.

2.3 Augmented Piano Tutor

The *Augmented Piano Tutor* application prototyped in [6] teaches chords and scales on the piano through an augmented reality-based setup. The setup consists of a piano keyboard, a webcam to track the piano, and a computer monitor on which the augmented view of the piano is shown (as in Figure 2.5). Input is read from the piano and feedback on correct or incorrect key presses is provided, just as in the augmented piano system presented here. In Piano Tutor, augmentation of the keyboard is restricted to on-screen visual cues, meaning feedback on the physical instrument is not possible.

Although the thesis setup differs from the setup used in Piano Tutor, the application shows that chords and scales can be taught intuitively by highlighting keys making up a particular chord. This concept can be applied in future work.

Figure 2.5: The augmented view of the piano keyboard in the Augmented Piano Tutor.

---

[3]To the degree which is desired: ranging from learning simple melodies on the piano using a piano roll, to teaching music notation and music theory, as discussed in Section 5: Future Work

2.4 The P.I.A.N.O. System

Well into the course of writing the thesis, [4] introduced the *P.I.A.N.O. System*. Their setup is almost identical to the setup that is used in the thesis: a piano roll is projected to-scale at the physical piano which is fasciliated by a projection surface adjacent to the piano, and input from the user is processed using a MIDI-to-USB interface, see Figure 2.6. In addition, they utilized tracking of the fingers to provide feedback on the pianist's finger positioning during play. Their system also supports the MusicXML format, which gave them access to several sheet music notation elements as discussed in Section 5.1: Adding Learning Value. These elements add to the expressive power of the piano roll. They included visual elements for note dynamics, ornaments and note articulation, which is also covered in Section 5.1: Adding Learning Value.
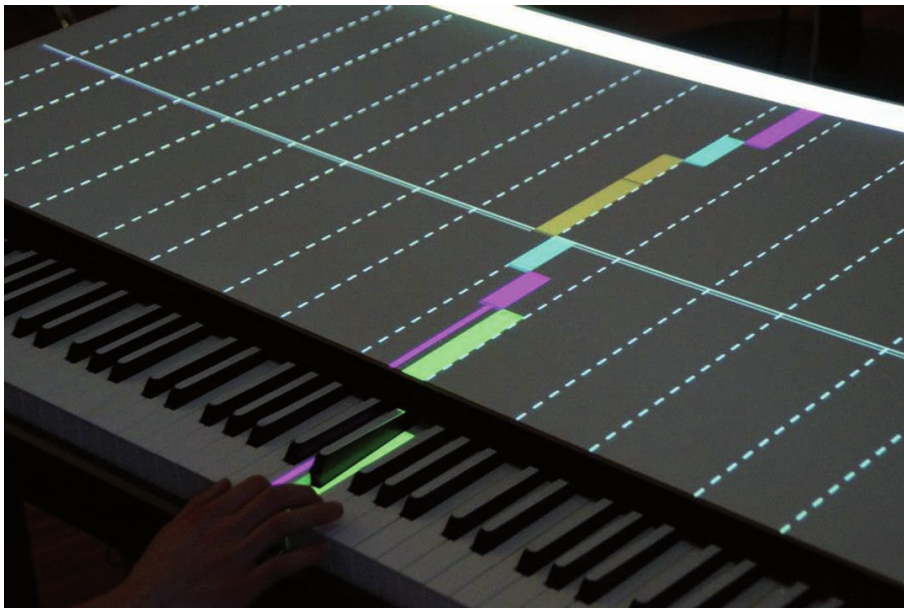
Figure 2.6: The piano roll visualization in the P.I.A.N.O. system.

In a small-scale evaluation of their system, they found that half of the test participants stated that their visual scope included both the piano keys and approximately half of the adjacent projection surface. The visual scope of the other half of the participants reached only to about 10 cm above the keyboard. This implies that the projection surface used in the thesis could be reduced in size to achieve minimum space requirements while still showing enough of the piano roll to see upcoming notes. Additional testing should be done to determine a suitable projection surface size.

3 The Prototype

3.1 Physical Setup

3.1.1 Setup Methods

In choosing the setup method to bring the virtual piano roll onto a real piano, the following requirements have been taken into account.

- **Visual feedback on piano keys:**
  This must be possible as it greatly enhances the learning experience. (e.g., note names on keys, indicating which keys are to be pressed next, showing chord patterns,...)

- **Minimal software overhead**:
  To avoid distraction from the main goals of the thesis, the setup-specific implementation should add minimal complexity to the software.

Keeping these requirements in mind, three different setups have been compared: a display-based, a projection-based, and an augmented reality-based setup. A short overview of these three setups follows, and a comparison between them is given at the end of the section.

(Touch) Display

A display-based setup involves placing a standard sized computer monitor running the software behind the physical piano. As mentioned in Section 1: Introduction, the issue with this setup is a confusing mapping between the small, virtual piano on the screen and the much larger physical piano. To eliminate this issue, a wider display could be used that spans the entire width of the piano. It can then be placed vertically, sloped or horizontally, while letting the monitor reach the piano keys as closely as possible. An alternative is to use a large touch screen or touch table, adding the option for input via touch. Both of these setups however miss out on providing visual feedback on the physical piano keys. A solution to this may be to draw a virtual piano keys at the bottom of the display and in the size of the physical piano keys, as in Figure 3.1.
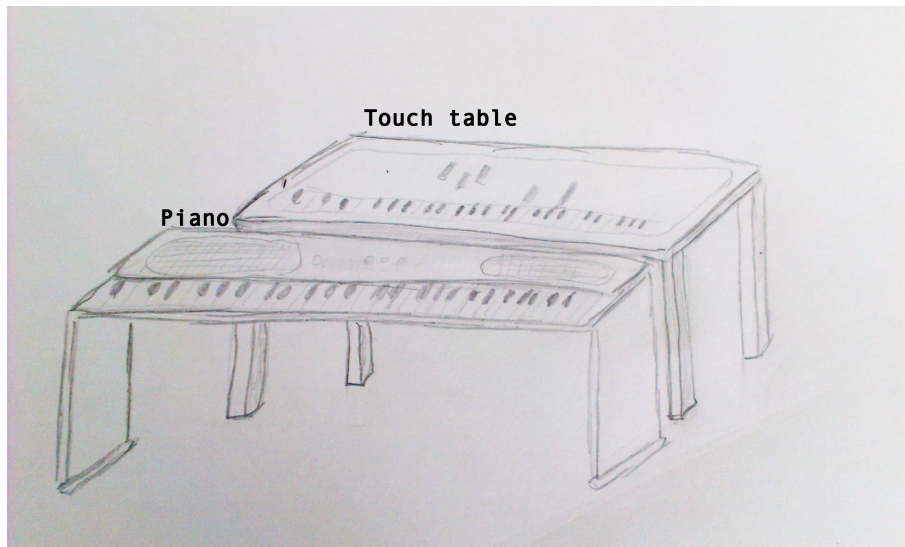
Figure 3.1: A sketch of the display or touch table-based setup. This shows the setup should a display, touch screen or touch table be placed right behind the piano.

Projection

In a projection-based setup, the piano roll can be projected onto the piano itself, onto a wall, onto a surface placed horizontally on the piano starting at the keys, or onto any combination of these. This method allows for projection on the keys of the piano itself, adding a whole range of possibilities for learning purposes such as projecting note names that keys represent directly onto the corresponding keys.

A micro-projector don't offer a satisfying solutoins because this requires tracking to keep the projection stationary, which greatly increases the complexity of the software. In this setup the projector would also be very close to the piano, leaving the projection angle severely restricted and making it difficult if not impossible to project over the entire width of a full-sized piano. A stationary projector mounted above the piano provides a much simpler setup and less complex software, though calibration when moving the setup is necessary.

When using a projector, there needs to be some area where it is meant to project onto. Using just the piano as the projection area would severely restrict the software's possibilities, as it shrinks the projection area down to a height of just a few centimetres. Another issue with projection on the physical piano alone[1] is that buttons, sliders and other structural elements of the piano itself can obscure the projection. This depends on the piano in question. For these reasons, extending this projection area is a good choice. A rectangular board can be mounted on the piano so that it begins it aligns with the piano keys and spans a desired area in front of the piano, as in Figure 3.2. This leaves room for the piano roll to be projected upon, with no structural objects degrading the projection quality. Note that this setup can only work with a piano that allows for the board to be mounted in connection to the keys. This means upright or grand pianos cannot be used.

---

[1]And thus, above the piano keys as well.
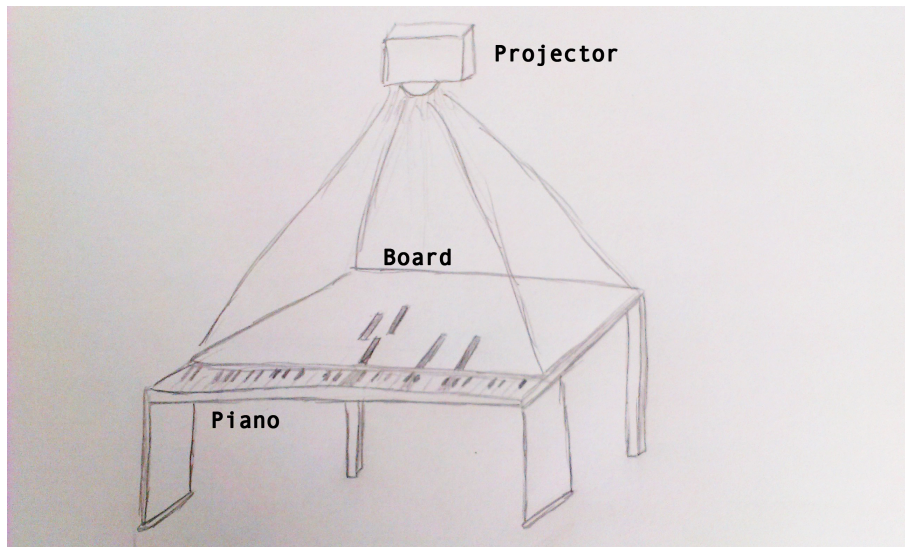
Figure 3.2: A sketch of the projection-based setup.

Augmented Reality

An augmented reality (AR)-based setup would give even more freedom than the projection-based setup, allowing 2D and 3D virtual objects to be drawn anywhere in the proximity of the piano. A three dimensional virtual piano roll could then be drawn attached to the piano and no physical setup would be needed apart from a device through which the augmented view of the piano can be seen. A Head-Mounted Display (HMD) can fill this purpose. Even though mobile phones or tablets also support AR tools, they are highly impractical because they require the user to hold the device at all times, and they must look at a small screen in order to see the augmented piano. Figure 3.3 shows how such an AR setup using a HMD may look.
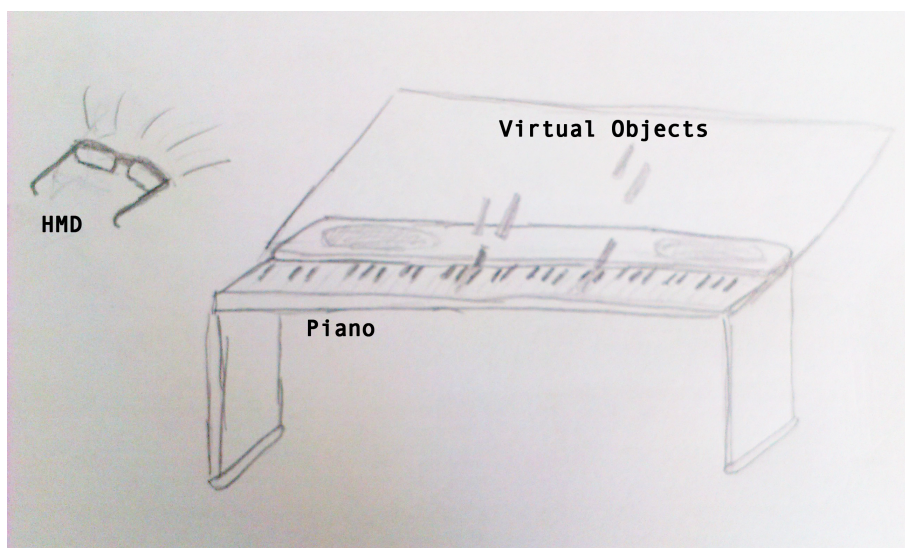
Figure 3.3: A sketch of the AR-based setup. Virtual objects are seen when looking through the HMD.

The basic issue with AR systems in the context of the thesis goal is the *registration problem* in a dynamic context, as coined in [7]:

> *Assume that the viewpoint and all objects remain still. Then the lag does not cause registration errors. No matter how long the delay is, the images generated are appropriate, since nothing has moved since the time the tracker measurement was taken. Compare this to the case with motion. For example, assume a user wears a see-through HMD and moves her head. ... [end-to-end delay occurs]... To the user, the virtual objects appear to "swim around" and "lag behind" the real objects.*

A pianist doesn't remain perfectly still during play. The resulting constant movement of the player's head induces the effect just described. To ensure this effect does not occur, a HMD with high accuracy trackers and sensors would be required.

When a HMD is used, only the person wearing the device will be able to view the virtual piano roll. This leaves out possible tutoring by another person, unless multiple HMDs are used.

Table 3.1 further compares the above setups.

	Display	Projection	Augmented Reality
Visualization Area	Restricted to the display's surface, 2D	Everywhere in the projection range, but restricted to 2D overlays	No restrictions: 2D overlays and 3D virtual objects
Visual Feedback on Piano Keys	On virtual piano keys only.	On the physical piano keys.	On the physical piano keys.
Visibility	Everyone	Everyone	Restricted to person wearing AR device
Added Software Complexity	None	Calibration	Calibration, marker system, robust tracking, lag-free rendering
Setup-specific Issues	No visual feedback whatsoever on physical piano.	Sensitive to room lighting	Head movement, wear fatigue

Table 3.1: A comparison between setups.

Table 3.2 summarizes the above comparison with respect to the requirements set at the beginning of this section. The projection-based setup is chosen as the setup method for use within the thesis, as it is most rapidly prototyped by still allowing for visual feedback on the physical piano.

The next section provides details of the setup that was used within the thesis.

	Display	Projection	Augmented Reality
Visual Feedback on Physical Keys	No	Yes	Yes
Software Overhead	None	Small	Substantial

Table 3.2: A comparison between setups.

3.1.2 The Projection-based Setup

The projection-based setup consists of three parts:

- **The piano**
  a Casio CDP-100.

- **The projector**
  a wide projecting Epson projector.

- **The projection surface**
  Two kinds of projection surfaces have been constructed:

    - A flat, rectangular board (Figure 3.4),
    - A two-piece board, top piece adjustable in slope (Figure 3.5).
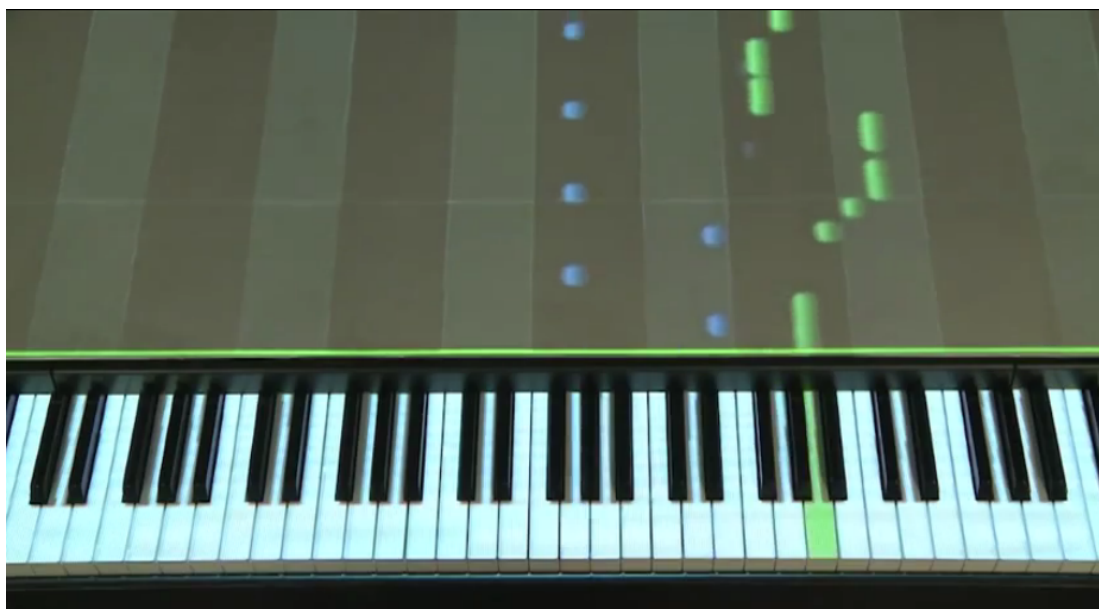
Figure 3.4: The setup with an 88-key piano and flat projection board.
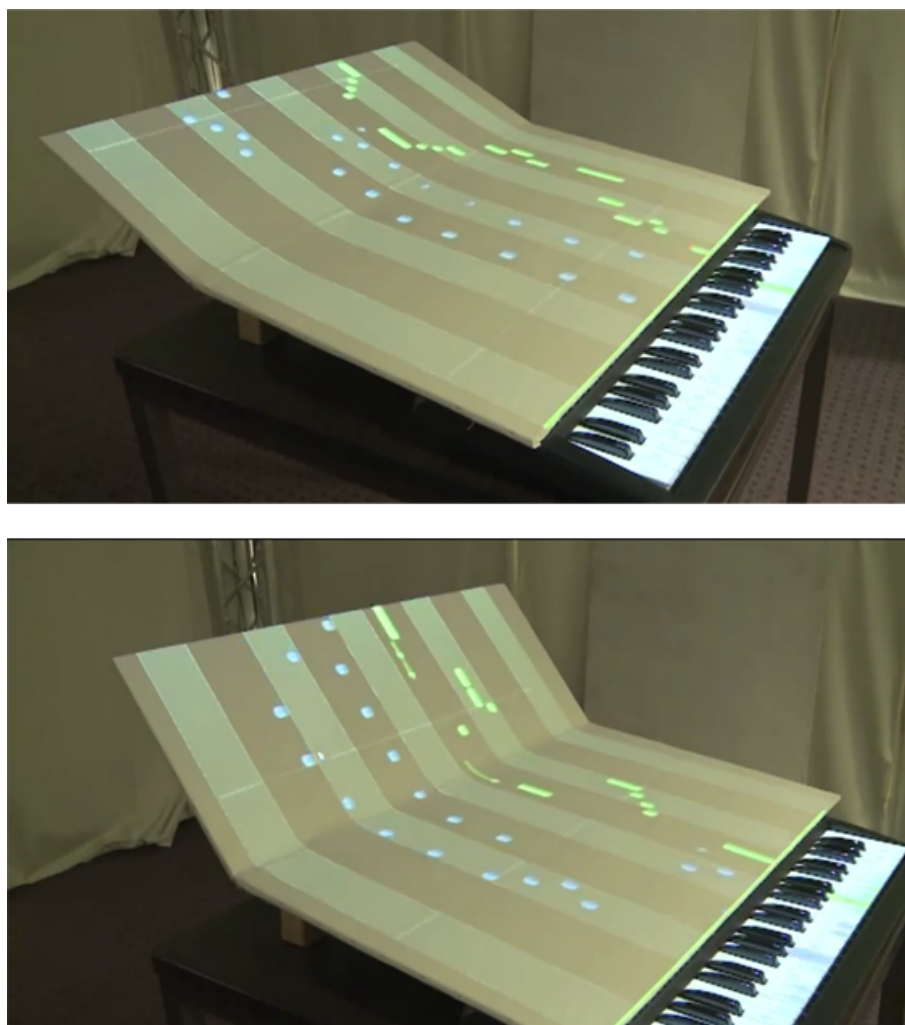
Figure 3.5: The setup using a two-piece projection surface. Here, projection is done on a 61-key piano.

3.2   Software Functionality

This section presents an overview of the accomplished prototype system. First, a brief overview of all implemented features is presented here.

- **Projection onto sloped surfaces**

  Transformation of three pieces of the projection can be set separately:

  - The upper, movable piece of the projection surface,
  - The static, lower piece of the projection surface,
  - The keyboard keys.

  Calibration parameters are read from a file and include:

  - Width and height of white and black keys,
  - Number of white keys,
  - MIDI note number of the first key on the far left of the keyboard,
  - Height of upper and lower projection surfaces,
  - One transformation parameter per projection piece described above.

- **Loading a MIDI file**

  MIDI file constraints:

  - For proper visualization of the note bars, the MIDI file must either use the standard MIDI *note off event* or the *velocity 0 event* to signal that a key must be released.
  - Multiple tracks are only supported if the MIDI file specifies them.

- **Visualization of MIDI files on a piano roll**

  Adjustable settings:

  - MIDI file to be visualized,
  - Tracks to show: left hand and/or right hand,
  - Track(s) to be played as MIDI output,
  - Track(s) to be checked for correct input,
  - Playback speed,
  - Drop speed of note bars,
  - Playing aids:
    * Note names on keys ON/OFF,
    * Note names on falling note bars ON/OFF,
    * Gradual highlighting of keys ON/OFF.

- **A simple menu to configure the piano roll settings**

- **Interaction with the software**

  - Using the computer keyboard,
  - Using specified keys on the piano using a MIDI-USB interface cable.

- **Keystroke Evaluation and Feedback**

  - Real-time feedback of note hits,
  - Real-time feedback of note misses,
  - Real-time feedback of wrong key presses,
  - Counting of hit ratio,
  - Result screen which presents these to the user (Figure 3.6).
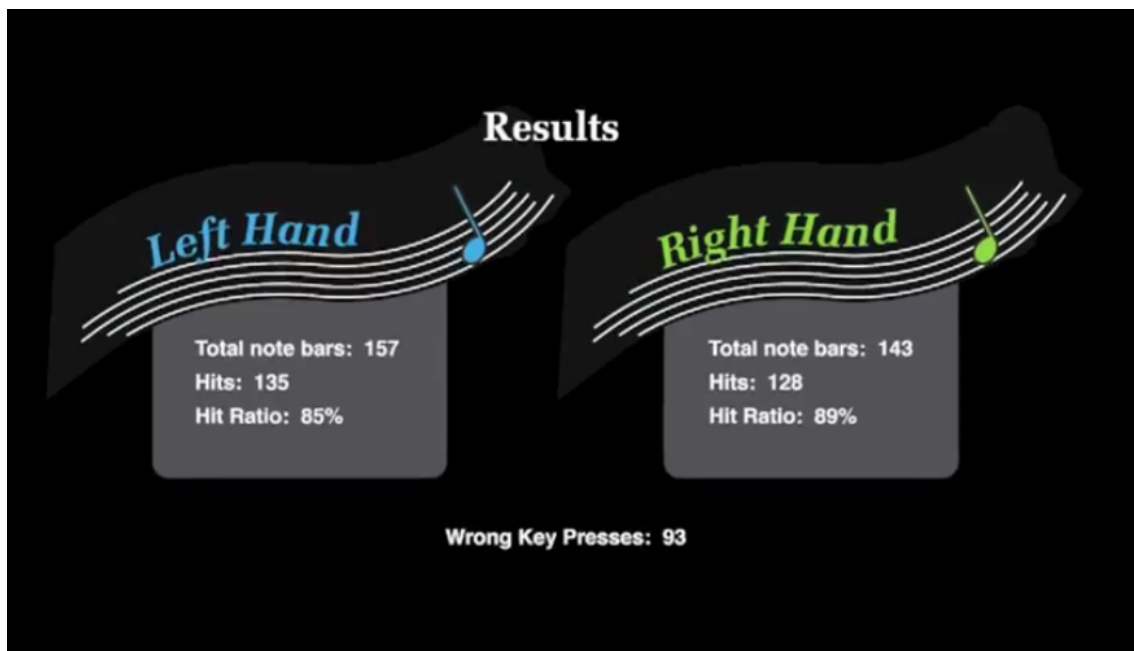
Figure 3.6: The result screen.

3.2.1 The Menu

The menu can be used to adjust the settings of the piano roll. Settings are grouped logically, and a different group of settings can be chosen from the tab pages on left-hand side. On the right-hand side, settings for this tab page are listed vertically and can be adjusted. Examples are the *Song* tab, where the midi file and its playback speed can be set, or the *Tracks* tab, where the user can specify options for the left-hand and right-hand MIDI tracks. See Figure 3.7.
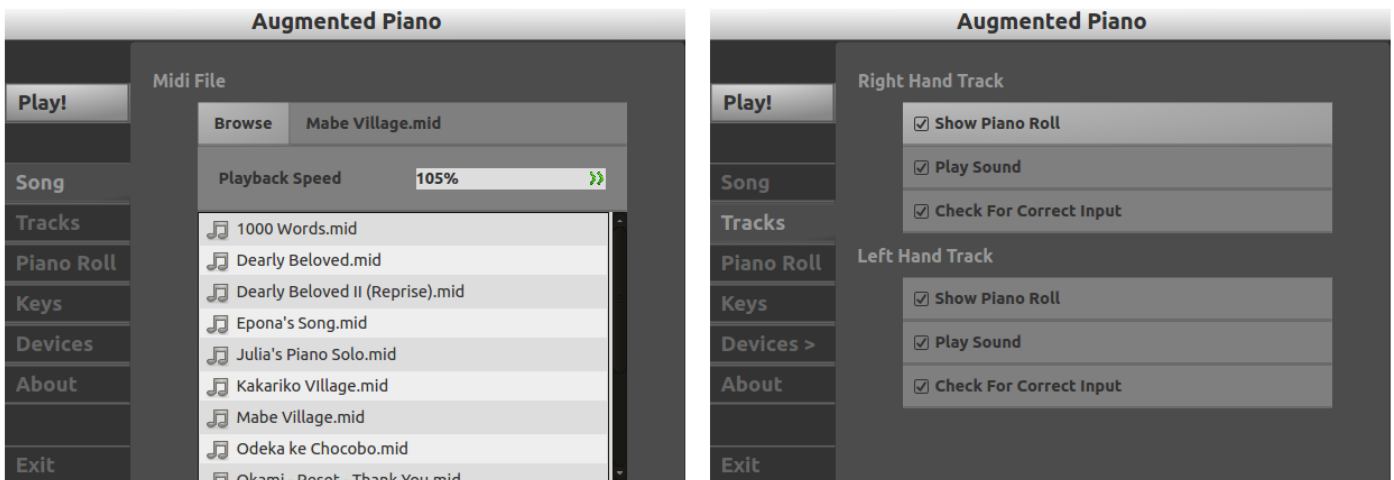
Figure 3.7: The *Song* and *Tracks* tabs in the menu[2].

Menu navigation and adjusting of settings can be done using either the computer keyboard or certain keys of the piano. This is further explained in Section 3.3: User Interaction. Once the *Play* button at the top of the left-hand side is pressed, the piano roll starts its visualization.

3.2.2 The Piano Roll

The piano roll is responsible for visualizing the user specified MIDI file. As mentioned in Section 1.1: Background, it does this by dropping note bars from the top of the piano roll to the bottom (see Figure 3.8). Each note bar falls straight down to one of the piano keys. Once a note bar hits the green line, the corresponding key is meant to be pressed until the note bar passes the green line. The length of the note bars reflect note duration: longer note bars signify longer sounding notes, meaning the key should be held down longer (see Figure 3.9). The key is highlighted completely with the note bar's colour as long as a note bar is falling onto it. This makes it easier for the user to locate the key should he miss it, and gives a real-time visualization of the keys that are to be played.

To distinguish between black and white keys, note bars have different shades of their main colour. Note bars corresponding to white keys have their full colour, while those corresponding to black keys the same colour, but darkened (see Figure 3.10).

---

[2]These screenshots were taken on-screen for clarity.
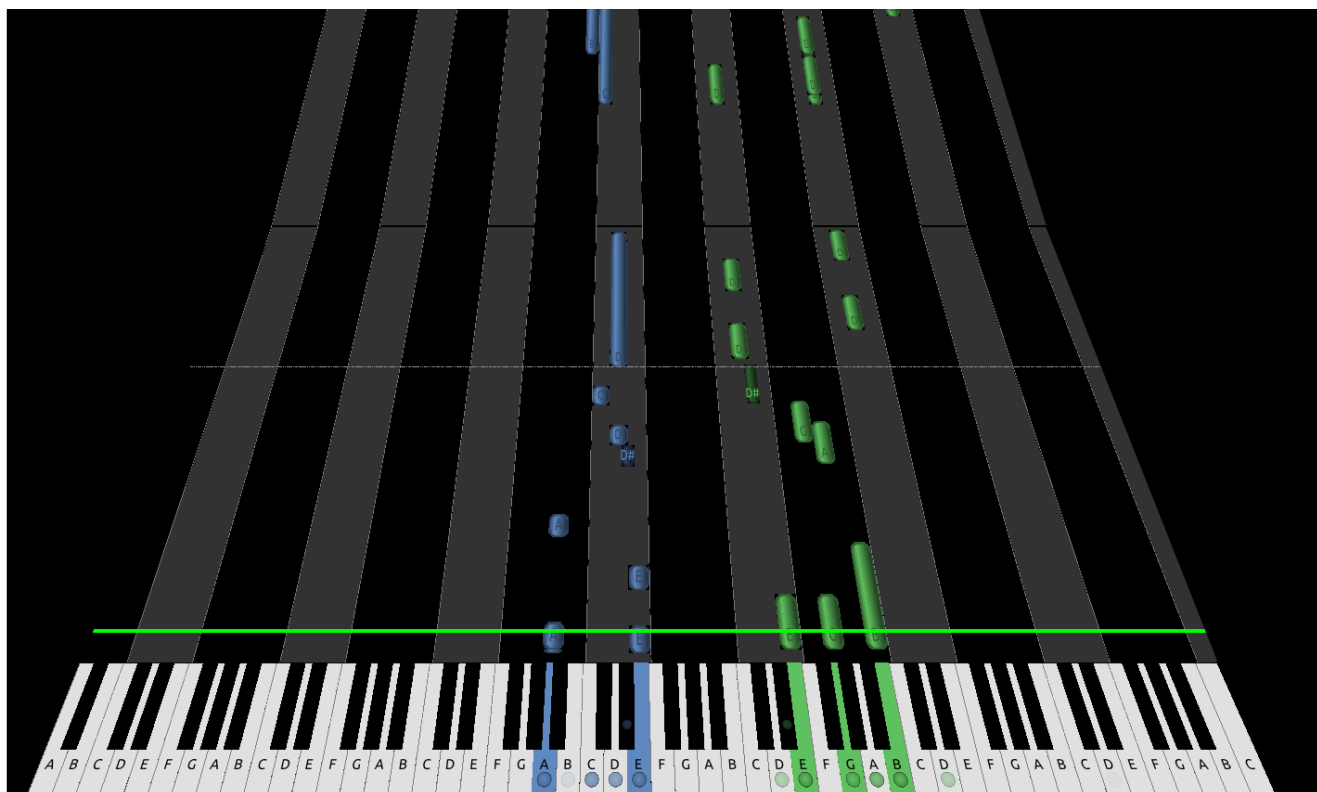
Figure 3.8: The piano roll on-screen.

Figure 3.9: Length of note bars signify note duration. Here, note names are disabled on both note bars and piano keys. Keys that are meant to be played are highlighted in the colour of the note bar.
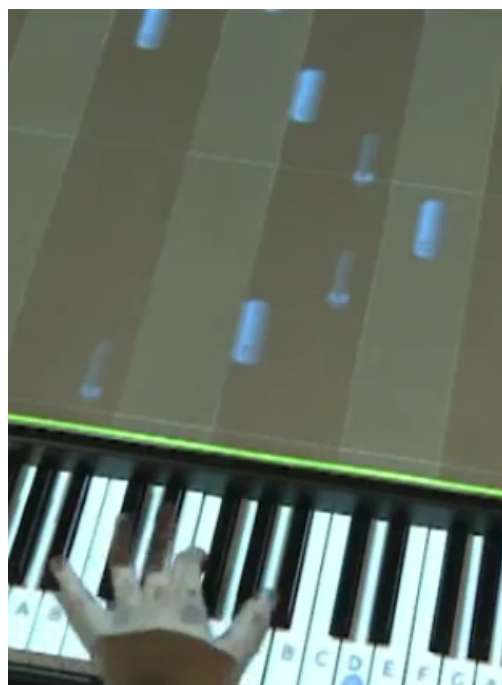
Figure 3.10: Note bars corresponding to white and black keys. Measures are identified by horizontal lines. Here, note names are drawn on both note bars and piano.

MIDI files may have separate tracks for the left and right hand. The piano roll distinguishes between these tracks by using two different colours: blue for the left hand, green for the right hand (see Figure 3.9). This means the left hand should play the keys in the blue track, and the right hand should play those in the green track. When the MIDI file doesn't specify multiple tracks and puts all notes on one track, there is no way to distinguish between right or left hand notes and the piano roll will display all note bars in the same colour.

In terms of sheet music, a musical piece is divided into *measures*. Each measure is a number of beats long, determined by the *time signature*[3]. To help the user recognize this beat in the song, horizontal lines are drawn at the start of each measure (see Figure 3.10).

Directing The User's Gaze

When looking at all these note bars falling down toward the keys, it may still take some time to build up the right reflexes which enable you to find and press the right keys quickly. Certain visuals aid cues are present to help direct the user's gaze from note bars to the corresponding piano keys.

As mentioned in Section 1.1: Background, groups of two black keys are always followed by groups of three black keys, and together they form an octave. The first addition utilizes this by drawing alternating vertical columns for each group of two and three black keys. By drawing the vertical columns above these key groups, the user can see immediately from the piano roll to which key group a note bar belongs, and more specifically, to which key within that key group it is moving. E.g., If a note bar is situated to the far right in a light grey column, such as the lowest blue note bar in Figure 3.9, the user will know immediately that it is moving toward the key representing an E.

To further aid the user in this, note names are drawn onto the note bars and the keys representing those notes (see Figure 3.10). This is possible because notes are in the same order in every successive octave. Once the user has built up a familiarity with keys and the note names they represent, he can choose to disable this feature.

To help direct the user's gaze even further, corresponding keys are highlighted using a dot graphic when a note bar is headed toward that key (see Figure 3.11 and Figure 3.12). Gradual highlighting is applied to give the user a sense of which key will be pressed first when multiple keys are highlighted: those with the clearest highlight will come before those with a feint highlight. A simple circle has been chosen as a means of highlighting the key, though other designs such the gradual colouring of the entire key, were also considered.

Providing User Feedback

Besides telling the user how to play a song, the piano roll can also tell the user which keys he hits or misses in real-time. When the user hits a key that is not meant to be played at that moment, the key is completely highlighted in red (see Figure 3.12). When a key is pressed at the right moment, the note bar corresponding to that key press is given a green border (see Figure 3.11). When the user misses a key, meaning the note bar reaches the bottom line and the user doesn't press the corresponding key in time, the note bar is given a red border (see Figure 3.12). Alternate methods of signifying key hits and misses that were considered can be seen in Figure **??**.

---

[3]The most common time signature is 4/4, which means one measure has the duration of four quarter notes.
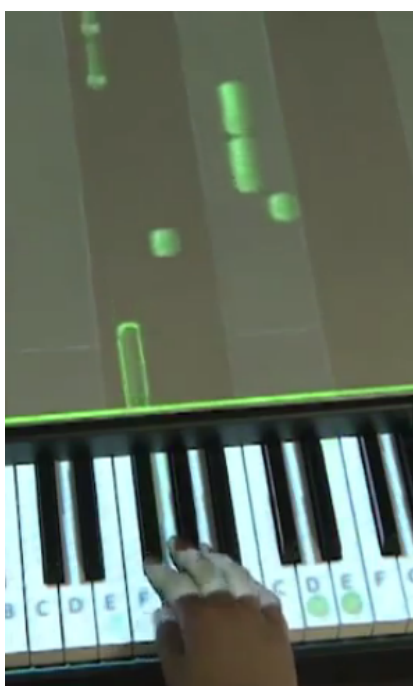
Figure 3.11: Key hit. The corresponding note bar is given a green border.
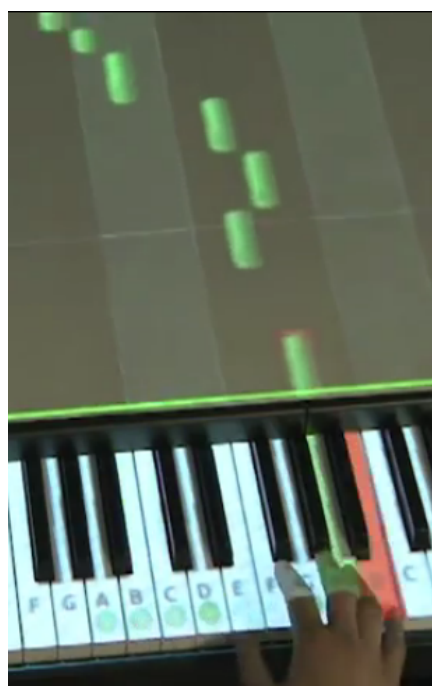
Figure 3.12: Key miss. The corresponding note bar is given a red border. Wrong keys are highlighted in red.

3.3 User Interaction

When sitting at the piano, it may become cumbersome having to use a computer keyboard as a primary means to interact with the system. This is why user interaction is supported in two ways: using the computer keyboard and using certain piano keys. As a plus, both the user sitting at the piano, and another person (perhaps a tutor) sitting at the computer, can control the system. Piano input is sent to the computer through the use of a MIDI-USB interface cable.

3.3.1 Menu Navigation

On the keyboard, the menu can be navigated using the arrow keys and the *enter* key. To navigate through the left-hand menu tabs and the right-hand menu items, the *up* and *down* keys are used. To switch from the left-hand menu to the right-hand page and back, the *left* and *right* arrow keys can be used. Values of combo boxes are changed using the *left* and *right* arrow keys. Navigating back to the left-hand menu form within a menu page can only be done when something other than a combo box is selected.

Figure 3.13: The arrow keys mimicked on a piano. The mouse click takes the role of the *enter* key on the keyboard. Also note that the UP arrow key is not visible on the black key, which is discussed in Section 4.2: Limitations.

On the piano, navigating a menu is not as straightforward. The following two approaches can be considered:

- Mimic keyboard keys on the piano,

- Utilize the available piano keys and the fact that they are spatially spread out across the projection area.

The first approach is directly compatible with the keyboard input methodology, and piano keys can simply be mapped to certain keyboard keys. In this way, the arrow keys and *enter* key can be easily mimicked, as figure 3.13 shows. The second approach is taken in [4], as shown in Figure 3.14 and Figure 3.15. For this thesis, the menu was not a focus point, so the first approach was chosen as it involved less implementation overhead.
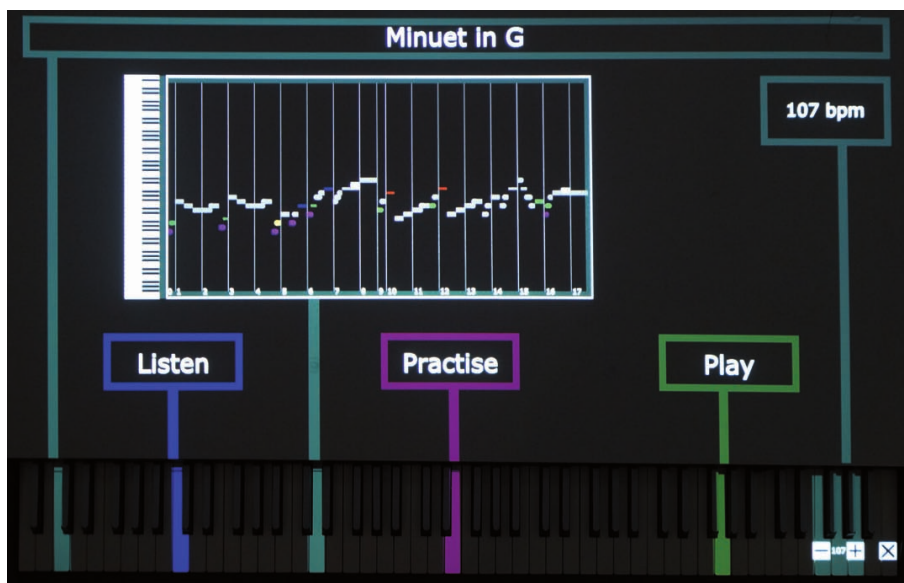
Figure 3.14: The menu in the P.I.A.N.O. system [4].
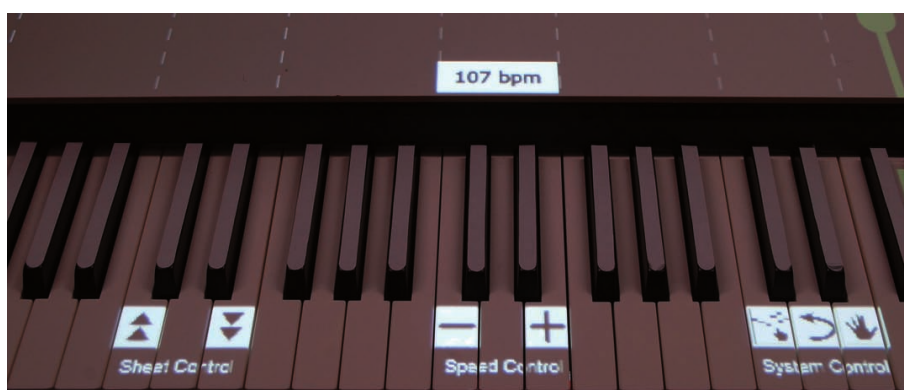
Figure 3.15: The secondary menu in the P.I.A.N.O. system [4], evoked by pressing a foot pedal during playback of a song.

3.3.2   During Play

When in piano roll mode, two actions are available: returning to the menu, and pausing.

On the keyboard, *ESC* can be used to return to the menu, while *P* can be used to pause.

On the piano, pressing the two leftmost keys of the piano returns the user to the menu. This can be two white keys, or a white and a black key, depending on the piano size. On a full-sized piano, this is a white and a black key. Pausing during the piano roll can be done by pressing the leftmost key and the third leftmost key. On a full-zied piano, these are the two leftmost white keys.

3.4 Software Technology and Tools

An overview of technologies and tools used in creating the prototype is given in Table 3.3.

Programming Language	C++
Application and GUI Toolkit	The Qt Framework [4]
Music Format	MIDI [5]
MIDI Library	JUCE [6]
Platform	Linux, Windows

Table 3.3: An overview of software technologies used.

3.4.1 Music Format: MIDI vs MusicXML

A music format is needed to gain access to note information of a song. This music format should allow for a simple way to create a piano simple roll from the stored music information. This means it must be easy to subtract note information: when a note should be played and how long this note lasts.

In deciding on a suitable music format, two major formats have been considered. Namely the MIDI format[7] and the MusicXML format[8]. The MIDI format stores music in the form of instructions and is mostly used for music playback. For example, A *note on* instruction means a certain note needs to be played and held until a corresponding *note off* instruction occurs. It also stores time signature and tempo, but besides this information, relatively little information is stored.

In contrast, the MusicXML format was designed specifically for storing and exchanging sheet music in an editable format. On top of simple note information, MusicXML files contain more complex information found on musical scores which are not present in the MIDI file format. Examples of such information are finger positioning, pedal instructions, articulation and dynamics of keystrokes. Having access to this information can add tremendous learning value to the system, as it would allow for sheet music music notation aspects to be integrated into the piano roll.

It is noted that most digital pianos have MIDI IN and OUT jacks that can be connected to a computer using a MIDI-to-USB interface, which makes it possible to read the user's keystrokes on the piano. This grants the possibility to provide the user with feedback on whether or not he played the right notes at the right times. Additionally, the computer can tell the piano which notes to play without any effort from the user. This is ideal for making the piano play a song by itself. Thus, it makes sense to implement a MIDI subsystem responsible for reading note information from the piano and sending note information to it. Note information from MIDI files can then be sent directly to the MIDI output device and thus the piano, without any conversion needed. This same note information can also be used directly in constructing the piano roll.

---

[4] http://qt-project.org/
[5] http://www.midi.org/
[6] http://rawmaterialsoftware.com/juce.php
[8] http://www.musicxml.com/

To additionally support the MusicXML format and gain access to additional sheet music information, a second subsystem responsible for parsing MusicXML files would be needed, and perhaps integrated with the MIDI subsystem. MusicXML note information would need to be converted to MIDI note information in order to have access to the piano through MIDI.

Even though incorporating the MusicXML format into the system would add learning value regarding music theory aspects, the MIDI format grants sufficient functionality to construct a simple piano roll, while also being the simplest format to implement. Therefore, the decision was made to focus solely on the MIDI format for the thesis implementation.

3.4.2 Brief Overview of the MIDI Protocol

Before continuing the discussion, the MIDI protocol is discussed here briefly. In its essence, the MIDI[9] protocol can be described as follows:

> MIDI is a system that allows electronic musical instruments and computers to send instructions to each other. ...When one MIDI device communicates with another, it's all about instructions: It's just one MIDI device telling another one what to do. [8]

There are many kinds of instructions, each kind carrying specific information about that instruction. The two relevant for this discussion are the *note on* and *note off* events. Among other information, these two events carry a *MIDI note number* representing a single note. On the piano, keys represent a single note and thus correspond to a single MIDI note number. The note numbers on a piano range from 21 to 108, from the leftmost key to the rightmost key. When a *note on* event is triggered carrying note number 21, this means the leftmost key of the piano was pressed. Then, a note off event signals the release of that key.

A sequence of MIDI messages can be captured and written to a *MIDI file*, which uses the .mid file extension. A MIDI file can contain several instruments, which may or may not be separated into different tracks. In music notation, notes played by the left and right hand of a pianist are written on separate staffs. In a MIDI file, the left and right hand can each be written to a different track. Depending on how the MIDI file was created, the left hand and right hand notes may be put onto a single track, leaving no way to discern which note should be played by which hand.

3.4.3 MIDI Library: JUCE

To circumvent the need for writing a MIDI file parser and thus learning about the low-level details of the MIDI format, using a C++ MIDI library is necessary. The library should support high-level MIDI input/output processing and MIDI file access. Various linux-compatible candidates were found, including JUCE[10], Midiio[11] and PortMidi[12].

After further inspection of the library features and API documentations, the JUCE library proved to have the most comprehensive MIDI support, clear and self-explaining class structure and methods, and an extensive support community. It is also easily integrated into a project by including the sources files of the required submodule into the local project.

---

[9]MIDI stands for *Musical Instrument Digital Interface*.
[10]http://www.juce.com/
[11]http://midiio.sapp.org/
[12]http://portmedia.sourceforge.net/

JUCE[13] is actually not a MIDI library, it is a general C++ application framework with wide-ranging submodules ranging from UI modules to audio and video playback modules. The following overview lists the JUCE MIDI classes that have been incorporated into the implementation, along with brief descriptions.

MidiFile [14]	Represents a MIDI file. Contains functions to easily retrieve information about the file and the separate MIDI tracks it contains.
MidiMessage-Sequence[15]	Represents a sequence of MIDI messages and is contained within the MidiFile class, where it represents a single MIDI track. Contains functions to easily access MIDI messages within the sequence.
MidiMessage [16]	Represents a single MIDI event. Contains functions to retrieve information about the event, such as event type and note number (in case it was a note on or note off event).
MidiInput[17], MidiOutput[18]	Represent MIDI input and output devices. They contain functions for retrieving a list of MIDI devices, opening/closing a device, sending/retrieving MIDI messages to and from the device.

Table 3.4: An overview of JUCE MIDI classes used.

3.5 Software Architecture

3.5.1 Overview of Important Classes

This section provides a high-level overview of the resulting software architecture. Table 3.5 lists the most important classes along with a brief description of their roles within the system.

3.5.2 Moving the Piano Roll

Several of these classes are responsible for making the piano roll move once the user plays a song. An overview of how these classes work together to accomplish this is given in Figure 3.16, a brief explanation follows.

Once the song is played, the MidiSongReader is started. This object keeps a timer and the time of occurrence for the next MIDI event. Once the timer has reached this time of next occurrence, one of two signals is emitted: that a new MIDI event has occurred, or that a new note ON event has occurred. When the first occurs, this MIDI event is forwarded to the MidiOutputDevice, which passes the messages to the piano. If the second occurs, the NoteBarVisualizer object is informed and drops a new note bar based on the note's duration and track type (left or right hand). Because MIDI files don't have events that signal the start of a new measure, the MidiSongReader also keeps track of the times on which a new measure starts. This is calculated from the file's time signature and tempo. Once a new measure starts,

[13]Which stands for *Jules' Utility Class Extensions*
[14]http://www.juce.com/api/classMidiFile.html
[15]http://www.juce.com/api/classMidiMessageSequence.html
[16]http://www.juce.com/api/classMidiMessage.html
[17]http://www.juce.com/api/classMidiInput.html
[18]http://www.juce.com/api/classMidiOutput.html
[19]http://www.juce.com/api/classMidiMessageSequence_1_1MidiEventHolder.html

MidiFileReader	Utilizes the JUCE library to obtain a MidiFile object from a MIDI file on the hard disk. Constructs a Song object using this file.
Song	Encapsulates the JUCE MidiFile class and constructs Track objects out of the MidiFile's separate MidiMessageSequences. Determines which track represent a left hand or right hand track. Also calculates the time signature and tempo at a given timestamp.
Track	Encapsulates the MidiMessageSequence class. Keeps track of which event was last read and which event comes next.
MidiSongReader	'Plays' a Song object by reading MIDI events divided over its different tracks. Emits signals as MIDI events occurr. Emits separate signal when a note ON or OFF events occur. The signals are emitted at the correct times.
MidiInputDevice	Encapsulates the JUCE MidiInput class. Used to open an input device (the piano) and to receive MIDI messages from it when the user presses a key. Emits signals when note ON and OFF events are received.
MidiOutputDevice	Encapsulates the JUCE MidiOutput class. Used to open an output device (the piano) and to send note ON and OFF messages to it. This makes the piano play a note.
NoteBarVisualizer	Responsible for drawing the piano roll. It drops note bars as it receives signals from a MidiSongReader instance. It moves note bars forward and removes them when they reach the bottom, emitting various signals as note bars hit or pass the bottom.
Keyboard	Represents the projected keyboard. Holds Key objects and upon receiving signals, can update the appearance of keys such as giving it a pressed look, enabling the highlighting dots or turning note names on/off.
InputChecker	Responsible for analyzing whether a keystroke was a hit or a miss, upon receiving key press/key release signals. Uses signals from the NoteBarVisualizer to determine when note bars are near the bottom.
ProjectionSetup	Holds the projection parameters which it reads from a text file.

Table 3.5: An overview of important classes.

a signal is sent so that the NoteBarVisualizer can drop a horizontal line which represents a measure.

The NoteBarVisualizer periodically moves note bars that are currently on the piano roll. Each time the note bars move, several checks are done. Some of these include: whether the note bar has reached the bottom, which makes the keyboard press a key (visually); whether the note bar moved passed the bottom, which makes the keyboard release a key (visually); or wether the bottommost note bar has moved, which triggers an update of the key's highlight graphic opacity, enabling gradual highlighting of keys.

Finally, when user presses a key on the piano, the MidiInputDevice registers this and sends a signal to the InputChecker object. Here it is determined whether or not the keystroke was a 'hit', or simply a wrong key press.
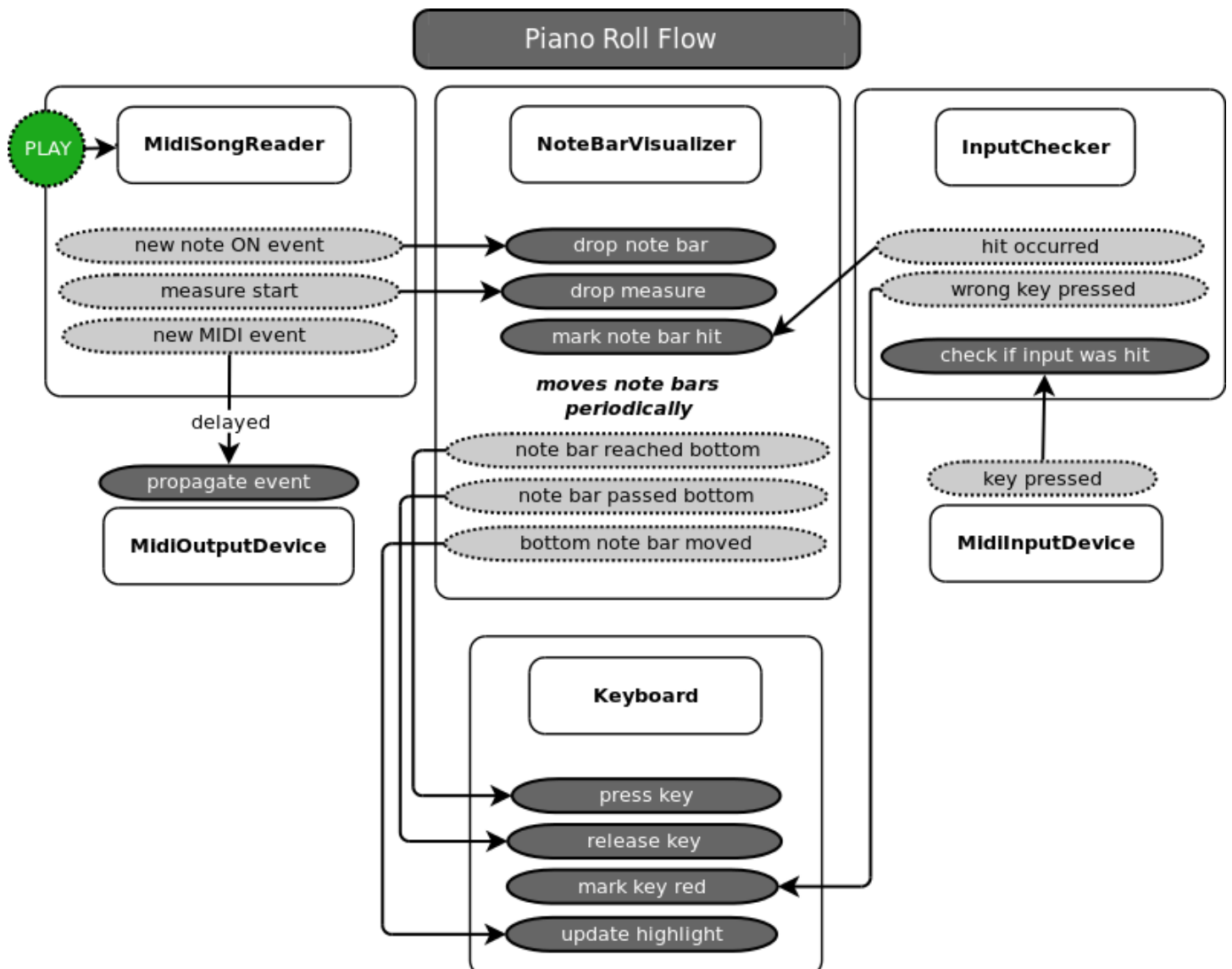
Figure 3.16: How the piano roll is moved. Light boxes represent emission of a signal, arrows leading to dark boxes represent a reaction to the corresponding signal.

4 Evaluation

4.1 User Test

A small-scale user test was done involving two children and an adolescent, which will be referred to as CH1 (child 1, age 5), CH2 (child 2, age 8), ADO (adolescent, age 20). All testers were female and had no background in music. CH2 and ADO had experience with games requiring quick reflexes.

The tests were done independently of each other. Each tester played two melodies with the right hand: first they were asked to play Twinkle Twinkle Little Star, after a few tries they moved on to Brother Jacob[1]. Both melodies included black keys to be pressed. Brother Jacob was slightly more difficult as it contained two trickier parts timing-wise.

The testers played each melody between 4 and 8 times, starting at 50% of full playback speed. Test performances are summarized in Table 4.1. Additional observations made during testing are summarized in Table 4.2.

	CH1	CH2	ADO
Initial Performance (50% speed)	Very poor.	71% hit rate, 9 wrong keys pressed.	100% hit rate, 3 wrong keys pressed.
Twinkle Twinkle Little Star	Consistently late in pressing keys.	Steady progress to 70% of playback speed, could not yet achieve a 100% hit ratio at full playback speed.	Achieved 100% hit ratio at full playback speed on fourth try.
Brother Jacob	Same as before.	Consistently struggled at Brother Jacob's difficult part. Could eventually play this part from memory, but not along with piano roll.	100% hit ratio at 50% playback speed on first try, progressed to 96% hit ratio at 70% playback speed on fourth try.

Table 4.1: Testers' performances.

---

[1]Also known as *Frère Jacques, Brother John, Brother Peter* or *Are you Sleeping?*.

	CH1	CH2	ADO
Used Peripheral View	No. Focused on piano keys only, looking for the gradual highlighting dots.	At first, very little, then suddenly 'got it' and performed better.	Yes.
Finger Use	Index finger, consistently	Index finger, consistently	At first, index finger. After seeing test organizer play a melody with entire hand, tried to use multiple fingers as well but struggled finding fingering that worked.
Black Key Accuracy[2]	Always missed.	Missed often at first, then same as white keys.	Same as white keys.
Level of Enthusiasm	Very high.	Extremely high. Stated she was having fun multiple times, did not want to stop.	Medium.
Additional Notes	Difficulty with timing and rhythm.	Spontaneously used note letter terminology 'so first C, then D, then C again...', even though test supervisor had not used the words.	None.

Table 4.2: Test findings.

Findings concerning finger usage of the test participants are in agreement with results found in [1], where they concluded that abstract visual ques (here, note bars) with no positioning hints attached to the visuals results in incorrect finger usage.

Findings concerning usage of peripheral view support earlier findings in [4], though here it is most likely attributed to the age category of the participants.

Although of little statistical value, these test performances and additional findings suggest that users can successfully learn one-handed melodies rapidly through the use of the augmented piano system.

---

[2]Projection on black keys is not visible, so they are not highlighted and remain black throughout, as mentioned in Section 4.2: Limitations

4.2   Limitations

4.2.1   Setup Limitations

Certain issues and limitations are inherent to the projection-based nature of the prototype setup, they are discussed next.

Sensitivity to lighting

Inherent to the use of projection, the setup is sensitive to lighting. When the environment is too light, little of the projected image will be visible. The material used for the projection board[3] may play a role in this. For optimal projection, the current setup should be placed in a partially darkened room.

Limited resolution

Due to the projector's limited maximum resolution (which is 1400x1050) in conjunction with the large projection area used, the resulting projection image has a limited resolution. This affects the amount of detail that can be put in the graphics used in the software.

Projection on black piano keys

Black surfaces absorb the light from the projector, this means that projection on black piano keys is note possible. This could be counter-acted by placing thin white strips on top of the black keys and then projection black onto these strips to camouflage them. In this way, projection of other colours will be visible on the keys. This was not tested however and may become an annoyance for the piano player.

Mounting the projector

The projector must be mounted high enough for the entire projection surface and piano keyboard to be included in the projected area. Suitable equipment or furniture is thus needed to construct the setup.

Need for calibration

Each time the setup is moved, the system must be re-calibrated for optimal projection. Depending on how much the setup components' positions have change in relation to each other, this may take some time to setup properly.

---

[3] Which is simply a wooden board painted white.

4.2.2 Software Limitations

The prototype has several limitations since it is not a polished piece of software. These limitations are discussed briefly in this section.

No detailed track selection

There is currently no option to select from the available tracks in the MIDI file. The software does present predetermined left hand and right hand tracks, based on a simple algorithm. These two tracks can then be customized. When there are more than two tracks present, the software does not allow these tracks to be customized.

Depency on quality of the MIDI file

The quality of the piano roll depends greatly on the quality of the MIDI file. If the MIDI file has poor quality, this will reflect itself on the piano roll. If the MIDI file puts all instruments onto one track, there is no way for the software to make a distinction between left hand and right hand notes, even though both are present in that one track.

Manual calibration

Right now, calibration of the projection parameters is done manually by specifying the parameter values in a text file. This means that when moving the setup to another location or when moving the projector, the setup has to be calibrated again. In future work, automatic calibration could be added so that the software can correctly project itself on a projection surface and piano. To make this possible, one-time tracking of the piano has to be done using for example a set of markers and a webcam mounted on the projector. Then, using computer vision techniques, the distance and angle to the piano could be measured. From these values, the projection parameters could be determined. This would be a complex addition to the system.

Simple menu

The current menu is more an interface to parameters in the software than it is an interface that is user-friendly. As such, limited attention has been brought to the appearance and functionality of the menu. This could be improved upon. More information and settings could be added as well, such as:

- Presenting additional MIDI file information,
  (e.g., which tracks are present, duration, tempo, time signature,......)

- Setting the default directory to search for MIDI files, or add multiple directories,

- Offer testing of input and output devices,

- Setting colour of the left and right hand tracks

- . . .

Non-adjustable settings during playback

Settings such as playback speed, visibility of tracks and drop speed of note bars cannot be adjusted once playback of a song has started. One has to return to the menu, change the desired settings and start playback from the beginning of the song.

Fixed playback from start to end

Songs can be played from start to end and paused at any moment. Selection of parts in the song to play, rewinding and fast-forwarding is not supported. This functionality could be added after extending the MidiSongReader class functionality.

No timer or progress bar

The current implementation has no timer or progress bar that shows how far into a song the piano roll currently is. This can be added easily since the MidiSongReader class has a timer which keeps the current time in miliseconds, and the Song class includes the total duration of a song.

Partial MIDI support

As mentioned in Section 3.2: Software Functionality, only those MIDI files that use one of the previously mentioned methods for signaling note off events are supported. During playback of MIDI files that don't use these methods, note bars never end and the piano roll becomes unclear very quickly, as seen in Figure 4.1. Support should be added for those MIDI files using other methods.
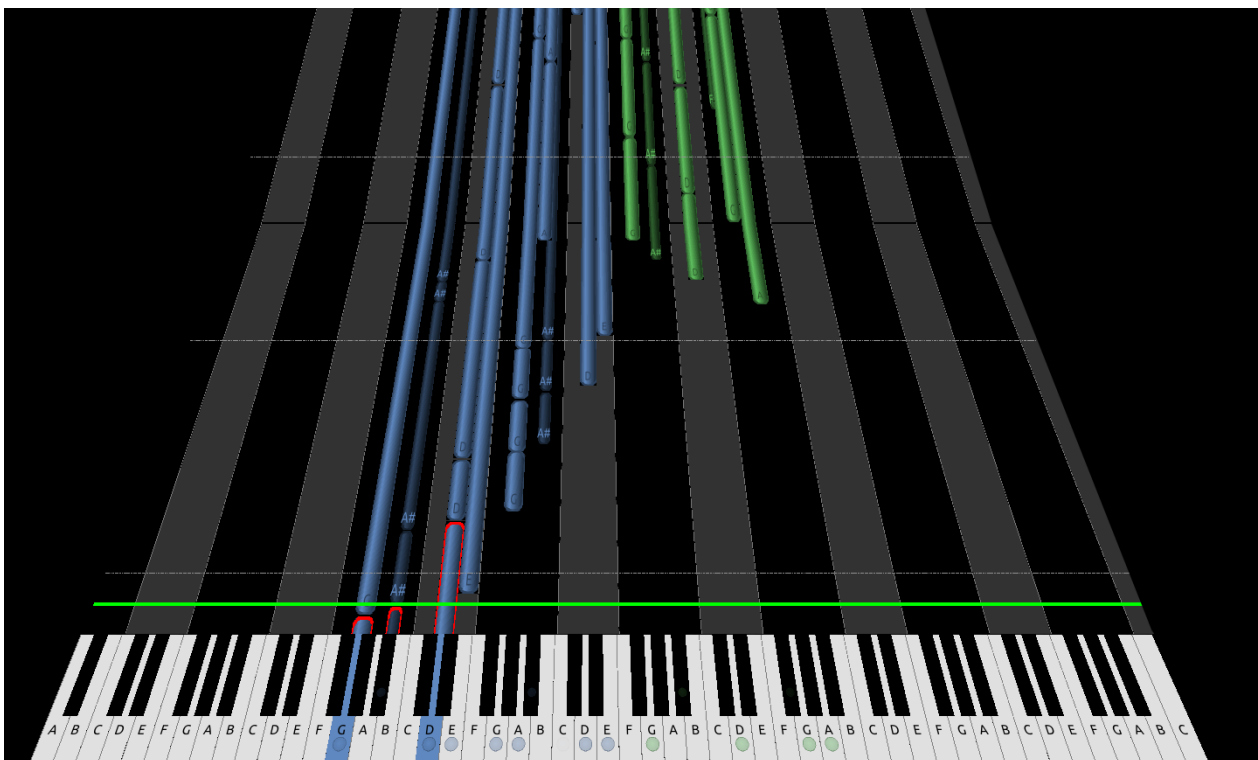

Figure 4.1: The piano roll when an unsupported MIDI file is played. Note bars remain *on* once that note is played once.

5 Future Work

This section discusses various additions to the augmented piano prototype system that can enhance the learning experience for beginning pianists, and make it a more complete system. It also offers some examples of potential real-world usage of the system, should it be developed further.

5.1 Adding Learning Value

At this moment, the system can be paused during playback, it can show when keys are to be pressed, note duration, note names on keys and note bars, and provide simple feedback on the user's input. Many additional features could be added that aid in piano learning in general. This section discusses some of these.

5.1.1 Improving Song Learning

In the current system, the user can customize the piano roll freely, but the available features are limited. For example, it cannot loop over smaller parts of a song. In this section, several goals for which the system could be used are discussed. From these, additional features will arise that can help the user when using the system to learn a song.

Familiarization

The user may want to become familiar with the song before deciding whether he wants to learn it or not. To support this, the system can simply play out the entire song through the piano roll. This can be done by the prototype system by disabling the input checks for left and right hand tracks. No new features need to be added.

Practice

One of the biggest difficulties in learning a song with the current system is that there is no way to repeat smaller parts of a song. It needs to be played from beginning to end. All the user can do during playback is pause and continue. When practising a musical piece on any instrument, usually small parts of the piece where the player is struggling are repeated until the desired level of proficiency for this part is reached. This is especially true for difficult parts. Currently, the system has no support for this way of practising. What the user can do at this moment, is pause the song just before a difficult part is to be played. Then he can take his time to learn which finger positioning works for that part and can slowly practice it without the piano roll moving. Optimally, the user should be able to select certain parts of the song he wants to practise, and loop these parts continuously until he wants to move on to other parts. This is not yet supported.

Another useful feature for practising is making the piano roll wait for correct input from the user, as is demonstrated in [4]. Currently the piano roll does not wait for the user. The user will have to repeat small parts at some slower speed until he can play that sequence. Depending on the user's experience, this may result in persistent key misses, possibly leading to frustration in the user. Having the piano roll wait while the user takes his time to find the correct keys can be of tremendous help to a user who is just beginning practice on a new musical piece, especially if he has little prior experience with playing the piano. This allows him to acquaintance himself with the piece at his own pace.

In conclusion, to provide better support for practising songs, two features could be added:

- Selecting parts of the song for playback,
  (in stead of forcing playback of the entire song)

- Looping over selected parts,

- Wait for correct input if desired.

Memorization

A downside of playing along with the piano roll is that it restricts the user in his musical freedom, as it imposes strict timing of notes. This stands in the way of emotional and musical expression. So at some point, the user may want to memorize a song to be able to play it without needing the piano roll to accompany him. Or the user may want not want to play along with the piano song at all, and utilizes the system for memorization only. Therefore, the system should provide features that aid the user in memorizing songs.

Memorization of a musical piece means the player cannot rely on any other reference point than his own memory to know what needs to be played next. Full attention must be brought to the hands, the structure of the song and boosting muscle memory. This is a gradual process and requires patience, especially if one is not used to memorizing musical pieces.

To see how the system could support memorization, one method to memorize a musical piece is discussed here briefly[1], though there are many different ways to accomplish this. In this method, the first thing to do is to learn the overall structure of the song, such as learning to play the right hand from memory. This can be done by dividing the song into smaller segments and memorizing them separately. Then, these segments can be put together until the entire song's right hand is memorized. For thorough memorization, the musician should be able to start playing from any of these separate segments in the song.

Then, focus can be brought to adding the left hand to each of these segments. For each segment, the left hand should be practised separately, and when the musician is ready, he can start playing that segment both hands. Eventually, the musician will be able to play the song entirely from memory using both hands[2].

The system could allow the user to mimic this process by offering a set of features that reflect different aspects of it. These features are as follows:

---

[1]This discussion serves a mere exemplary role. The method discussed is not intended to be the best method for memorization, though it is advocated in *Fundamentals of Piano Practice* [9].

[2]Note that in the method just discussed, attention is brought *immediately* to memorization, only afterwards does practice occur.

- Dividing the song into segments,

- Practising of a particular segment or a chain of segments,

- Testing of the user's ability to reproduce a segment or chain of segments from memory.

5.1.2 Transitioning to Sheet Music Notation

Besides helping the user learn a musical piece, the system could aid in teaching the user how to read sheet music. In this case, support for MusicXML files should be added since they store sheet music notation elements.

Adding Subtle Sheet Music Notation Elements to the Piano Roll

If the user has no background in music theory, e.g., does not yet know terms such as accidentals, articulation, dynamics, it may help to add subtle visual elements to the piano roll that represent these concepts. Once the user moves on to reading sheet music, he will already be familiar with these concepts and will only need to learn the sheet music notation for them.

Note accidentals[3] are already integrated into the piano roll. Sharps and flats (black keys) are represented by note bars with darker colours than note bars representing natural notes (white keys), as seen in Figure 3.10 in Section 3.2.2: The Piano Roll. Note articulation, such as whether notes should be played staccato or legato, has been successfully integrated into the piano roll by [4], see Figure 5.1 for their solution. In a similar manner, visual elements can be added for note dynamics and other sheet music notation elements not discussed here, such as time signature or tempo changes. The system should first teach the user what each of these elements mean in an intuitive manner. However, care has to be taken that the piano roll does not get too overwhelming, since adding too many visual elements can cause confusion in the user. This approach will not work for all elements of sheet music notation, but it may nonetheless help ease the transition from piano roll to sheet music.

Deliberate Teaching of Sheet Music Notation Elements

When the user wishes to transition to sheet music, the system can switch from the piano roll to sheet music notation. This is possible once MusicXML files are supported. The first steps would be familiarization with the basics, such as learning what a grand staff and clefs are. Then the user will have to learn which note on the grand staff represents which key. This is a skill the user can only develop by practising, and here the system can be of help.

The system could proceed like common music education software[4], where notation and music theory elements are taught and then tested by taking user input and giving feedback on that input. An example is showing a note on on the grand staff and asking the user what that note is called[5], or showing a few measures with notes and asking the user to 'tap' the duration of those notes.

Another approach is to incorporate the concept of a *sheet music roll* to train the user's sight-reading ability. This assumes the user can read notes to a certain extent, so this approach may be used in conjunction with the approach discussed in the previous paragraph.

---

[3]Natural, flat or sharp notes.

[4]Such as the free and open-source online tool MusTeacH: http://www.musteach.com

[5]See an example here: http://www.musteach.com/en/music_training/theory/note_names/10
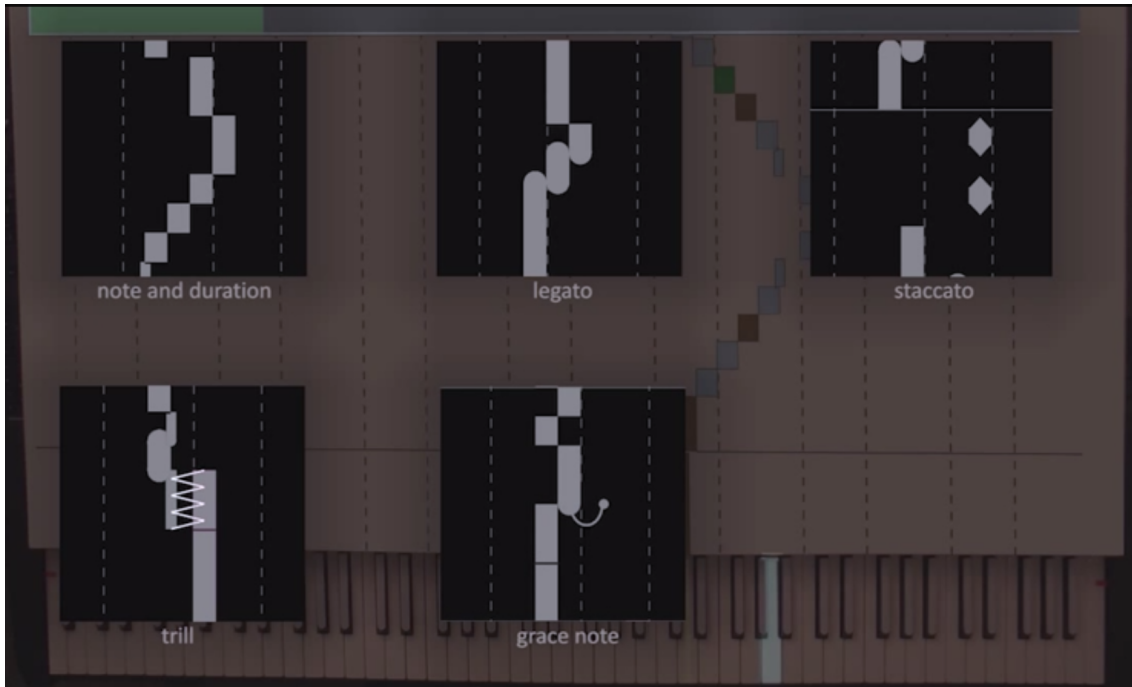
Figure 5.1: Representations for legato, staccato, trills and grace notes in the P.I.A.N.O. system [4].

A software example of this concept is PianoBooster[5], an open-source piano teaching program depicted in Figure 5.2.

Here, a grand staff is shown stationary on the screen, and notes move from the right side toward the left, much like note bars on the piano roll that move down toward the keys[6]. The main difference is that real sheet music notation is being used which trains the user's sight-reading abilities. In PianoBooster, the sheet music roll can be configured to wait for the user's correct input. It can also provide feedback when notes are played correctly or incorrectly, as is annotated in Figure 5.2.

In summary, the following features could support music notation learning:

- Piano roll visuals that hint at music notation elements,

- Features for teaching the basics of music notation,

- Playback of a song using a sheet music roll in stead of a piano roll.

It is noted that the features mentioned in Section 5.1.1: Improving Song Learning can also be applied when the concept of a sheet music roll is used.

---

[6]An example of PianoBooster in action can be seen here: https://www.youtube.com/watch?v=UGbfm8Tv-20

Figure 5.2: PianoBooster uses a sheet music roll to train the player's sight-reading ability. Image extracted from [5].

5.1.3   Chords and Scales

Chords and scales are an integral part of music theory, they help the pianist gain deeper musical understanding and help in improving playing techn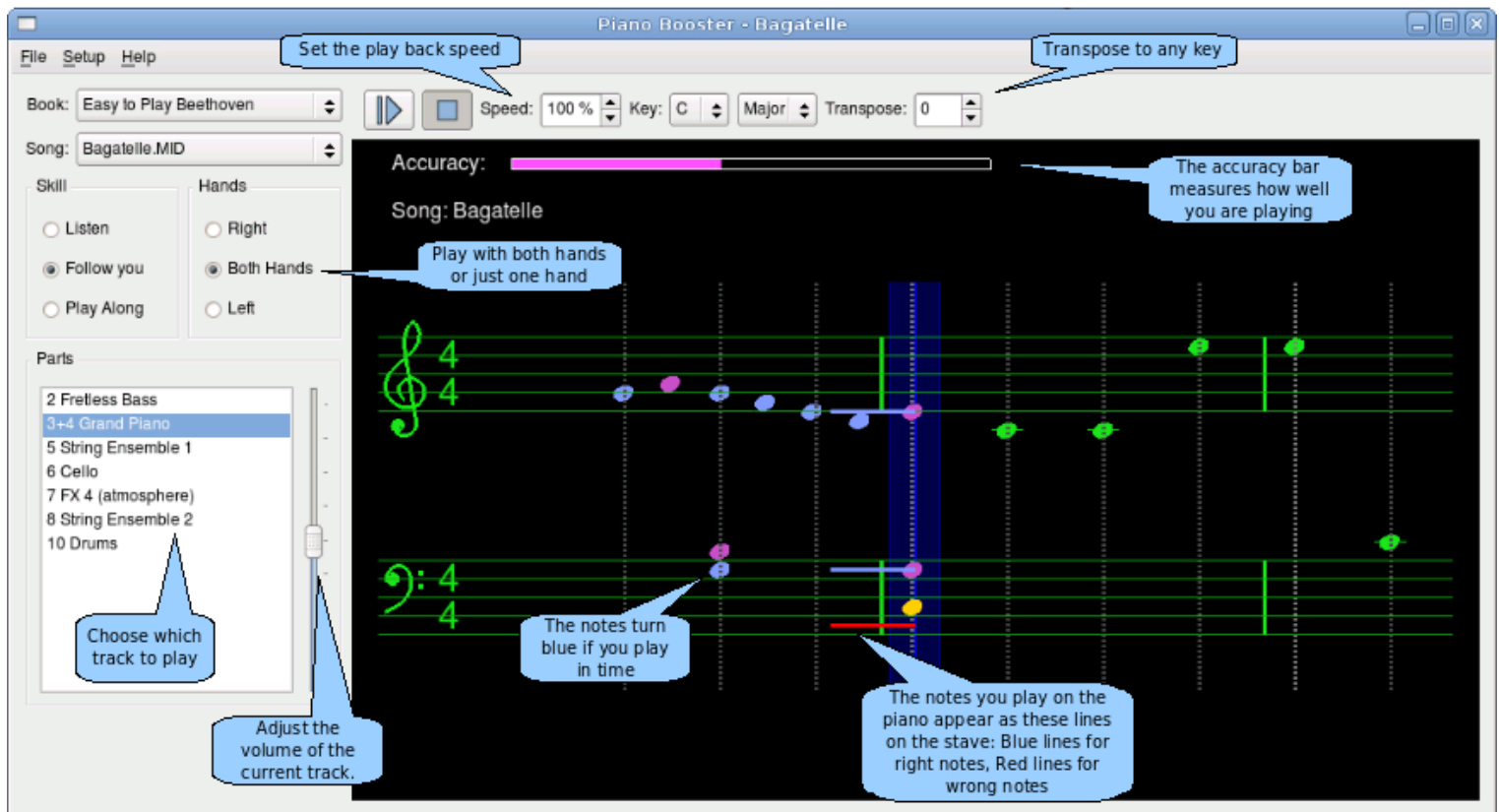ique. The system could help the user learn chords, chords patterns and scales in interactive ways, similar to [6]. This can be done dynamically using a piano roll or sheet music roll, requiring the user to play chords or scales, or statically such as questioning what the name of a chord is, as is done in most music education software. The ability of the system to project onto the piano keys should also be utilized here, such as highlighting keys that make up a particular chord or scale, and marking keys red when a chord or scale is played wrongly.

When playing scales, one goal is to play fast as possible while still using correct form. Thus, learning a new scale is more complex and requires more practice than learning a new chord. For this reason, there should be a way for the user to practise a particular scale. At first, the scale could be played while the piano roll waits for input. This allows the user to acquaintance himself with the scale and memorize it. Then, the user could work on the accuracy and speed at which he can play that particular scale. The same can be applied to learning chord patterns, where for example, the user is asked to play a number of chords in succession.

To keep track of the user's progress, the system could contain a chord catalogue and a scale catalogue. Statistics such as his maximum scores in both accuracy and speed, recognition ability, and his evolution over time and can be kept for each entry.

Another addition to the system could be for the system to recognize chords and scales played by the user. This allows the user to learn about new chords and scales when he is experimenting freely.

In conclusion, the following features could be implemented to support chords and scale learning:

- A chord/scale catalogue,
- Modes for:
    - Practising chords/scales,
    - Testing the user's ability to recognize chords/scales,
    - Testing the user's ability to play chord patterns,
    - Testing the user's ability to play particular scales (accuracy/speed),
- Chord/scale recognition of a user's keystrokes.

5.1.4 Finger Positioning

Sheet music can sometimes give hints as to how the player's fingers should be positioned to play a particular part. This usually indicates the most effective way to play that part. See Figure 5.3 for an example. Especially when learning scales, it is important to apply the correct fingering to develop proper technique. The importance of providing fingering hints when using abstract visual cues is also noted in [1]. To access these finger positioning hints, MusicXML files must be supported.[7].

Figure 5.3: A segment of sheet music with finger positioning hints. The user's fingers are numbered from 1 to 5, 1 being the thumb and 5 being the pinky finger. These numbers are put above notes to indicate which finger should be used to play that note.

To incorporate this information into the piano roll, the numbers could simply be added to the note bars. Another approach as applied by [4] is to use colours which indicate particular fingers. In a sheet music roll mode, this information can be added directly to the corresponding notes.

When finger positioning hints are not present in the MusicXML, the user may still want to remind himself in the future which finger positioning works for certain parts, in case he does not play the piece for a long time and forgets the fingering he had used in the past. To support this, the system could let the user add finger positioning hints, both in the piano roll and sheet music roll mode, and write this information to the file.

When finger positioning hints are present providing feedback on the user's finger usage is not straightforward. It could be accomplished by tracking the fingers, as is executed by [4].

To summarize, these features could be added to better support finger positioning hints:

- Add visuals to the piano roll which can indicate fingers, such as the numbers 1-5,

- Allow the user to add these hints to note bars or notes when they are not present, and write these to the MusicXML file.

---

[7]Hints can be set using the *fingering* element, found here: http://www.musicxml.com/for-developers/alphabetical-index/

5.2 Real-world Usage

Before the system can be put to public use, certain improvements (Section 4.2: Limitations and extensions (Section 5.1: Adding Learning Value) should be added to turn it into a well-rounded piano learning system. Even though there are some limitations with the projection-based setup, it may be still be used in situations where the benefits of the system outweigh these issues. Alternatively, a different setup method[8]could be used which does not have these limitations. As such, there are multiple areas outside the research area where such a finished system could be used. This section discusses the system's potential usage in those areas.

5.2.1 Music Education

Music Schools and Piano Lessons

A potential area of use is in music schools or any kind of institution offering music lessons where the student's primary instrument is the piano. Some institutions require a mandatory, pre-instrumental year where the student learns music theory and music notation before he is allowed to start playing an instrument of choice, while others offer hands-on instrument lessons right away.

As mentioned in Section 1.1: Background, becoming familiar with music notation takes time, patience and effort. In all kinds of beginner classes, the augmented piano system may be used to grant immediate piano playing experience without the need for sheet music music notation knowledge. In this way, simple songs could be learned immediately to get a feel for the piano while the student develops an understanding of sheet music music notation. Introducing sheet music notation could be done entirely separate from the system or in an integrated way, where the system itself is used to teach music notation concepts. In the latter, the students can gradually move away from the system as they become more familiar with reading sheet music. This could be especially interesting for children.

Supporting Autodidacts

Taking music classes is not the only option for those who wish to learn an instrument. Those choosing to learn by themselves may turn to books or the Internet. For these individuals, the system could be deployed as a personal piano learning system intended for home-use. The system can then act as a virtual teacher, which guides the individual from playing along with the piano roll to learning to read sheet music, if they wish to do so.

When a beginning pianist sees a note or chord in a book or on the Internet, but plays it wrongly on the piano, he may end up consistently pressing the wrong keys and he may not find out until much later. This holds true for other aspects such as when practising scales or when he is just starting to read notes. An advantage of the system is that it can provide immediate feedback in all these cases, meaning the player will know immediately if he is playing incorrect notes. This can help the autodidact in learning more quickly and with less mistakes.

---

[8]Such as using a touch table positioned behind the piano, discussed in Section 3.1.1: Setup Methods.

5.2.2 Entertainment

A completely different area in which the system could be used is in entertainment. Music video games today enjoy widespread popularity, including games such as Guitar Hero[9], Rockband[10], Rocksmith[11], the earlier mentioned Synthesia game[12], Dance Dance Revolution[13], the mobile game Tap Tap Revenge[14] and the open-source game Frets on Fire[15]. Even though each individual game may be different, they are similar in that the player is to press a button or perform an action based at precise times, determined by the rhythm of the music and aided by visual cues on-screen. The player is then usually awarded points based on how accurately he can press the required buttons, and a result screen shows how many hits or misses he scored.

These game concepts can be applied to the augmented piano system in various degrees. They may be applied as gamification elements in an educational-oriented version of the system, such as rewarding points for correct keystrokes, scoreboards for individual songs, online leaderboards, and so on, while still focusing on learning songs and/or music education. Or the game concept can be the centerpoint of an entertainment-oriented version of the system which does not intend to have much educational value.

An example of what such an entertainment system may be like is the Japanese game Keyboardmania[16], which was originally developed as an arcade system but has also been released for PlayStation 2 and PC with an accompanied controller keyboard (see Figure 5.4). The game in action can be viewed here[17]. The system could be developed into a similar game which then takes place behind a real, digital piano, using projection in stead of a computer monitor. Two players could be seated next to each other behind the same piano, and then battle each other during the same song. This VS mode can also be applied with two people on two separate pianos, which are put adjacent to each other and share a similar projection board. In stead of a VS mode, two players may play together to help each other in stead of battling each other.

As the previous discussions show, there is plenty of opportunity for the system to be developed further.

---

[14]http://en.wikipedia.org/wiki/Tap_Tap_Revenge

[15]http://guitarhero.com/

[15]www.rockband.com/

[15]http://rocksmith.ubi.com/rocksmith/en-GB/home/index.aspx

[15]http://www.synthesiagame.com/

[15]http://en.wikipedia.org/wiki/Dance_Dance_Revolution

[15]http://fretsonfire.sourceforge.net/

[17]Test participants did this several times after formal testing was completed. All that was needed was a modified MIDI file containing two identical tracks for left hand and right hand track.

[17]http://en.wikipedia.org/wiki/Keyboardmania

[17]http://www.youtube.com/watch?v=yV2DKNpkCvo

Figure 5.4: The game Keyboardmania.

6 Conclusions

6.1 Overview

The aim of the thesis has been to prototype an augmented piano system that utilizes the piano roll concept, and to identify possible future additions which can add to the learning value of the system. This system was then implemented successfully[1], and positive results were obtained in a small-scale user test suggesting that the concept can be advanced further in the area of piano learning.

Main benefits of the system include the interactive and to-scale visualization on the physical piano, delivery of immediate feedback, and the ability for users to play the piano immediately without requiring prior knowledge of sheet music notation or music theory.

Major limitations of the system in a projection-based setup include sensitivity to environmental lighting, limited resolution of the projected image and lack of projection on black piano keys, though the latter may be solved by applying a material onto the top of the black keys. All these issues may be be resolved by considering a touch table-based setup in which visualization on keys is retained, though in virtual form, by visualizing to-scale piano keys at the bottom of the screen.

Incorrect usage of fingering was observed in all participants of the user test. This should be resolved by adding fingering information to the piano roll, or by adopting the methods of [4]. Another possibility is to join the Orphan interface [1] with the piano roll to place both detailed hand and fingering information and an overview of upcoming notes in the view of the user. Although not formally tested, another potential drawback attributed to the use of a piano roll is that it may encourage *reaction* to falling note bars in favour of memorization of notes. Research should be conducted that investigates this.

It was illustrated that the thesis results can be built upon for use in two main domains: music education and entertainment (Section 5: Future Work). In music education, the system could be expanded to support the beginning pianist in transitioning to the traditional sheet music notation by levering the interactive and to-scale visualization inherent to the system. To strive toward an optimal learning experience, the system could be further evaluated in the conceptual framework for serious games [3]. Support for MusicXML is to be added if advancements in the music education domain are to be made. Enough opportunities exist for the system to be used solely as an entertainment system.

The system is currently only suited for use with a digital piano which has the right physical characteristics to accommodate the projection surface. To expand its usage to upright and grand acoustic pianos, the prototype setup in [10] involving a grand piano could be investigated. Hand gestures and upper body visualization could then be replaced by the visualizations discussed here.

---

[1]And can be seen in action here: http://research.edm.uhasselt.be/tap/

6.2   Lessons Learned

It was my first time working with a projection-based setup, so I had to adjust what is drawn on-screen to produce the required output on the piano. Initially, I had some fears regarding to whether the projected image could be calibrated properly onto the piano keys. Despite those fears, calibration of the setup proved to be less difficult than I had thought.

As is the case for most students pursuing a bachelor's degree in Computer Science, this thesis represents my most comprehensive work in both writing and implementation so far. Undertaking such a large project has been a challenge, but I have managed to complete the project successfully which will aid me in similar undertakings in the future. Specifically, I learned more about the research environment by reviewing selected pieces of related work.

I have also learned that when trusting the gut feeling that sometimes nudges you to move outside of your comfort zone, new and unforseen opportunities may arise unexpectedly.

Bibliography

[1] X. Xiao and H. Ishii, "MirrorFugue : Communicating Hand Gesture in Remote Piano Collaboration," *The Organ*, pp. 13–20, 2011.

[2] E. Cano, S. Grollmisch, and C. Dittmar, "Songs2See : Towards a New Generation of Music Performance Games," no. June, pp. 19–22, 2012.

[3] A. Yusoff, R. Crowder, L. Gilbert, and G. Wills, "A Conceptual Framework for Serious Games," *2009 Ninth IEEE International Conference on Advanced Learning Technologies*, pp. 21–23, 2009.

[4] M. Weing, A. Rohlig, K. Rogers, J. Gugenheimer, F. Schaub, B. Konings, E. Rukzio, and M. Weber, "P.I.A.N.O. - Enhancing Instrument Learning via Interactive Projected Augmentation," 2013.

[5] "PianoBooster." http://pianobooster.sourceforge.net/. Accessed: August 2013.

[6] I. Barakonyi and D. Schmalstieg, "Augmented Reality Agents in the Development Pipeline of Computer Entertainment ,"

[7] R. T. Azuma, "A Survey of Augmented Reality ," *Presence: Teleoperators and Virtual Environments*, vol. 6, pp. 355–385, August 1997.

[8] M. M. Association, "An Introduction to MIDI," 2009.

[9] C. C. Chang, *Fundamentals of Piano Practice*. August 2007.

[10] X. Xiao, L. Gust, and H. Ishii, "MirrorFugue2 : Embodied Representation of Recorded Piano Performances," pp. 2–5.

[11] "Synthesia." http://www.synthesiagame.com/. Accessed: April 2013.

[12] J. Kleimola, "Visually Augmented Musical Instruments," May 2008.

Acronyms

API Application Programming Interface. 44, *Glossary:* API

AR Augmented Reality. 44, *Glossary:* augmented reality

HMD Head-Mounted Display. 44, *Glossary:* head-mounted display

MIDI Musical Instrument Digital Interface. 44, *Glossary:* MIDI

Glossary

accidental a sign indicating a momentary departure from the key signature by raising or lowering a note.. 44

API An Application Programming Interface (API) is a particular set of rules and specifications that a software program can follow to access and make use of the services and resources provided by another particular software program that implements that API. 44

articulation clarity in the production of successive notes.. 44

augmented reality a technology that superimposes a computer-generated image on a user's view of the real world, thus providing a composite view.. 44

beat a main accent or rhythmic unit in music or poetry.. 44

chord a group of (typically three or more) notes sounded together, as a basis of harmony.. 44

clef any of several symbols placed at the left-hand end of a staff, indicating the pitch of the notes written on it.. 44

computer vision a branch of artificial intelligence and image processing concerned with computer processing of images from the real world.. 44

dynamics the varying levels of volume of sound in different parts of a musical performance.. 44

flat a musical note lowered a semitone below natural pitch.. 44

grand staff a set of five horizontal lines and four spaces, each of which represents a different musical pitch.. 44

head-mounted display a display device, worn on the head or as part of a helmet, that has a small display optic in front of one (monocular HMD) or each eye (binocular HMD).. 44

instrument an object or device for producing musical sounds.. 44

keystroke a single depression of a key on a keyboard.. 44

legato in a smooth, flowing manner, without breaks between notes.. 44

measure any of the sections, typically of equal time value, into which a musical composition is divided, shown on a score by vertical lines across the staff; bar.. 44

melody a sequence of single notes that is musically satisfying. 44

MIDI a widely used standard for interconnecting electronic musical instruments and computers.. 44

music video game a video game where the gameplay is meaningfully and often almost entirely oriented around the player's interactions with a musical score or individual songs.. 44

MusicXML an open, XML-based music notation file format.. 44

note a single tone of definite pitch made by a musical instrument or the human voice.. 44

piano roll a roll of perforated paper that controls the movement of the keys in a player piano or similar instrument, so producing a particular melody.. 44

scale an arrangement of the notes in any system of music in ascending or descending order of pitch.. 44

score a written representation of a musical composition showing all the vocal and instrumental parts arranged one below the other.. 44

sharp a musical note raised a semitone above natural pitch.. 44

staccato with each sound or note sharply detached or separated from the others.. 44

tablature a form of musical notation indicating fingering rather than the pitch of notes, written on lines corresponding to, for example, the strings of a guitar or the holes on a flute.. 44

tempo the speed at which a passage of music is or should be played.. 44

time signature an indication of rhythm following a clef, generally expressed as a fraction with the denominator defining the beat as a division of a whole note and the numerator giving the number of beats in each measure.. 44